ICCE 2018
36TH INTERNATIONAL CONFERENCE ON COASTAL ENGINEERING 2018
Baltimore, Maryland | July 30 – August 3, 2018
The State of the Art and Science of Coastal Engineering

MODELING EFFECTS OF VEGETATION ON SETUP AND RUNUP OF RANDOM WAVES

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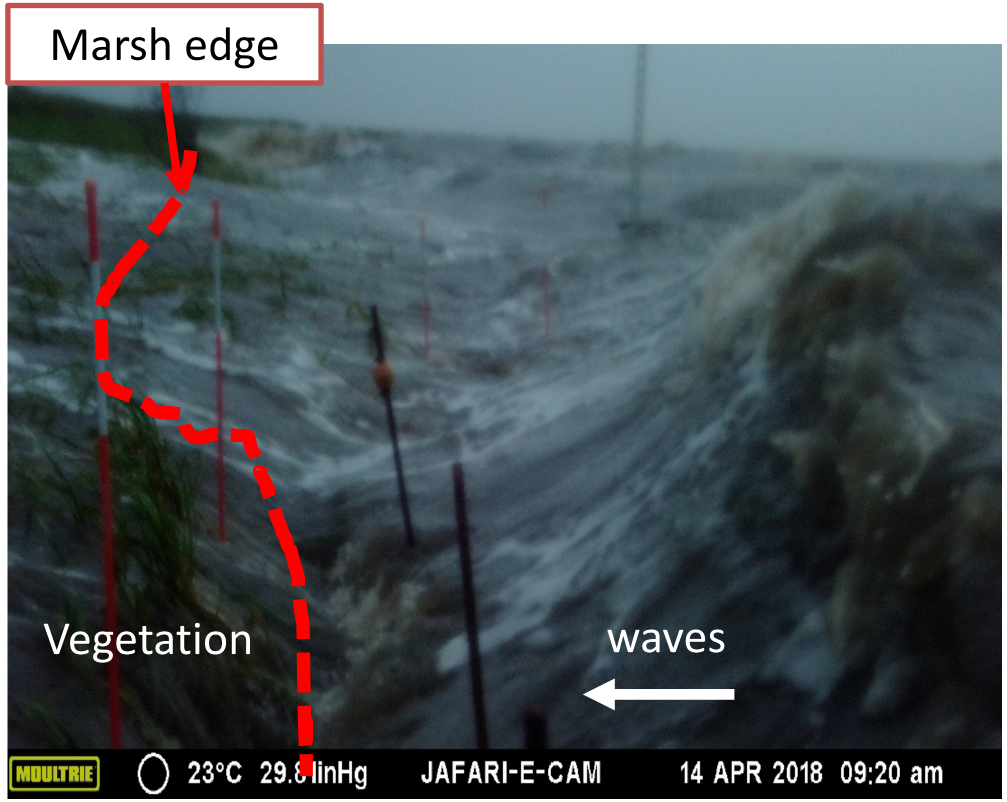
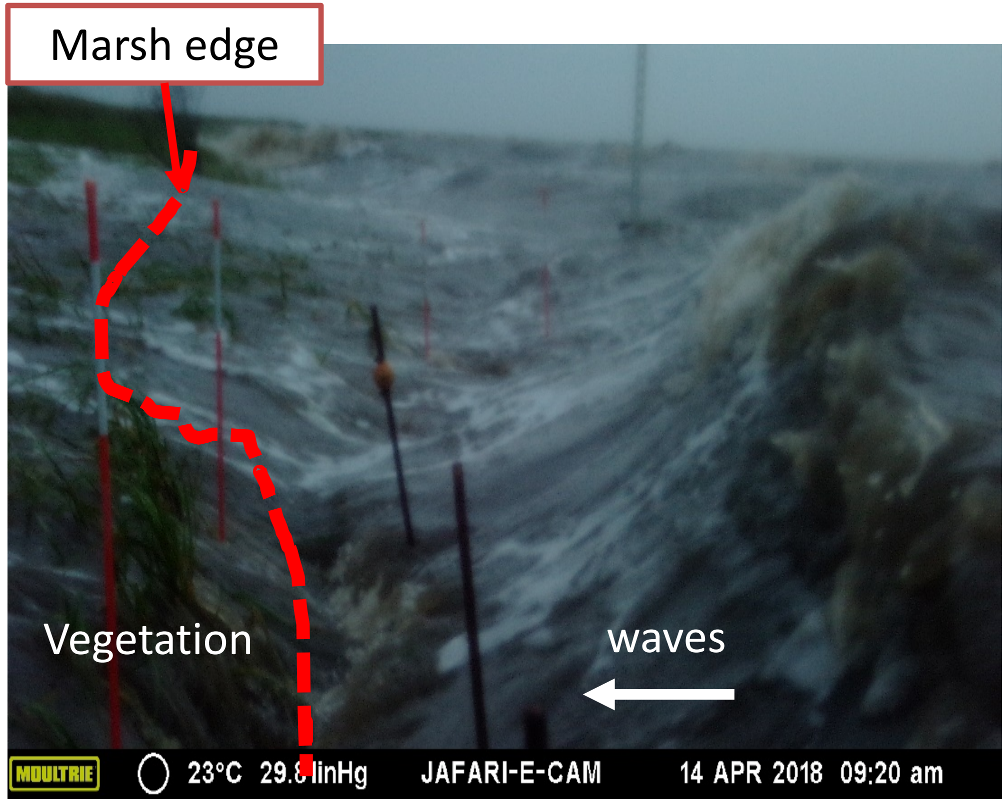


Photos taken on April 14, 2018 capturing a major storm strike the shoreline in Terrebonne Bay, LA.
(Photo courtesy: Navid Jarafi)



Photos taken on April 14, 2018 capturing a major storm strike the shoreline in Terrebonne Bay, LA.
(Photo courtesy: Navid Jarafi)

- Vegetation attenuates wave heights due to **instantaneous drag force**.
- Vegetation suppresses the increase of mean water level due to **phase-averaged drag force**.
- Vegetation reduces the wave runup due to (i) altered wave height distribution, and (ii) reduced wave heights and MWL.

Objectives

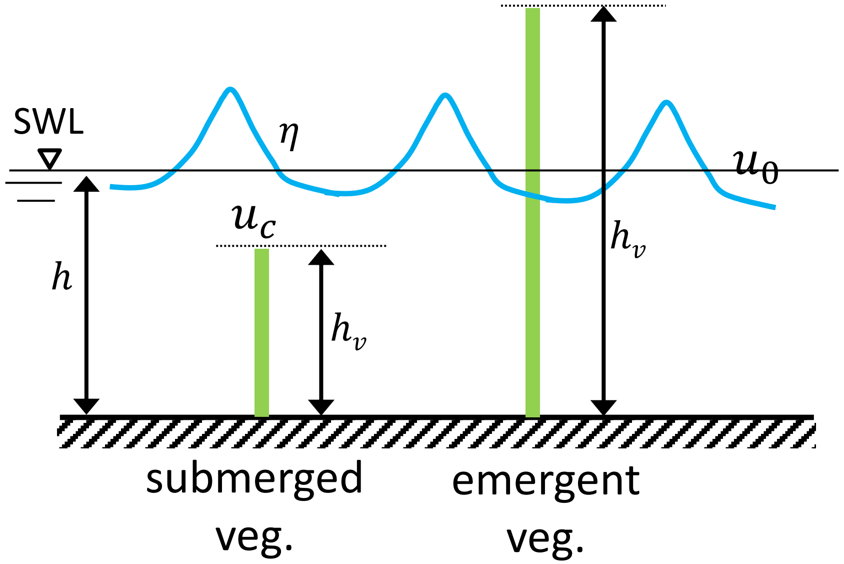
- Developing a model of phase-averaged drag force (F_v) that could be used in phase-averaging wave models (e.g. CSHORE*).
- Developing a model of wave runup ($R_{2\%}$) based on the Weibull distribution accounting for the effects of vegetation.
- Implementing the two developed models in CSHORE, and studying the effects of vegetation on (i) wave height decay, (ii) wave setup, and (iii) wave runup using field collected data.

CSHORE*: Cross-Shore numerical model (Johnson et al. 2012; Kobayashi et al. 2008).

