Numerical Simulations of Vegetated Wave Hydrodynamics for Practical Applications

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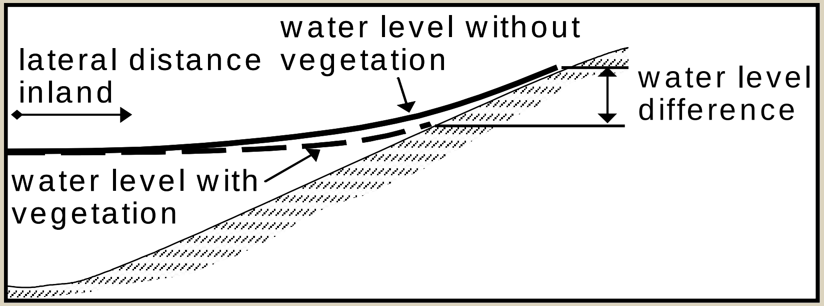
Motivation

- **to investigate the impact of vegetation on wave-induced flow**
  - wave attenuation
    - energy loss through work performed on plants
    - function of plant characteristics and wave parameters

$$\frac{\partial E}{\partial t}+\frac{\partial\left(EC_G\right)}{\partial x}=\underline{-\varepsilon}$$



  - reduce wave setup
    - component of storm surge

$$\rho g(h+\overline{\eta})\frac{\partial\overline{\eta}}{\partial x}=-\frac{\partial S_{xx}}{\partial x}-\underline{f_x}$$

Overview of Methodology

- **Field visit to Galveston Bay, Texas**
- **Laboratory flume experiments**
  - conducted in 3-D wave basin at Texas A&M's Haynes Coastal Engineering Laboratory
  - seven different random cylinder arrays
  - three water depths
  - monochromatic waves with wave periods between 1-2 s
  - obtained free surface elevation and velocity measurements
- **Development of a simple 1-D wave transformation model**
  - implements numerical description of vegetative effects on waves derived by Dalrymple et al. (1984)
  - best fit to experimental data obtained considering drag coefficient C_D as only calibration parameter

Summary of Conclusions

- **implementation of Dalrymple et al. (1984) formulation feasible**
  - drag coefficient must be calibrated for specific plant type
- **focus on drag coefficient**
  - C_D decreases with increasing density for longer wave periods
  - C_D increases with larger stem spacing standard deviation
  - possibly due to upstream wake sheltering effects (Nepf,1999)
- **wave attenuation by vegetation is a highly dynamic process**
  - quantification highly desirable and important for accurately predicting coastal hydrodynamics

Outline

- Literature Review
- Experimental Methods
- Preliminary Results
- Numerical Analysis
- Conclusions
- Future Research

Literature Review

- **coastal vegetation known to provide diverse habitats and economic benefits as well as dissipate wave energy**

Author	*Results*
Knutson et al. (1982)	50% wave energy dissipated within first 2.5m
Möller et al. (1999)	wave attenuation over saltmarsh 50% higher than sandflat
Dean et al. (2006)	setup reduced by 2/3 by linear theory in shallow water limit
Augustin et al. (2009)	wave attenuation 50 to 200% higher in emergent than near-emergent

- **influence of vegetation not fully quantified nor implemented in wave and hydrodynamic models**
  - typically accounted for using bottom friction terms such as Manning's n
  - bottom friction approximations do not accurately capture the impact of vegetation (Kadlec, 1990)
- **numerous models exist that attempt to explain the interactions between waves and vegetation**

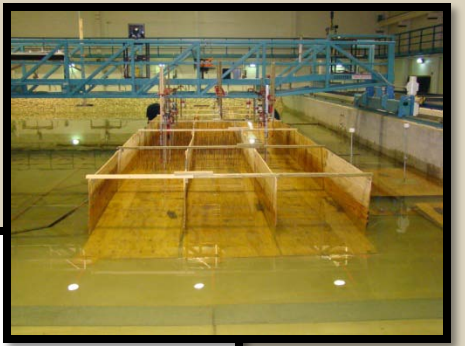
Author	*Method of Formulation*
Dalrymple et al. (1984)	conservation of wave energy, linear theory
Kobayashi et al. (1993)	continuity and linearized momentum equations
Asano et al. (1992)	expanded upon Kobayashi to include plant motion
Mendez et al. (2004)	expanded upon Dalrymple to develop an empirical model for monochromatic and random waves, variable depth, and wave breaking

