

CSHORE-Veg: Implementing vegetation drag forces for depth-varying plant morphology

CIRP Tech Discussion - 8 July 2025

Clara Zwolanek
Elizabeth Holzenthal
Yan Ding
Bradley Johnson



U.S. ARMY



US Army Corps
of Engineers®



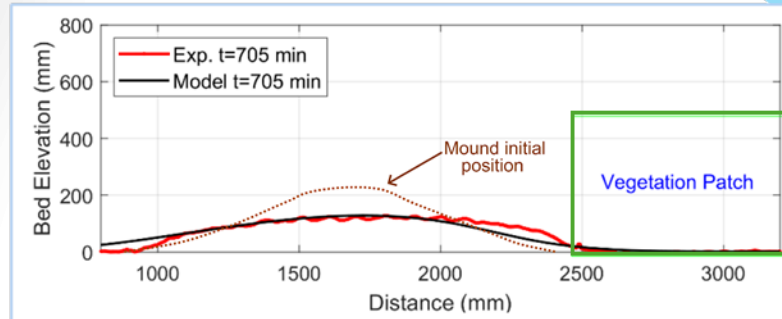
ERDC
ENGINEER RESEARCH & DEVELOPMENT CENTER



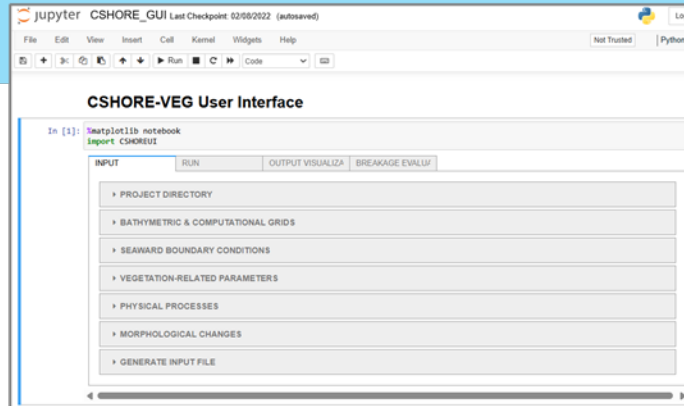
Project Roadmap

Preliminary effort (Y. Ding)

Sediment transport
around/near vegetation



*CSHORE-Veg: Jupyter notebook for
1D attenuation by vegetation*



Aug 5 TD:
Nat Harris &
Yan Ding

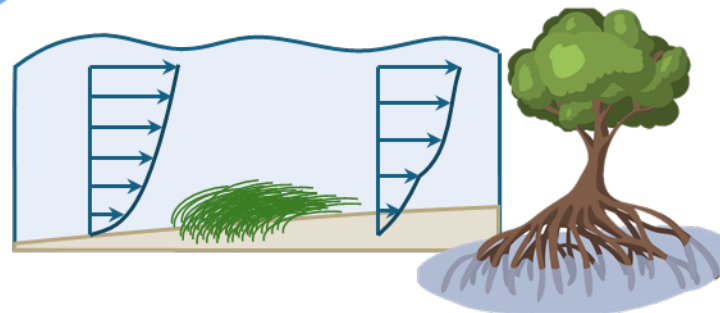
CSHORE-Veg

CSHORE (B. Johnson)

Wave attenuation and impact on
momentum balance



*Drag-related characteristics can vary
over depth (and with time)*



Today's
TD:
Mangroves



Wave Energy Flux Dissipation by Vegetation

$$\frac{\partial E_f}{\partial x} = -\varepsilon_f - \varepsilon_b - \varepsilon_v$$

CSHORE (Johnson & Kobayashi, 2012)

Dissipation due to wave breaking (Battjes & Stive 1985)

$$\varepsilon_b = \frac{\rho g a_s Q H_b^2}{4T}$$

Dissipation due to bed friction

$$\varepsilon_f = \overline{\tau_b u} = \overline{\rho c_f u^2 |u|}$$

Dissipation due to vegetation-induced drag forces

$$\varepsilon_v = \overline{\int_{z_b}^{\eta} f_{drag} \cdot u \, dz} = \overline{\int_{z_b}^{\eta} \frac{\rho}{2} C_D b_v N |u| u \cdot u \, dz}$$



Evolution of equations to calculate dissipation



- Dalrymple et al. (1984) – energy flux dissipation rate ε_v over an array of rigid cylinders; monochromatic waves and flat bed assumption
- **Mendez and Losada (2004)** – extended Dalrymple et al. (1984) to random waves on a sloping bed

$$\langle \varepsilon_v \rangle = \frac{1}{2\sqrt{\pi}} \rho \overset{\text{Vegetation properties}}{\tilde{C}_D b_v N} \left(\frac{kg}{2\sigma} \right)^3 \frac{\sinh^3 k\alpha h + 3\sinh k\alpha h}{3k \cosh^3 kh} H_{\text{rms}}^3$$