Phase-Averaged Depth-Integrated Drag F_v

- Definition of F_v:

$$F_v = \overline{\int_{-h}^{\min(-h+h_v,\eta)} \frac{1}{2}\rho C_D b_v N_v u|u|dz}$$



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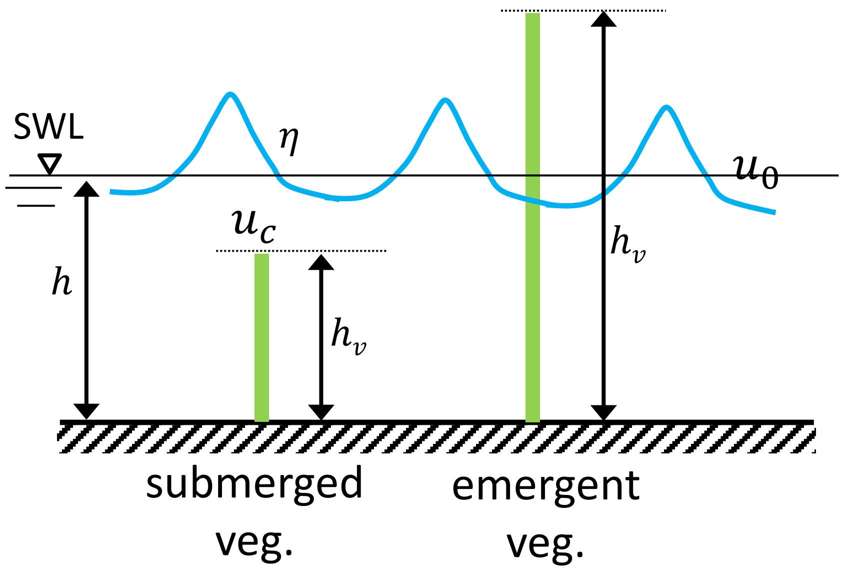

- Attempts to model F_v:
  - Method 1: $F_v = (2n - 0.5)\dfrac{\epsilon}{c_g}$

    based on assumption: $\partial\bar{\eta}/\partial x = 0$ over flat bottom.
  - Method 2: $F_v = \begin{cases} \frac{1}{2}\rho C_D b_v N_v \overline{u_0|u_0|\eta} & h_v \geq h \\ 0 & h_v < h \end{cases}$ from linear wave theory (Dean & Bender 2006).

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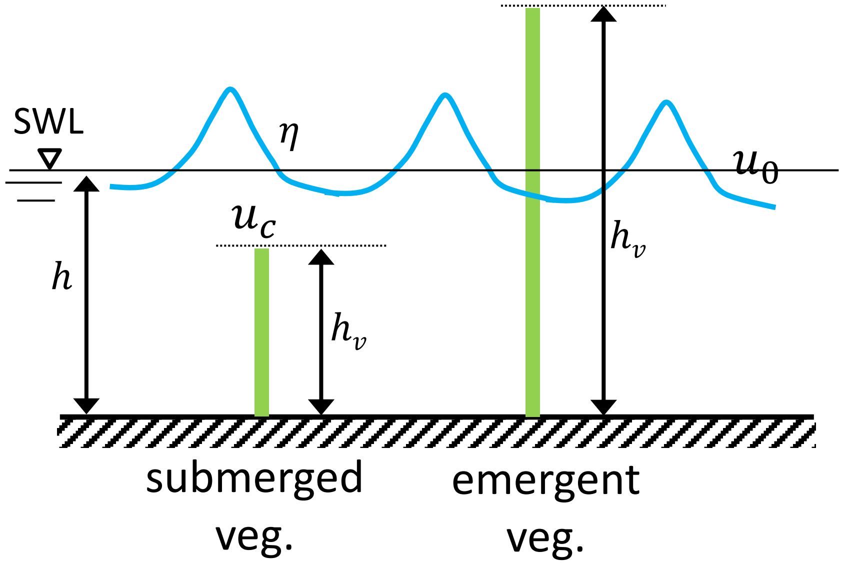

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    - ➢ For submerged vegetation ($h_v < h$) (or submerged part of emergent vegetation):
      - ✓ Linear waves → symmetric u → $F_v = 0$.
      - ✓ Nonlinear waves → asymmetric u → $F_v \neq 0$.

        (Guannle et al. (2015) approximated $F_{v,sub} = (h_v/h)F_{v,eme}$.)
  - Method 3: Zhu et al. (2018) based on Stoke's 2nd-order wave theory.
  - Method 4: van Rooijen (2016) based on a wave shape model.

Our Proposed Parametric Model of F_v − I

- For pure waves, we propose:

$$\boldsymbol{F_v = \frac{1}{2}\rho C_D b_v N_v \overline{u_c|u_c|\eta}\left(\frac{h_v}{h}\right)^m}$$

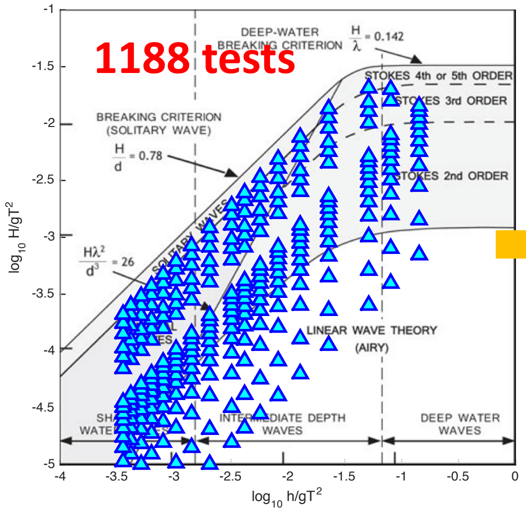
m is a function of:

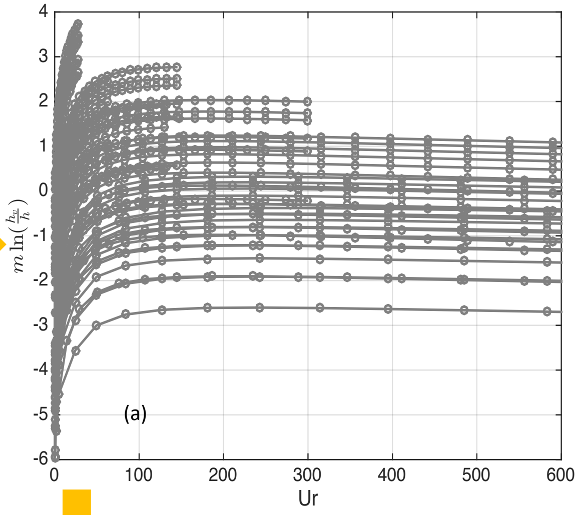
- ○ h_v/h,
- ○ H/h, and
- ○ Ursell number *Ur* ($= HL^2/h^3$).

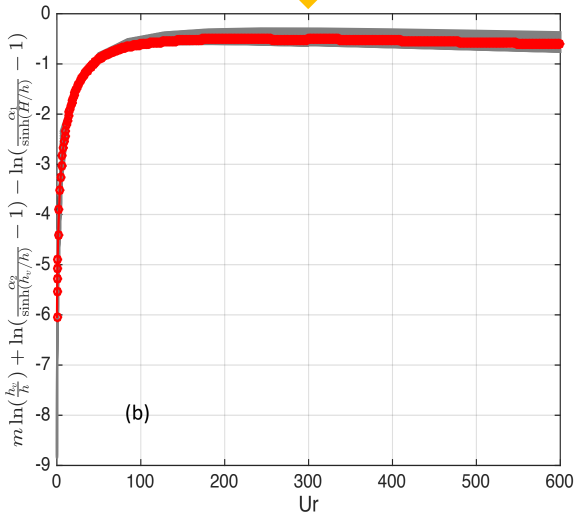
- A total of 1188 numerical tests with $h_v/h \in [0.1, 0.9]$ are conducted to determine m using stream function wave theory.

$$\underset{\textbf{SF*}}{\underline{F_v}} = \frac{1}{2}\rho C_D b_v N_v \underset{\textbf{LWT*}}{\underline{\overline{u_c|u_c|\eta}}}\left(\frac{h_v}{h}\right)^m$$

SF*: stream function wave theory, LWT*: linear wave theory.