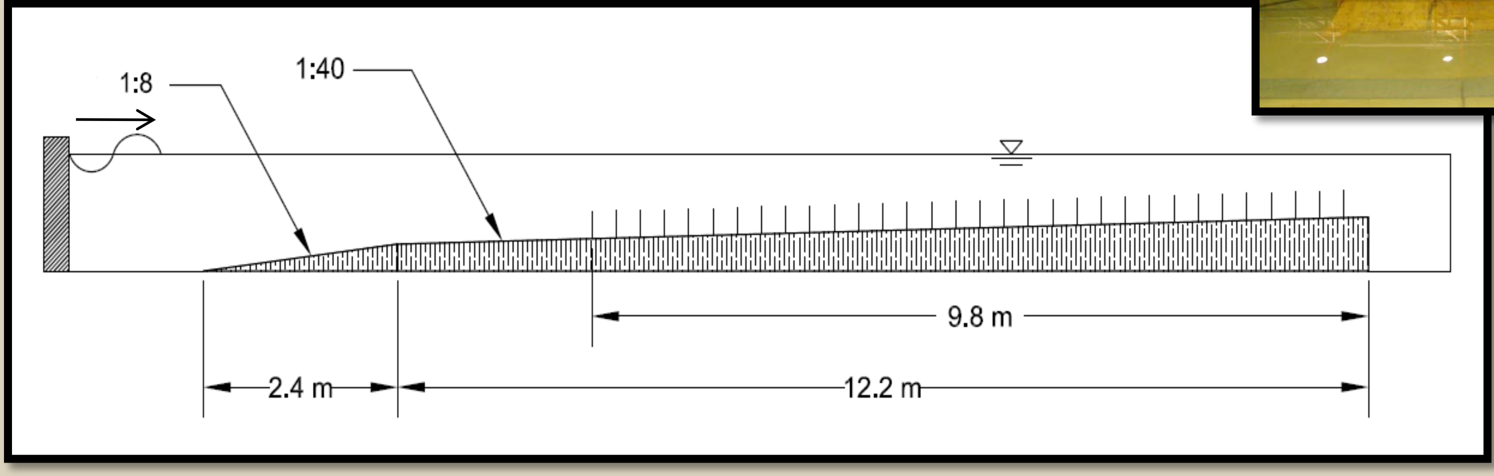
Experimental Methods

- **Field Visit to Galveston Bay, Texas**
  - primarily consisted of *Spartina alterniflora*
  - collected the following vegetation characteristics:
    - stem diameter
    - mechanical properties
    - density
    - stem spacing distribution
  - average diameter: 4.5 mm
  - dense areas averaged 7-10 cm spacing between stems while sparse areas averaged 10 cm spacing between stems

Experimental Methods

- **Model Setup**
  - conducted in 3-D basin at Haynes Coastal Engineering Laboratory
  - constructed three neighboring, individual flumes
    - 1.2 m wide,12.2 m long
    - 1:40 sloping bottom
  - vegetation field started 2.4 m from beginning of flume
  - secondary 2.4 m small ramp with 1:8 slope constructed at beginning to shoal waves to desired depth



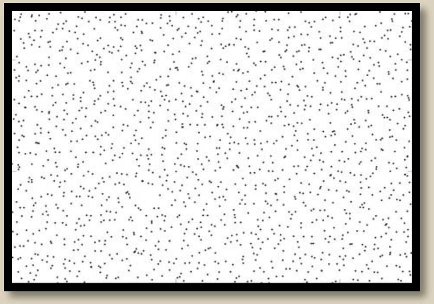


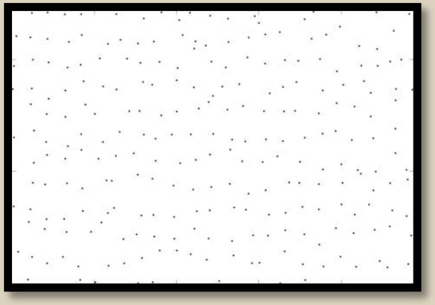
Experimental Methods

- **Synthetic Vegetation and Scenarios**
  - vegetation stems simulated by wooden dowel rods
    - 6.4 mm diameter, 0.3 m height
  - constructed random cylinder arrays
    - better representation of natural environment
    - majority of previous research conducted with cylinders spaced at regular increments