- Suzuki et al. (2012) – implement Mendez and Losada (2004) into the spectral wave model SWAN with multi-layer schematization

$$\langle \varepsilon_v \rangle_i = -\sqrt{\frac{2}{\pi}} g^2 \tilde{C}_{D,i} b_{v,i} N_i \left(\frac{\tilde{k}}{\tilde{\sigma}} \right)^3 \frac{(\sinh^3 \tilde{k}\alpha_i h - \sinh^3 \tilde{k}\alpha_{i-1} h) + 3(\sinh \tilde{k}\alpha_i h - \sinh \tilde{k}\alpha_{i-1} h)}{3\tilde{k} \cosh^3 \tilde{k}h} \sqrt{E_{\text{tot}}} E(\sigma, \theta)$$

- **Chen and Zhao (2012)** – develop frequency-dependent dissipation term

$$\langle \varepsilon_v \rangle(\sigma, \theta) = -\frac{1}{2} \frac{\tilde{C}_D B_v N}{g} \frac{\sigma^2}{\sinh^2 kh} \left\{ \int_{-h}^{-h+ah} U_{\text{rms}}(z) \cosh^2[k(h+z)] dz \right\} E(\sigma, \theta)$$



CSHORE GUI – Potential declaration of Rigid vegetation



jupyter CSHORE_GUI Last Checkpoint: 02/08/2022 (autosaved) Logout

File Edit View Insert Cell Kernel Widgets Help Not Trusted Python 3

CSHORE-VEG User Interface

In [1]: %matplotlib notebook
import CSHOREUI

INPUT RUN

- PROJECT DIRECTORY
- BATHYMETRIC & COMPUTATIONAL
- SEAWARD BOUNDARY CONDITION
- VEGETATION-RELATED PARAMETERS**
- PHYSICAL PROCESSES
- MORPHOLOGICAL CHANGES
- GENERATE INPUT FILE

VEGETATION-RELATED PARAMETERS

Vegetation module: With vegetation

Consider spatially-varying C_D : no

Wave energy dissipation: Mendez and Losada (2004)

Vegetal flow-drag resistance: parametric model (Zhu and Chen 2019)

Veg. from x = (m): 0

Veg. to x = (m): 10

vegetation erosion limit (m): 0.3

Vegetation type: Rigid w/ spatially constant traits

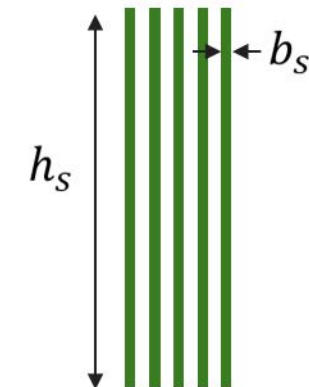
Vegetal drag coefficient C_D : default

maximum allowed C_D : 45

Stem population density (stems/ m^2): 400

Stem height (m): 0.2

Stem frontal width (m): 0.008



*also available as spatially varying



CSHORE GUI – Potential declaration of Flexible vegetation

jupyter CSHORE_GUI Last Checkpoint: 02/08/2022 (autosaved)

File Edit View Insert Cell Kernel Widgets

CSHORE-VEG User Interface

```
In [1]: %matplotlib notebook
import CSHOREUI
```

INPUT RUN

- PROJECT DIRECTORY
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Consider spatially-varying C_D : no

Wave energy dissipation: Mendez and Losada (2004)

Vegetal flow-drag resistance: parametric model (Zhu and Chen 2019)

Veg. from x = (m): 0

Veg. to x = (m): 10

vegetation erosion limit (m): 0.3

Vegetation type: Flexible w/ spatially constant traits

Vegetal drag coefficient C_D : default

maximum allowed C_D : 45

Stem population density (stems/ m^2): 400

Stem height (m): 0.2

Stem frontal width (m): 0.008

Young's modulus of stem (N/m^2): 80000000

Blade population density (stems/ m^2): 2000

Blade height (m): 0.7

Blade width (m): 0.005

Blade thickness (m): 0.00000685

Young's modulus of blade (N/m^2): 80000000

*also available as spatially varying

total height (h_{vt})

stem height (h_v)