Our Proposed Parametric Model of F_v – II

- For regular waves:

$$F_v = \frac{1}{12\pi}\rho C_D b_v N_v \omega^2 H^3 \frac{\cosh^2 kh_v}{\sinh^2 kh} \cdot \left(\frac{h_v}{h}\right)^m$$

Our Proposed Parametric Model of F_v – II

- For regular waves:

$$F_v = \frac{1}{12\pi}\rho C_D b_v N_v \omega^2 H^3 \frac{\cosh^2 k h_v}{\sinh^2 kh} \cdot \left(\frac{h_v}{h}\right)^m$$

- For random waves, with the following assumptions:
  - ○ narrow-banded wave spectrum
  - ○ unidirectional waves
  - ○ wave heights follow the Rayleigh distribution

The expected value of F_v:

$$\langle F_v \rangle = \frac{1}{16\sqrt{\pi}}\rho C_D b_v N_v \cdot \bar{\omega}^2 H_{rms}^3 \frac{\cosh^2 \bar{k} h_v}{\sinh^2 \bar{k} h} \cdot \left(\frac{h_v}{h}\right)^{\tilde{m}}$$

where $\bar{\omega} = \frac{2\pi}{\bar{T}}$, $\bar{T}$ is the mean wave period ($\approx T_p/1.35$).

$\tilde{m}$ is determined using H_s/h and $\frac{H_s \bar{L}^2}{h^3}$.

Model of F_v for Waves Coupled with Weak Currents

- With $u = u_w + V_0$, F_v can be partitioned into two parts (Guannel et al. 2015; Svendsen 2006):
  - ○ $F_{v,w}$ due to pure waves
  - ○ $F_{v,cw}$ due to wave-current interactions

$$F_{v,total} \approx \frac{1}{2}\rho C_D b_v N_v \left(\overline{\int_{-h}^{\min(-h+h_v,\eta)} u_w|u_w|dz} + 2\overline{\int_{-h}^{\min(-h+h_v,\eta)} V_0|u_w|dz}\right)$$

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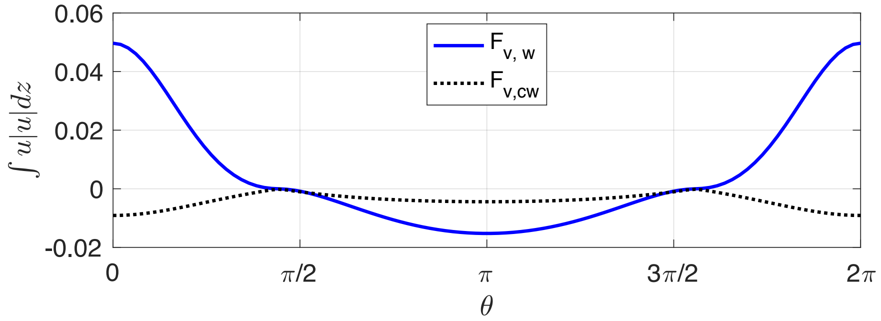

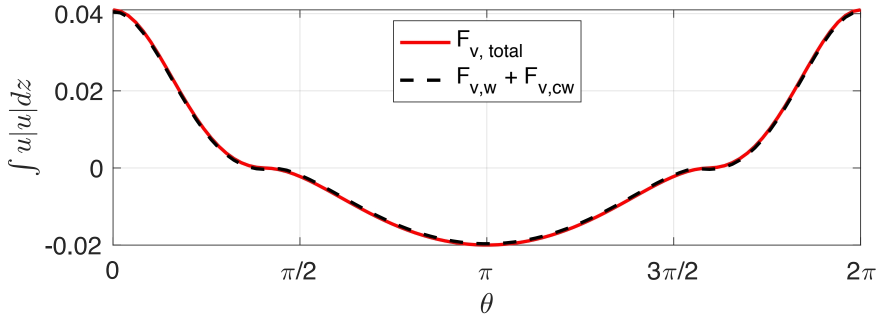

A test case:

water depth = 0.4 m

wave height = 0.12 m

wave period = 1.8 s

} magnitude of $u_w \approx 0.3$ m/s

$V_0 = -0.03$ m/s

$F_{v,w} = 0.00511\ m^3/s^2$

$F_{v,cw} = -0.00405\ m^3/s^2$

} $F_{v,w}$ and $F_{v,cw}$ have the same order of magnitude

$F_{v,w} + F_{v,cw} = 0.00106\ m^3/s^2$

$F_{v,total} = 0.00105\ m^3/s^2$

* $\frac{1}{2}\rho C_D b_v N_v$ is omitted here

Our Proposed Model of Wave Runup

- The wave height distribution in vegetation follows the Weibull distribution (Jadhav and Chen 2013), whose *cumulative distribution function* is

$$F(\xi) = e^{\left[-\phi^2\left(\frac{\xi}{1-k\xi}\right)^2\right]} \text{ where } \xi = \frac{H}{H_{rms}}.$$

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- We propose a model of wave runup as:

$$R_{2\%} = \overline{\eta_r} + \frac{C}{\sqrt{2}(1+\kappa C)}\left(R_{1/3} - \overline{\eta_r}\right) \qquad \text{where } C = \frac{\sqrt{\ln(50)}}{\phi}.$$

  - ○ The shape parameters ϕ and κ in the Weibull distribution are empirically determined in Jadhav and Chen (2013).
  - ○ Rayleigh distribution leads to $R_{2\%} = \overline{\eta_r} + 1.40\left(R_{1/3} - \overline{\eta_r}\right)$.

$$\frac{C}{\sqrt{2}(1+\kappa C)} \in [0.855, 1.42] \text{ for KC} \in [0, 140].$$

CSHORE Model Validation

- The parametric model of F_v is validated indirectly by
  - ○ Implementing $F_v = F_{v,w} + F_{v,cw}$ in the cross-shore momentum balance equation in CSHORE,
  - ○ Validating the modeled wave height (H_{rms}) and mean water level (MWL, $\bar{\eta}$) in vegetation with laboratory measurements (Wu et al. 2011).

Governing Equations:

$$\boldsymbol{\rho g(h+\bar{\eta})\frac{\partial\bar{\eta}}{\partial x} = -\frac{\partial S_{xx}}{\partial x} - F_{v,w} + F_{v,cw} + \tau_b + \tau_w}$$

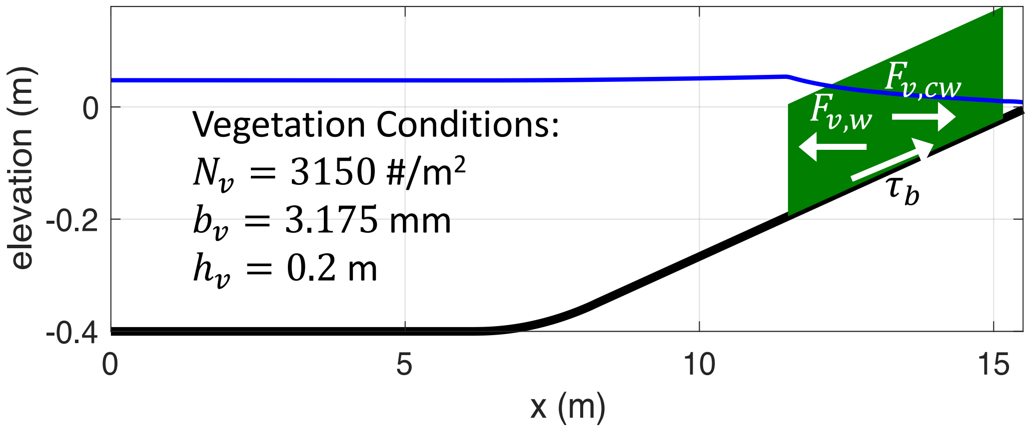
(momentum balance eq.)

$\frac{\partial EC_g}{\partial x} = -\epsilon_v$ (energy balance eq.)

$\bar{h}\bar{u} + \frac{g\sigma_\eta^2}{C} = 0$ (continuity eq.)

where $\sigma_\eta^2 = H_{rms}^2/8$, $S_{xx} = (2n-0.5)E$ and $E = \rho g\sigma_\eta^2$.

ϵ_v is determined from Chen and Zhao (2012).