Scenario Number	*Avg. Distance between stems (cm)*	*Density (stems/m^2)*	*Standard deviation - % of avg. distance (cm)*
0	-	-	-
2	4	625	1.6 (40%)
3	4	625	2.4 (60%)
4	7	204	1.4 (20%)
5	7	204	2.8 (40%)
6	7	204	4.2 (60%)
7*	11	83	6.6 (60%)
8	11	83	4.4 (40%)
9	11	83	2.2 (20%)

Scenario 2



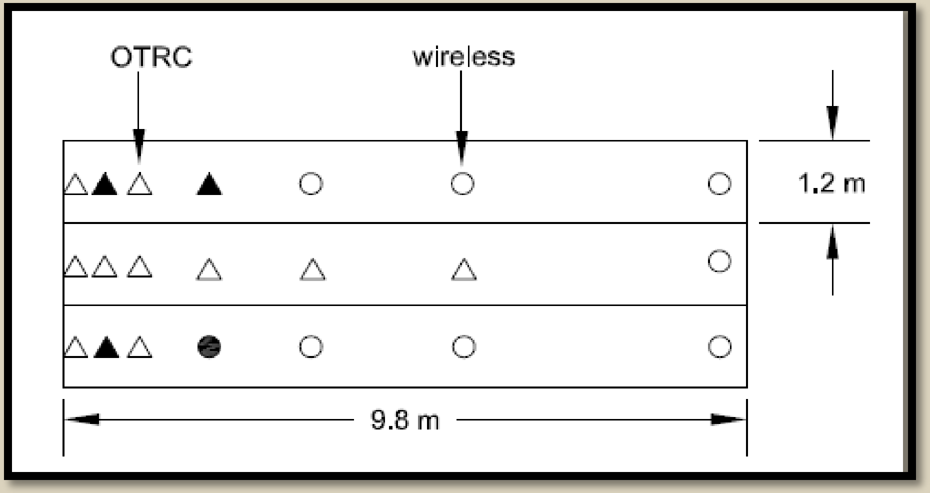


Scenario 9

*constructed but not implemented

Experimental Methods

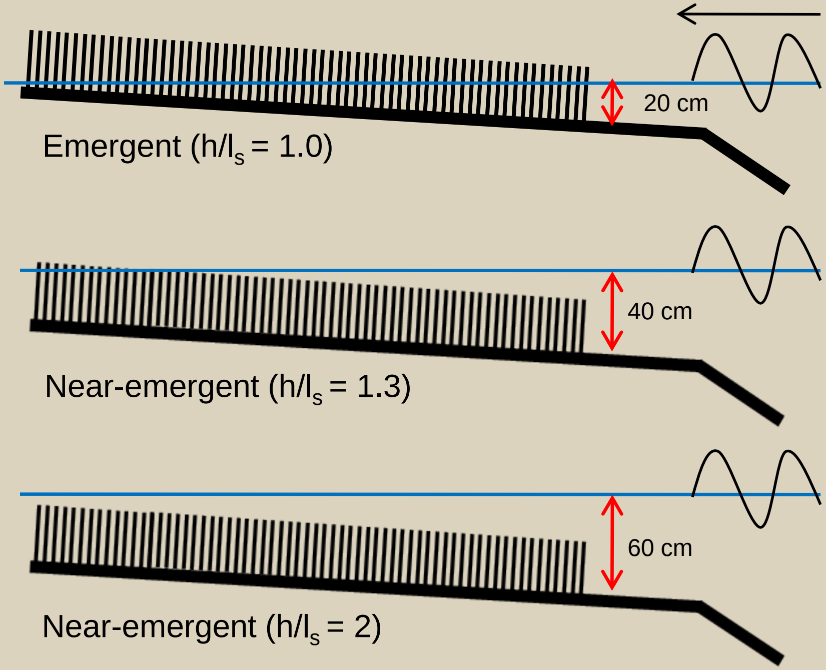
- **Instrumentation and Data Acquisition**
  - 21 capacitance wave gauges to measure free surface elevation
  - four 3-D Acoustic Doppler Velocimeters (ADV's) to measure orbital velocity
  - collected time series data for 300 s sampling at 25 Hz using LabVIEW Multiple Channel Data Acquisition System



Experimental Methods

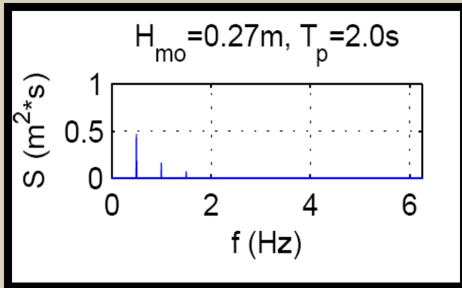
- **Hydrodynamic Conditions**
  - three water depths: 60 cm, 40 cm, 20 cm
    - correspond to a ratio of water depth to vegetation height (h/l_s) for emergent (h/l_s=1.0) and near-emergent conditions (h/l_s=1.3 and 2)
  - monochromatic wave conditions

Water Depth (cm)	Wave height at wavemaker (m)	Wave period (s)
60	0.28	1.2
	0.28	2.0
40	0.28	1.0
	0.28	2.0
20	0.17	1.0
	0.13	2.0
	0.10	2.0
	0.14	1.5
	0.13	1.0

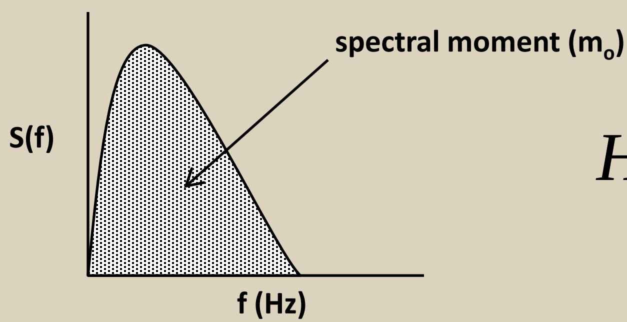


Preliminary Results

- **Wave Heights**
  - obtained for 60 cm and 40 cm water depths from time series data using spectral analysis
    - observed nonlinear processes such as presence of higher-frequency bound harmonics



  - spectral energy density calculated by transforming time series to the frequency domain using Fast Fourier Transformation

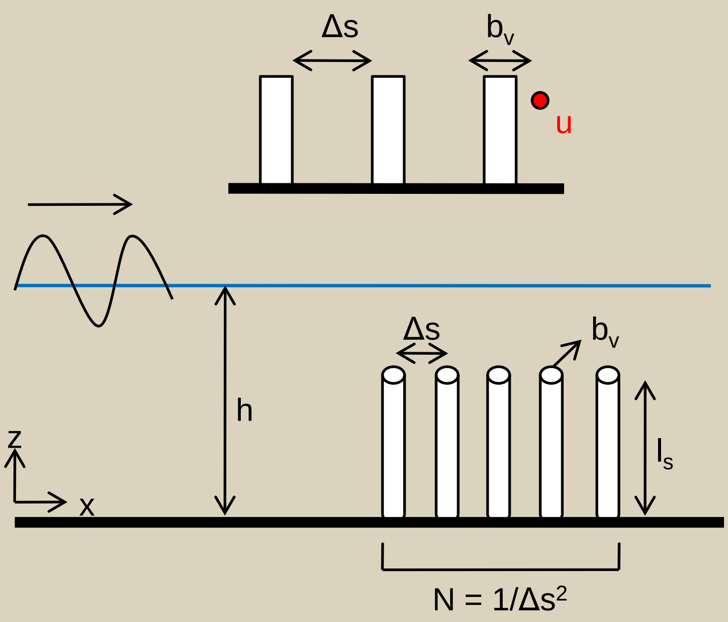


$$H_{mo} = 4\sqrt{m_o}$$

Numerical Analysis

- **Dalrymple et al. formulation**
  - represented vegetation as an array of vertical, rigid cylinders
  - considers arbitrary water depth and vertical extent of cylinders
  - based on conservation of energy equation and assumes validity of linear theory
  - dissipation only due to drag force, F_D