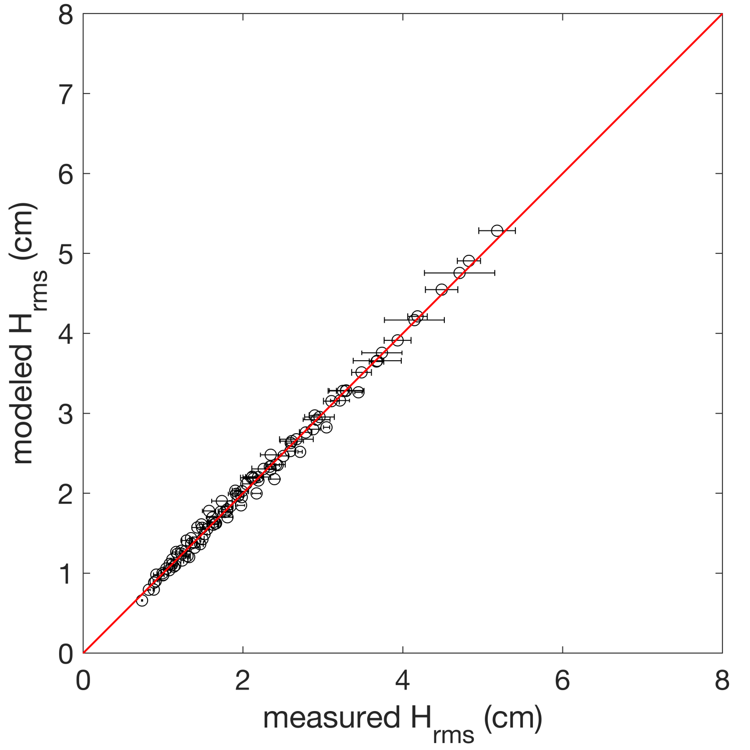


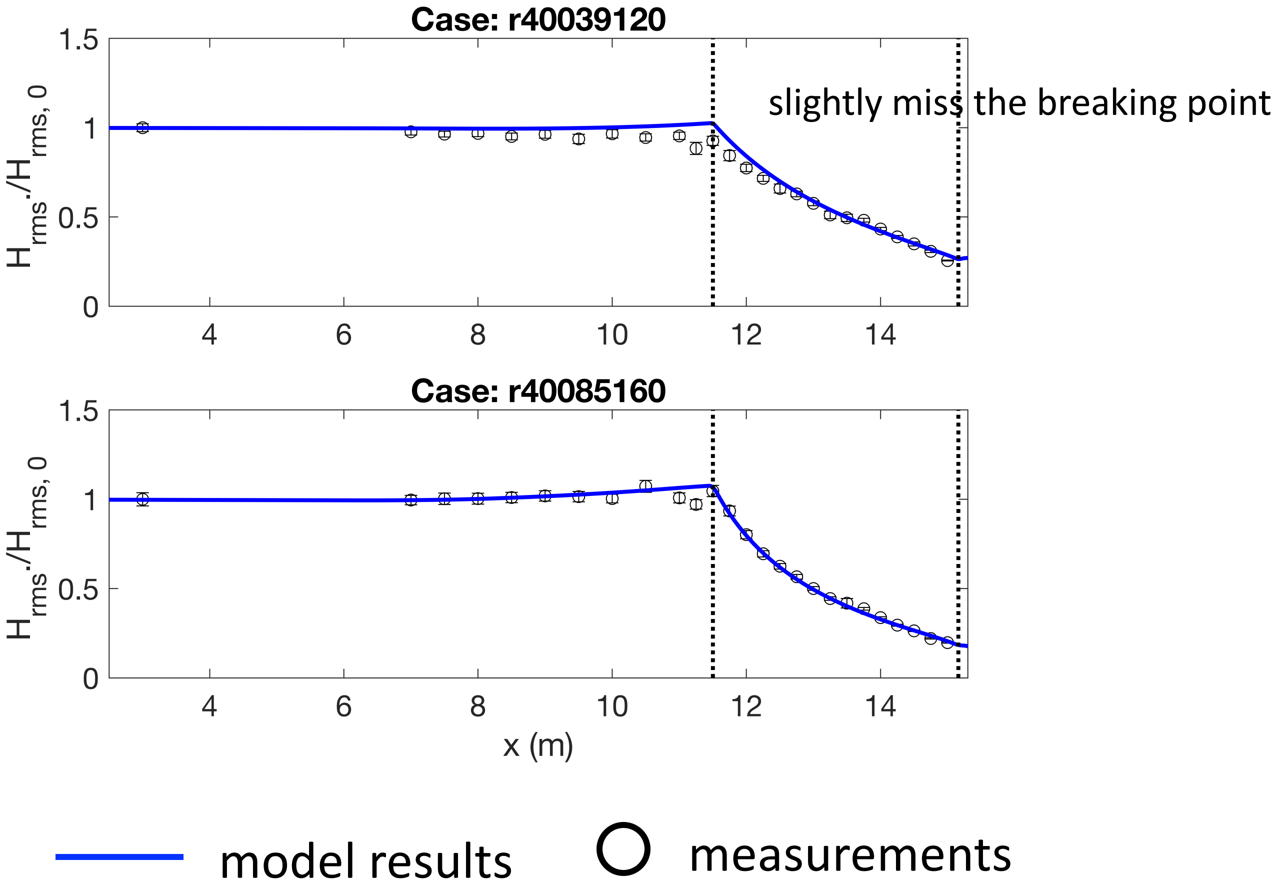
Vegetation Conditions:
N_v = 3150 #/m^2
b_v = 3.175 mm
h_v = 0.2 m

- Chen and Zhao (2012). “Theoretical models for wave energy dissipation caused by vegetation.” J. Eng. Mech., vol. 138(2), pp. 221-229.
- Wu et al. (2011). “Investigation of surge and wave reduction by vegetation.” SERRI Report, 80037-01.

CSHORE Model Validation – Wave Attenuation

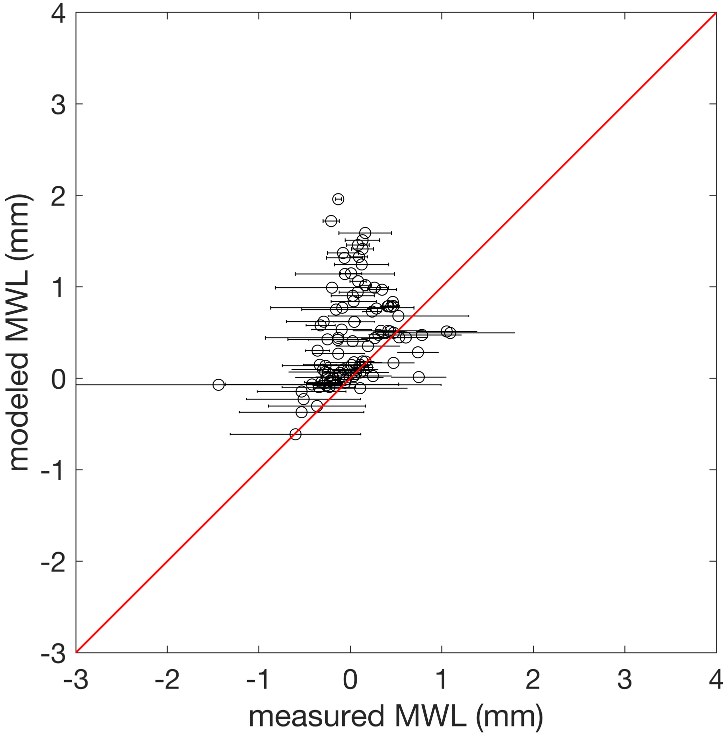
- The modeled and measured H_{rms} compare well.