$$F_D = \frac{1}{2}\rho C_D b_v N u|u| \qquad \varepsilon_v = F_D u$$

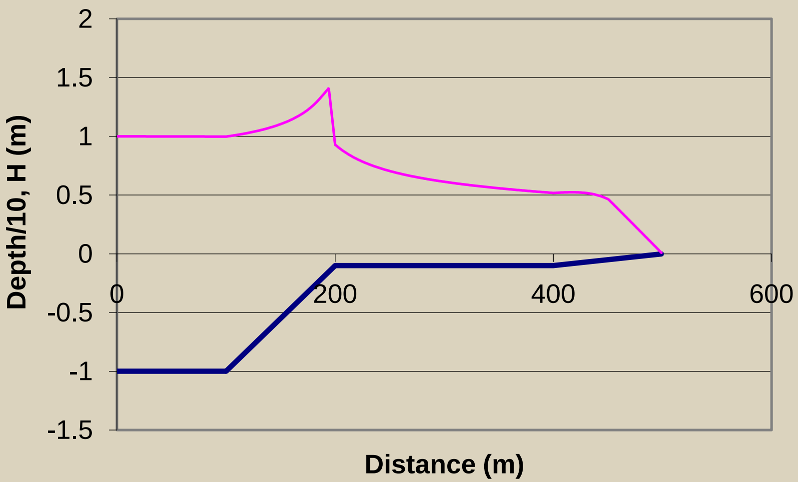


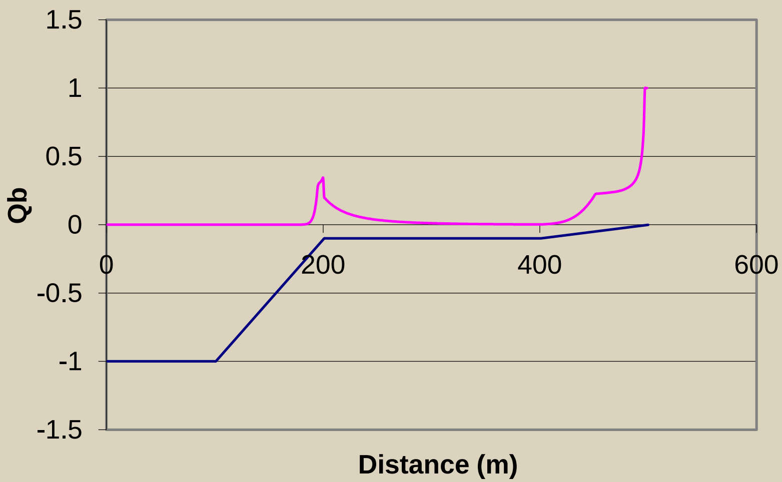
integrating over the length of the plant…

$$\frac{\partial(EC_g)}{\partial x} = -\varepsilon_v = -\frac{2}{3\pi}\rho C_D b_v N\left(\frac{kg}{2\sigma}\right)^3 \frac{\sinh^3 kl_s + 3\sinh kl_s}{3k\cosh^3 kh} H^3$$

Numerical Analysis

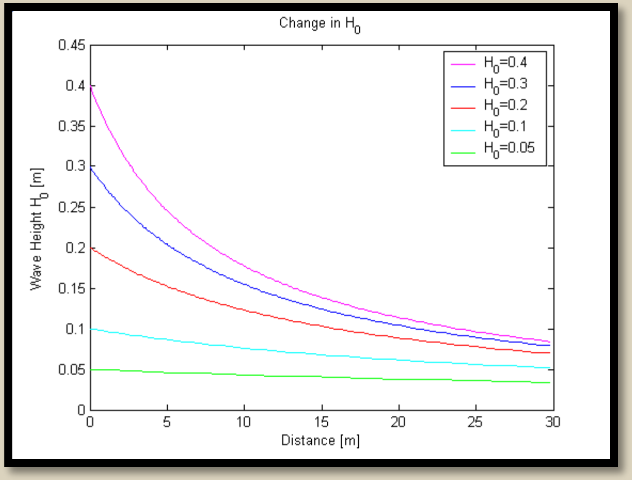
- **1-D Wave Transformation Model**
  - coded in Fortran90
  - accounts for shoaling, wave breaking (Battjes and Janssen, 1978), and wave energy dissipation due to vegetation (Dalrymple et al., 1984)
  - inputs: bathymetry, wave parameters, vegetation characteristics
  - outputs: wave heights, calibrated drag coefficient, ratio of breaking waves

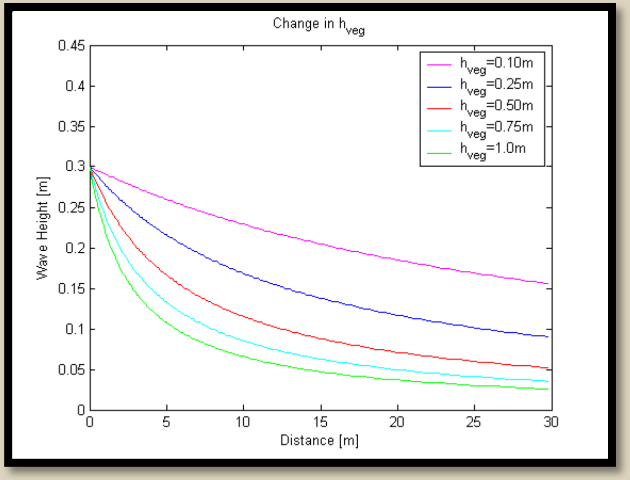


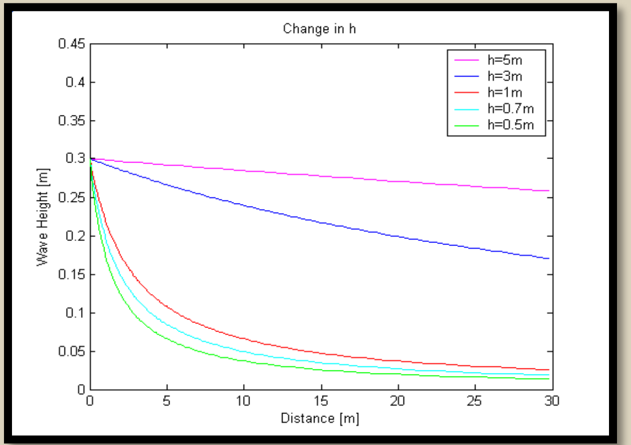


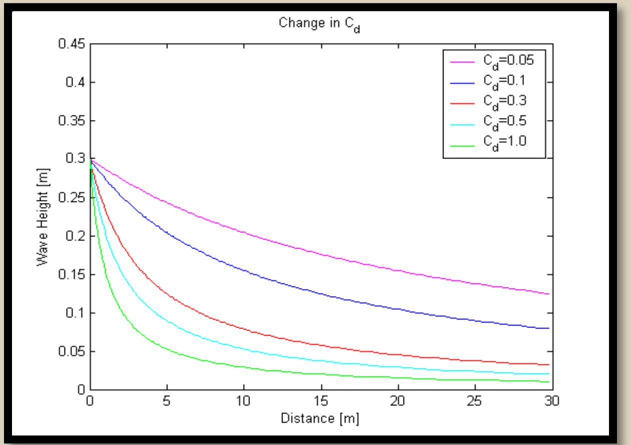
Numerical Analysis

- **Influence of model parameters on wave attenuation**



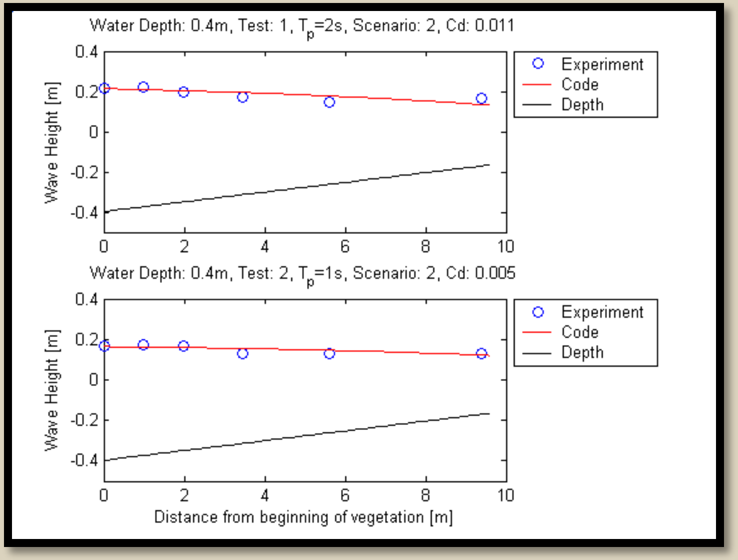


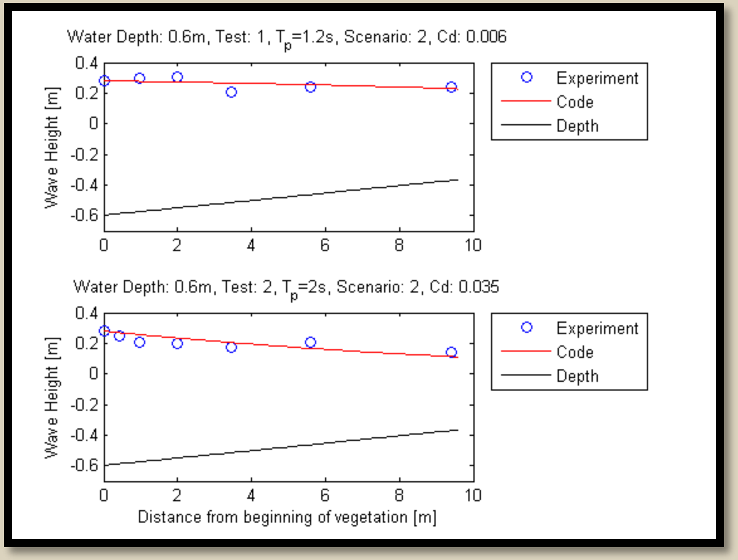




Numerical Analysis