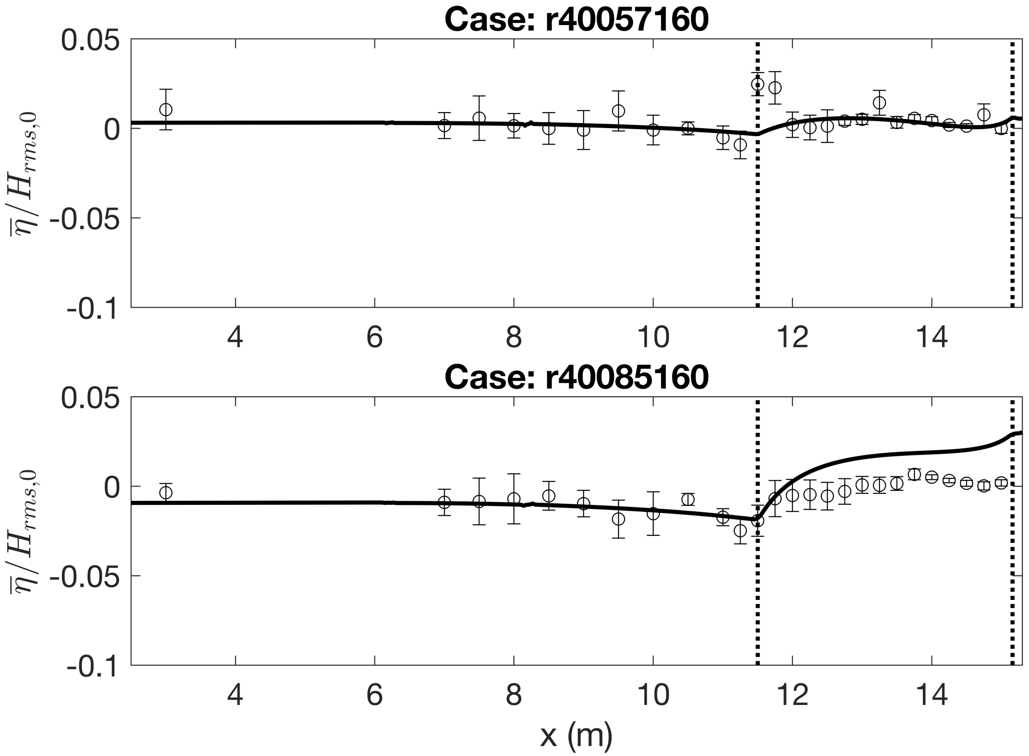



slightly miss the breaking point

CSHORE Model Validation – Wave Setup

- The model overestimates the MWL ($\bar{\eta}$) for cases with greater wave nonlinearity due to
  - overestimation of the mean current in vegetation
  - uncertainties in the effects of hydrodynamics from wave crest and trough on F_v.





smaller wave nonlinearity

larger wave nonlinearity

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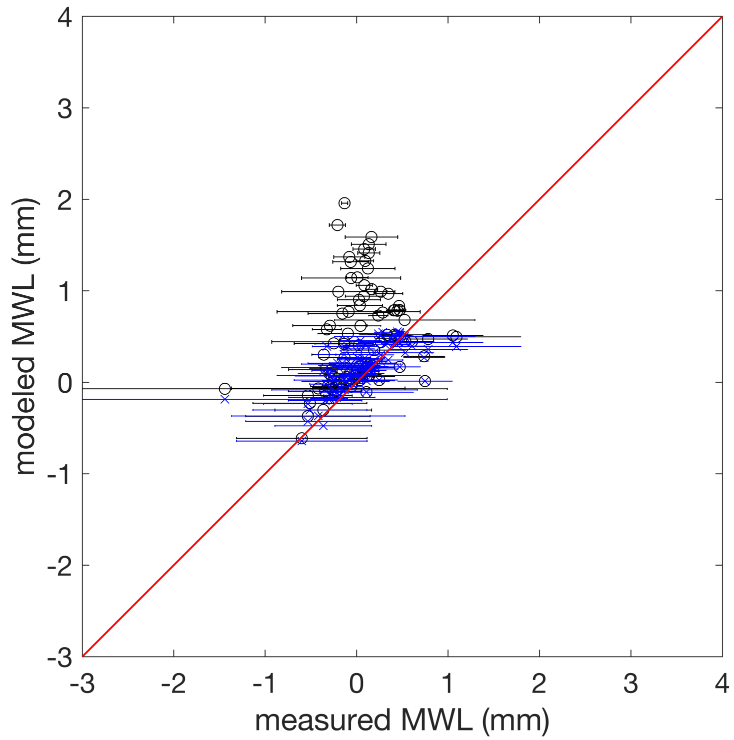
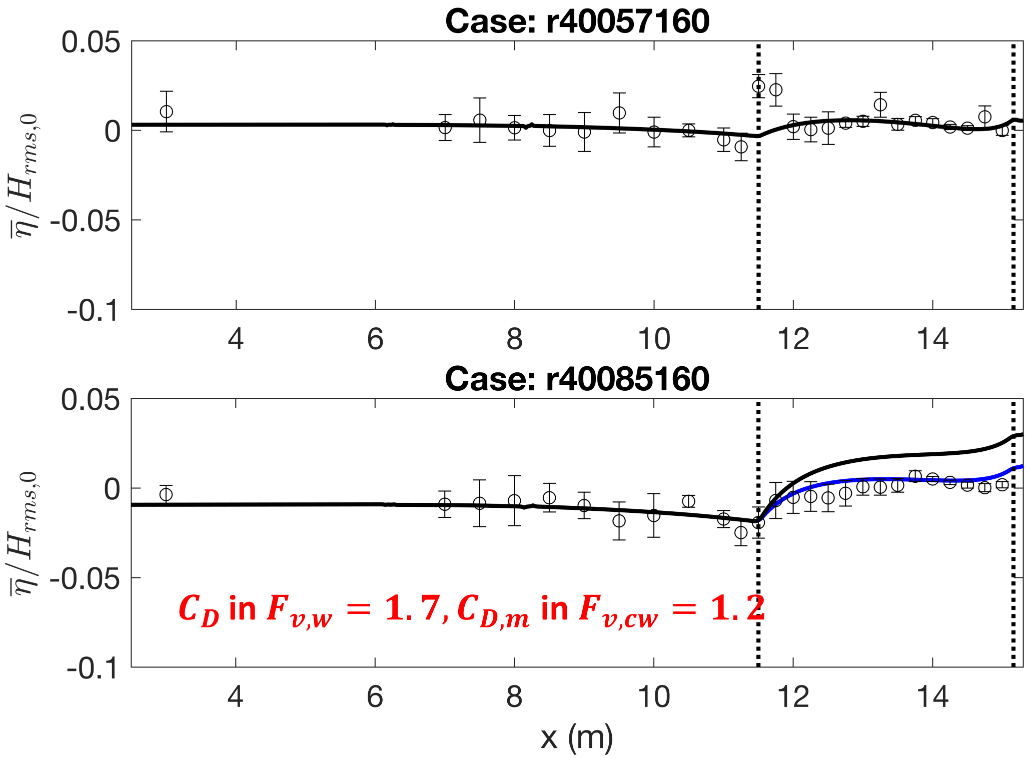




C_D in $F_{v,w} = 1.7, C_{D,m}$ in $F_{v,cw} = 1.2$

smaller wave nonlinearity

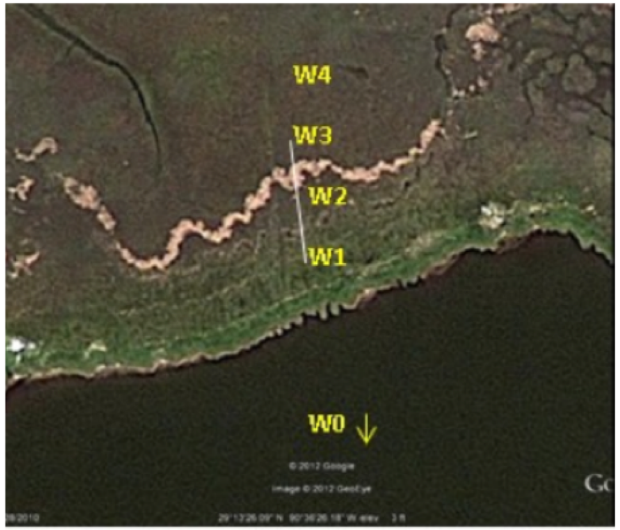
larger wave nonlinearity

- To account for the uncertainties in the mean current, different C_D are used in $F_{v,w}$ and $F_{v,cw}$.

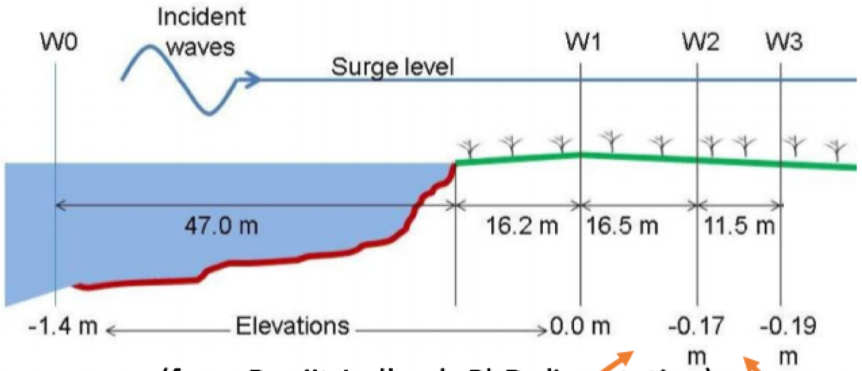
Application of CSHORE with Developed Models

- CSHORE with
  - energy dissipation rate ϵ_v modeled from Chen and Zhao (2012),
  - the proposed parametric model of F_v,
  - the proposed model of $R_{2\%}$ based on Weibull-distribution,

  is applied to simulate wave attenuation, wave setup and runup using field data collected from Tropical Storm Lee (Jadhav et al. 2013).