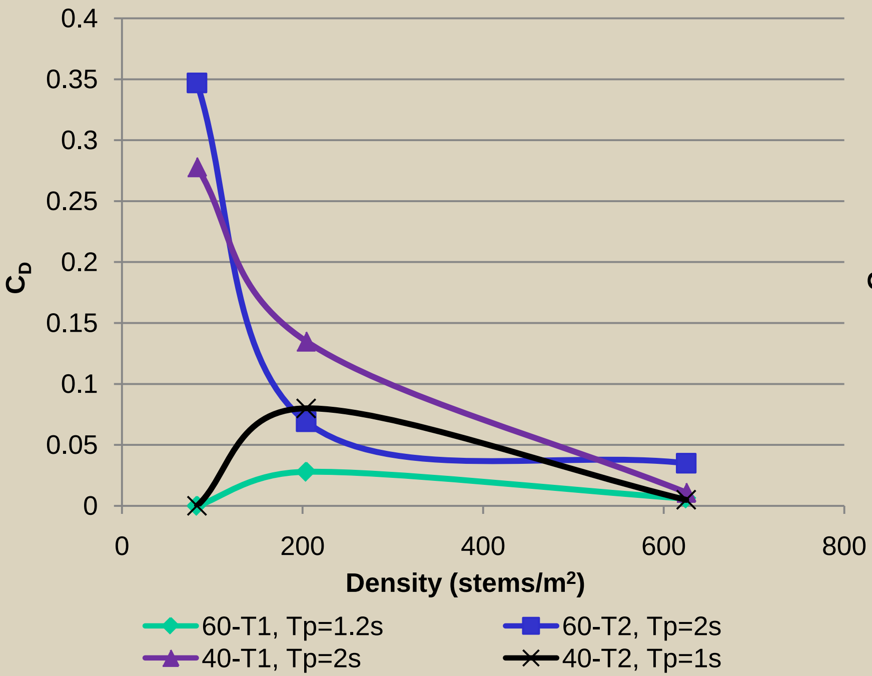
- **Interested in drag coefficient, C_D**
  - dependent on hydrodynamic and vegetation biomechanical characteristics, such as plant motion
  - assumed constant over the depth
  - best fit to experimental data obtained using least-squares method considering C_D as single calibration parameter

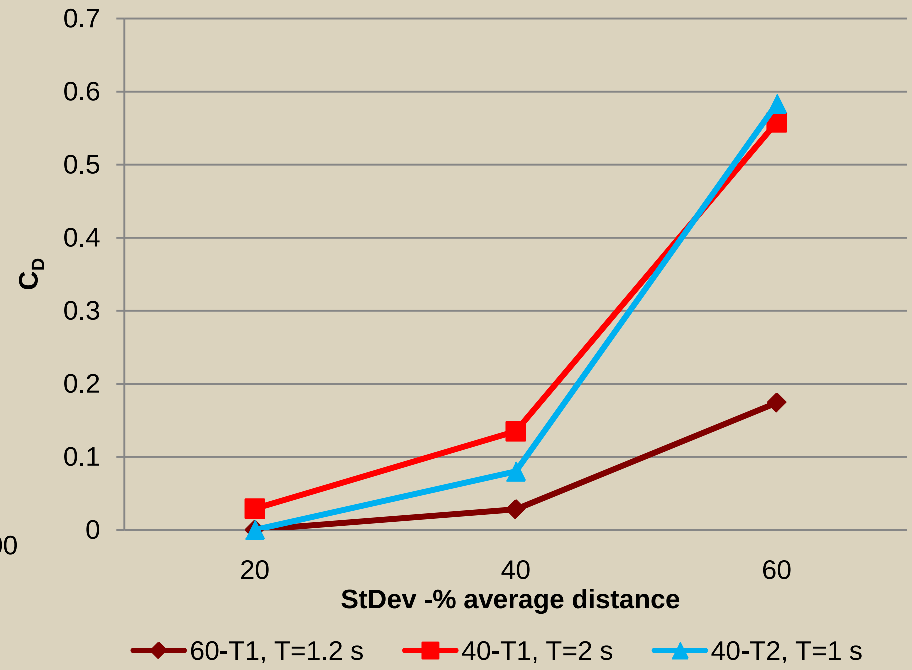




Numerical Analysis

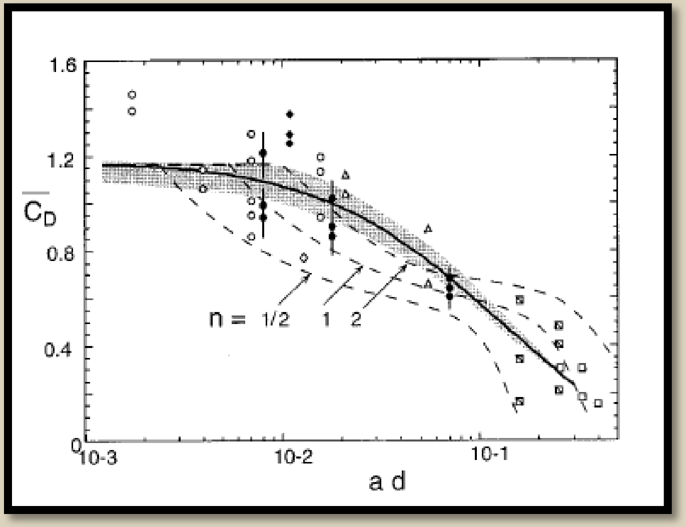
- **Behavior of drag coefficient**
  - C_D decreases with increasing density for longer wave periods but peaks at 204 stems/m^2 for shorter wave periods
  - C_D increases with increasing randomness of stem distribution





Numerical Analysis

- **similar results observed in Nepf (1999)**
  - investigated drag, turbulence intensity, and diffusion through emergent vegetation
  - considered 200-2000 stems/m^2 in staggered and random arrays
  - observed C_D as a function of stem density
    - decreased with increasing stem density for both configurations
  - attributed to wake sheltering effect
    - interaction between upstream and downstream cylinders
    - downstream cylinder impacted by lower velocity due to velocity reduction in wake from upstream cylinder
    - wake turbulence reduces drag on downstream cylinder by lowering pressure differential
- **applied to standard deviations**
  - higher standard deviations possibly result in smaller wake sheltering effects



Nepf (1999)

Conclusions

- **Dalrymple et al. (1984) formulation is a reasonable physical representation and implementation is feasible**
  - however, currently must calibrate drag coefficient for specific plant type
- **wave attenuation by vegetation is a highly dynamic process**
- **quantification important for accurately predicting coastal hydrodynamics**
  - adequate modeling of wave transformation along vegetation fields highly desirable

Future Research

- **complete analysis for 20 cm water depth**
- **determine wave height reduction per meter of propagation and per wavelength**
- **determine how wave height dissipation is influenced by stem density, standard deviation, and total water depth**
- **conduct similar experiment on a smaller scale in 2-D wave flume**
  - more controlled environment
  - flat bottom
  - verify existing results and investigate interesting observations

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