Terrebonne Bay, Louisiana coast



(from Ranjit Jadhav's PhD dissertation)

Transect W1 – W2:
N_v = 424 stems/m^2
b_v = 8 mm
h_v = 21 cm

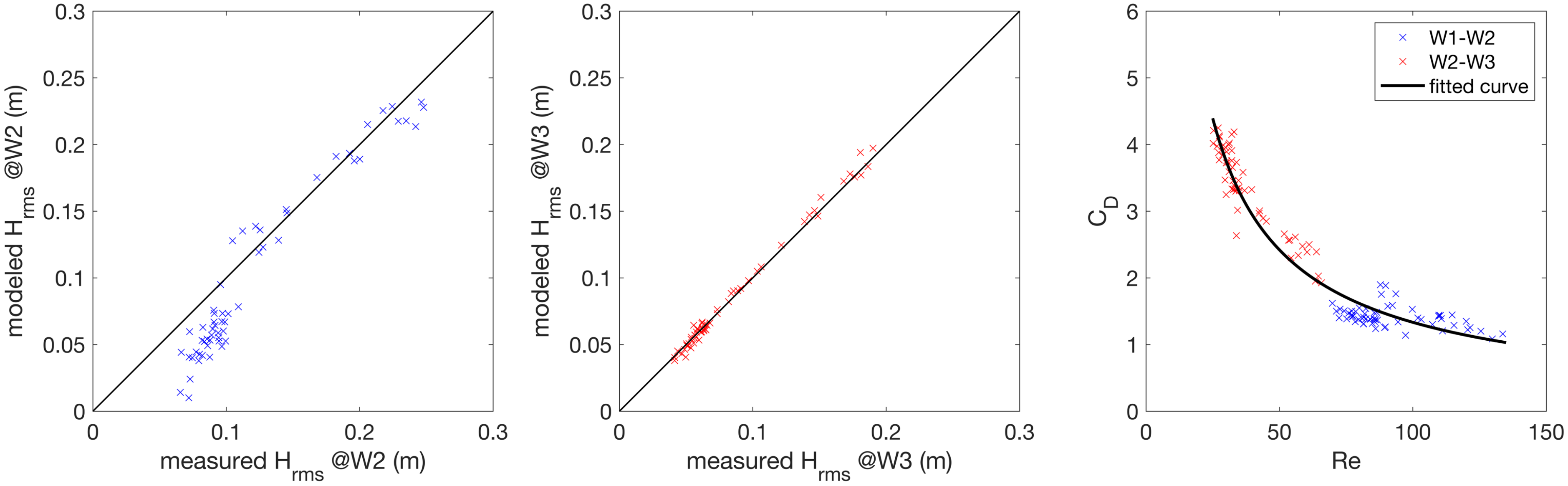
Transect W2 – W3:
N_v = 420 stems/m^2
b_v = 7.53 mm
h_v = 23 cm

Modeling of Wave Attenuation

- The measured wave spectra is used in the energy dissipation model.
- The drag coefficient is determined as

$$C_D = 70KC^{-0.86} \text{ (Jadhav et al. 2013)}$$

where $KC = (u_b\bar{T})/b_v$, $u_b = (H_{rms}\bar{\omega})/(2\sinh\bar{k}h)$.



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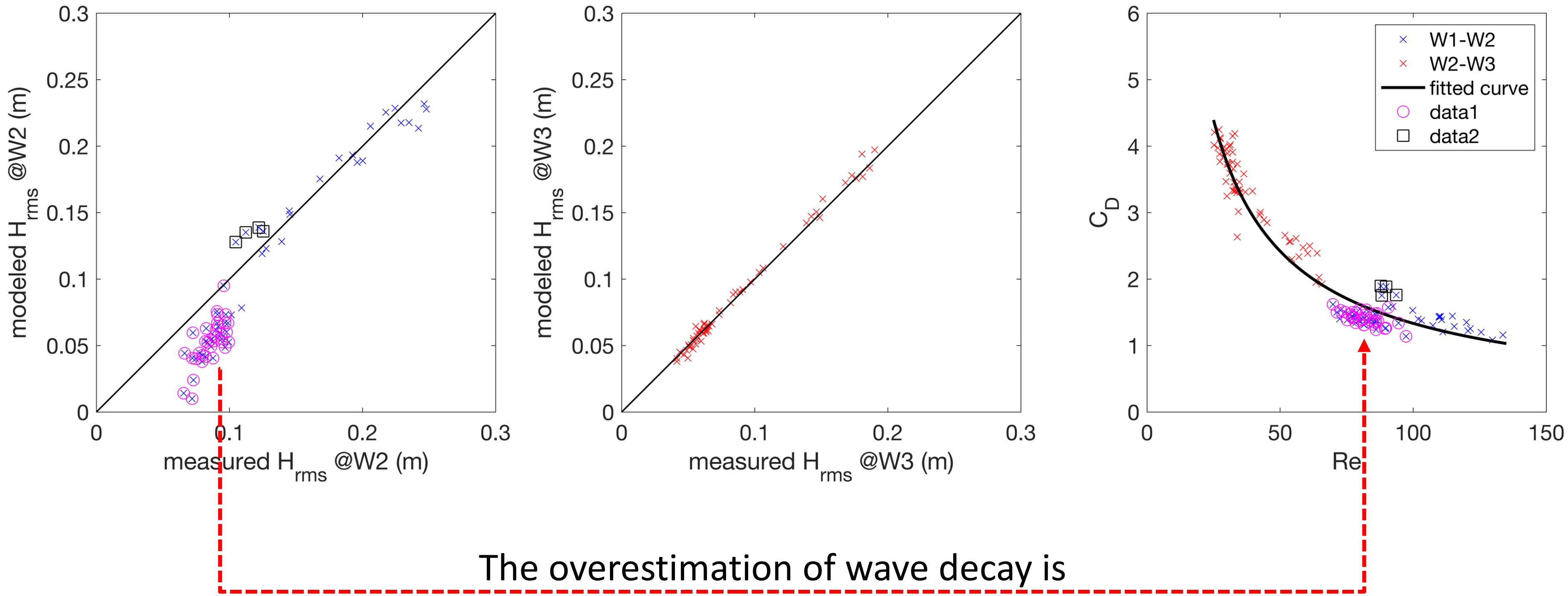
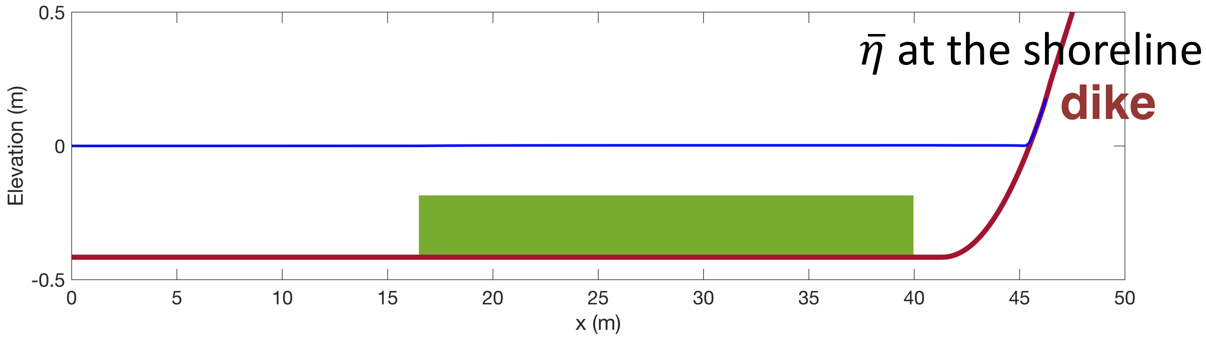
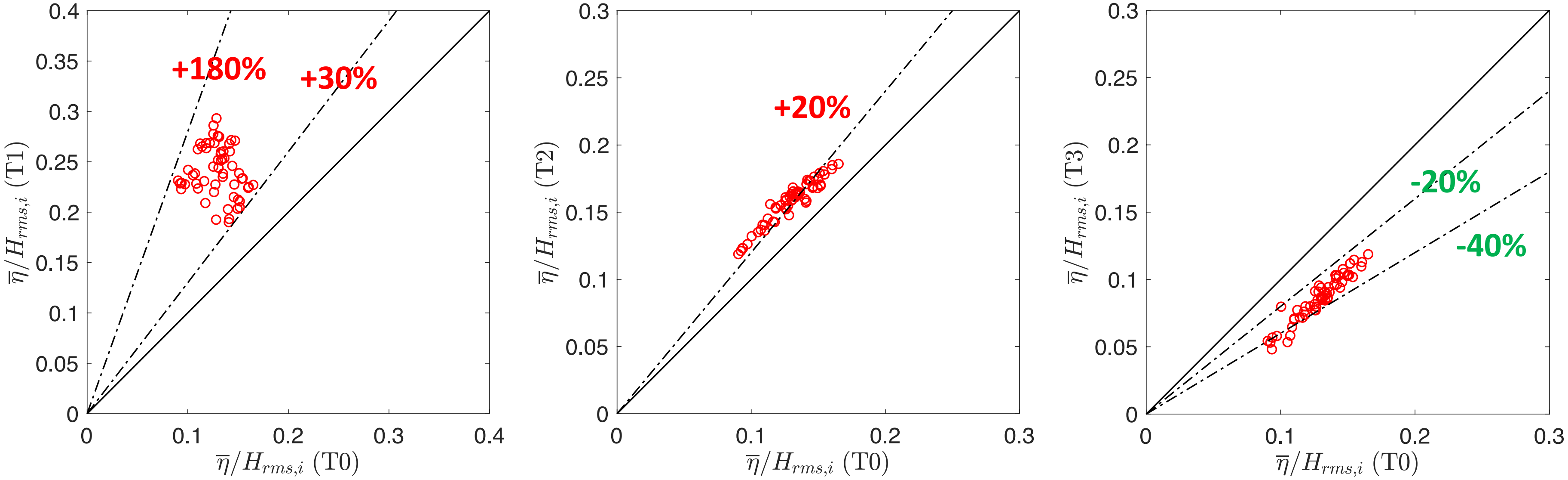


The overestimation of wave decay is correlated to the overestimation of C_D.

Modeling of Wave Setup

- A dike (1:4) is added after the vegetation.
- The effects of vegetation submergence and length of patch are investigated.
  - ○ Test 0: use measured vegetation conditions
  - ○ Test 1: remove vegetation
  - ○ Test 2: half the length of vegetation patch
  - ○ Test 3: half the length of vegetation patch & double the vegetation height h_v





Modeling of Wave Runup

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- The effects of vegetation submergence and length of patch are investigated.
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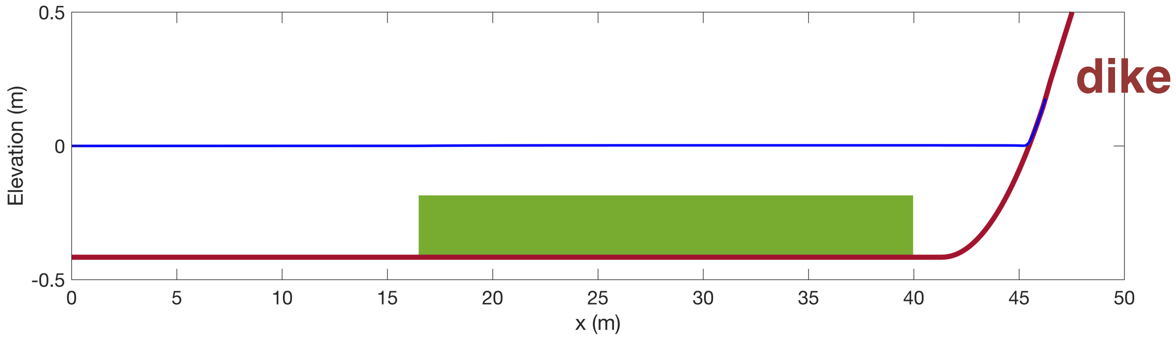
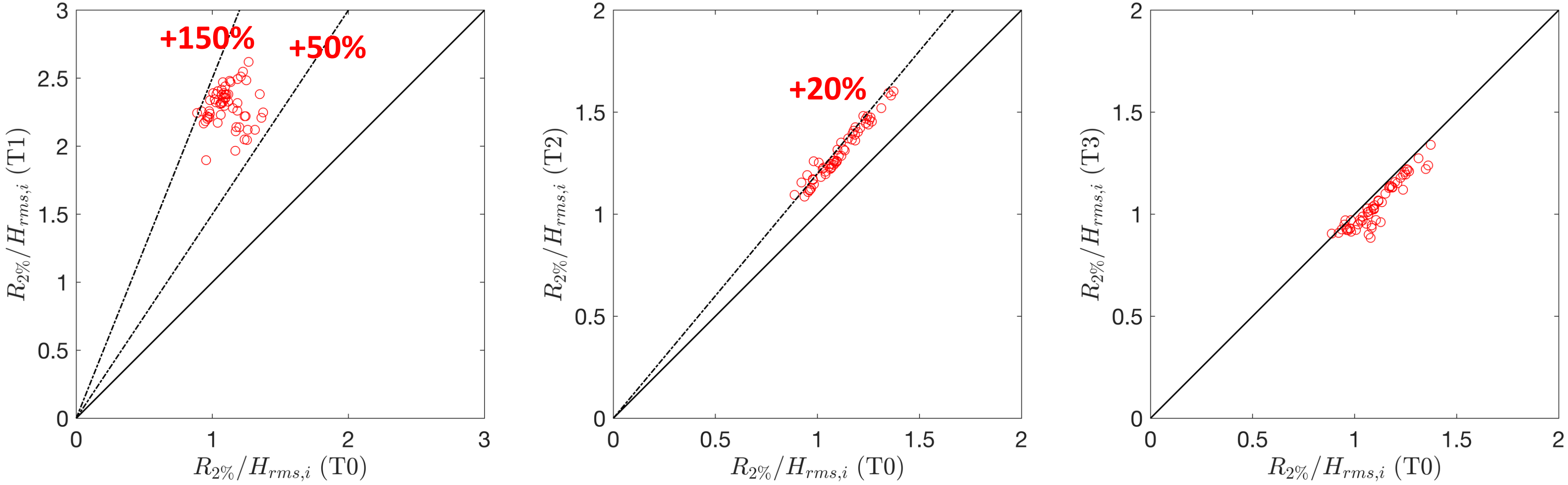
  - ○ Test 3: half the length of vegetation patch & double the vegetation height h_v





Conclusions

- A parametric model of phase-averaged drag force (F_v) based on stream function wave theory is developed and extended to random waves.
  - In the presence of weak currents, F_v can be partitioned into two equally significant parts:
    - $F_{v,w}$ due to pure wave,
    - $F_{v,cw}$ due to wave and current interactions.
- A model of wave runup ($R_{2\%}$) is developed based on Weibull distribution.
- The effects of vegetation on the wave attenuation, wave setup, and wave runup are modeled using an improved version of CSHORE equipped with the developed models of F_v and $R_{2\%}$.
- Field measurements of wave setup and runup in the presence of vegetation are needed for further model validation.

Acknowledgments

- Support for this study has been provided in part by the U.S. Army Corps of Engineers and the National Science Foundation (NSF) (Grant CCF-153956).

Thank You!
Questions?

Procedure of Computing m

- Compute Ur as $Ur = HL^2/h^3$ for regular waves and $H_s\overline{L}^2/h^3$ for irregular waves.
- Compute α_1 and α_2 as

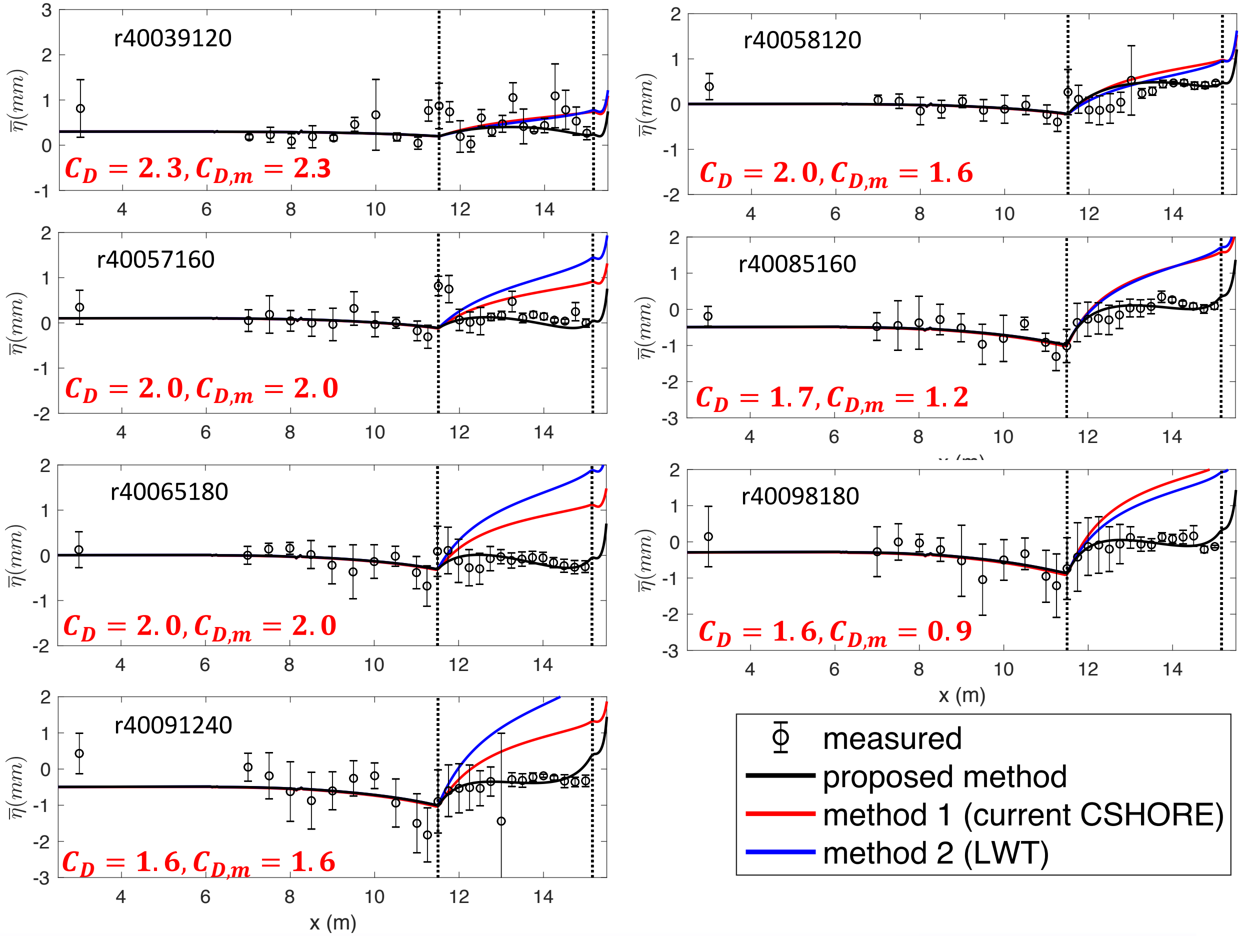
$$\alpha_1 = \begin{cases} -0.1\frac{h_v}{h} & 0.2 \le \frac{h_v}{h} \le 0.8 \\ 1.09 & \frac{h_v}{h} < 0.2 \\ 1.03 & \frac{h_v}{h} > 0.8 \end{cases}, \alpha_2 = 0.35\left(\frac{h_v}{h}\right)^3 - 0.16\left(\frac{h_v}{h}\right)^2 + \frac{h_v}{h} + 0.65.$$

- Determine m through linear interpolation.

Model Validation – Wave Setup

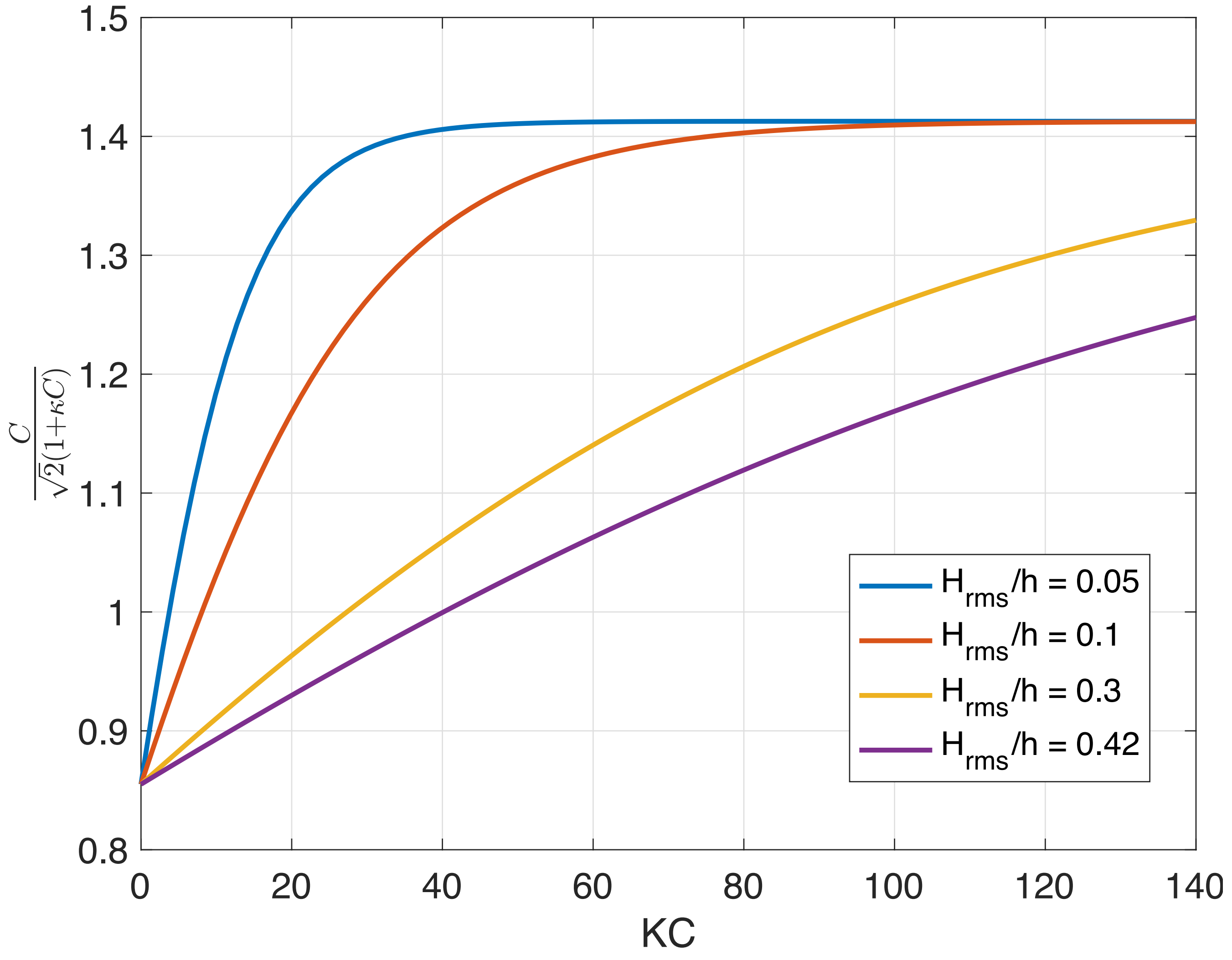
- The parametric model produces more accurate MWL.

As H/h increases, $C_{D,m}$ in $F_{v,cw} < C_D$ in $F_{v,w}$



As kh decreases, $\frac{C_{D,m} \text{ in } F_{v,cw}}{C_D \text{ in } F_{v,w}}$ decreases

Factor in Runup Model



$$m = 0.0044\left(\frac{H_{rms}}{h}\right)^{-1.11}$$

$$\kappa = 0.83e^{-m\mathrm{KC}}$$

$$\phi = -1.2\kappa + 0.99$$

$$C = \frac{\sqrt{50}}{\phi}$$