Blade Length

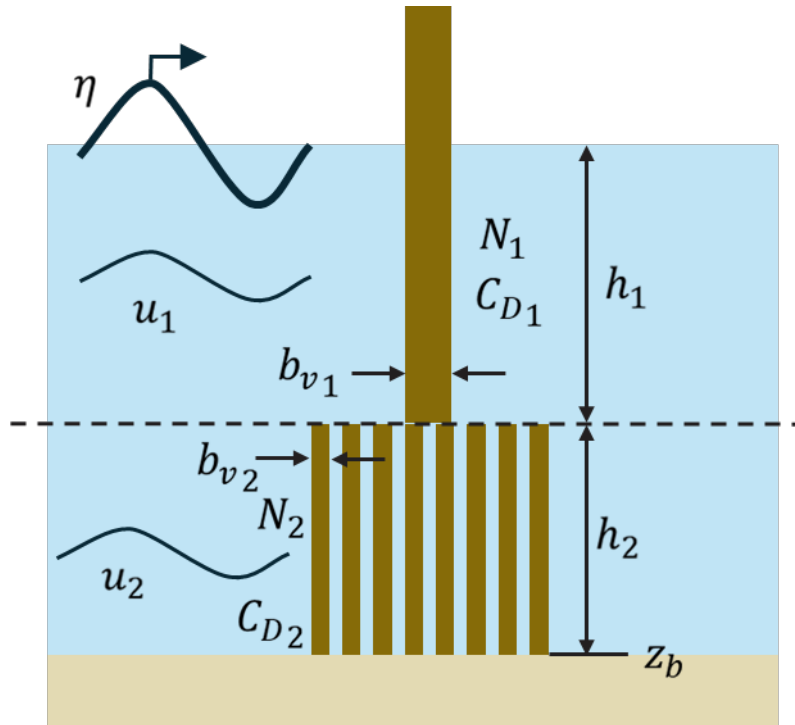
Last Leaf

First Leaf



Research question #1

$$\epsilon_v = \overline{\int_{z_b}^{\eta} f_{drag} \cdot u \, dz} = \overline{\int_{z_b}^{\eta} \frac{\rho}{2} C_D b_v N |u| u \cdot u \, dz}$$

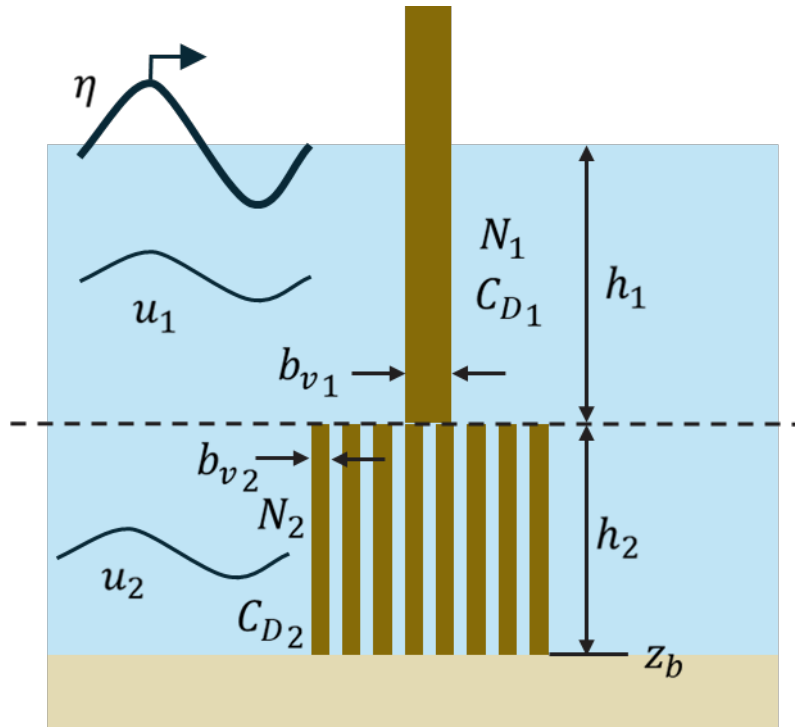


Research question: What is the most (1) practical, (2) physically meaningful method of predicting dissipation over vegetation with strong vertical variation?



RQ #1 – discussion

$$\epsilon_v = \overline{\int_{z_b}^{\eta} f_{drag} \cdot u \, dz} = \overline{\int_{z_b}^{\eta} \frac{\rho}{2} C_D b_v N |u| u \cdot u \, dz}$$



$$\begin{aligned} &= \overline{\frac{\rho}{2} \int_{z_b}^{z_b+h_2} C_{D2} b_{v2} N_2 |u_2| u_2 \cdot u_2 \, dz} + \overline{\frac{\rho}{2} \int_{z_b+h_2}^{\eta} C_{D1} b_{v1} N_1 |u_1| u_1 \cdot u_1 \, dz} \\ &= \frac{\rho}{2} \overline{C_{D2} b_{v2} N_2 |u_2^3| h_2} + \frac{\rho}{2} \overline{C_{D1} b_{v1} N_1 |u_1^3| (\eta + h_1)} \end{aligned}$$



RQ #1 – discussion, cont.

$$\epsilon_v = \overline{\int_{z_b}^{\eta} f_{drag} \cdot u \, dz} = \overline{\int_{z_b}^{\eta} \frac{\rho}{2} C_D b_v N |u| u \cdot u \, dz}$$

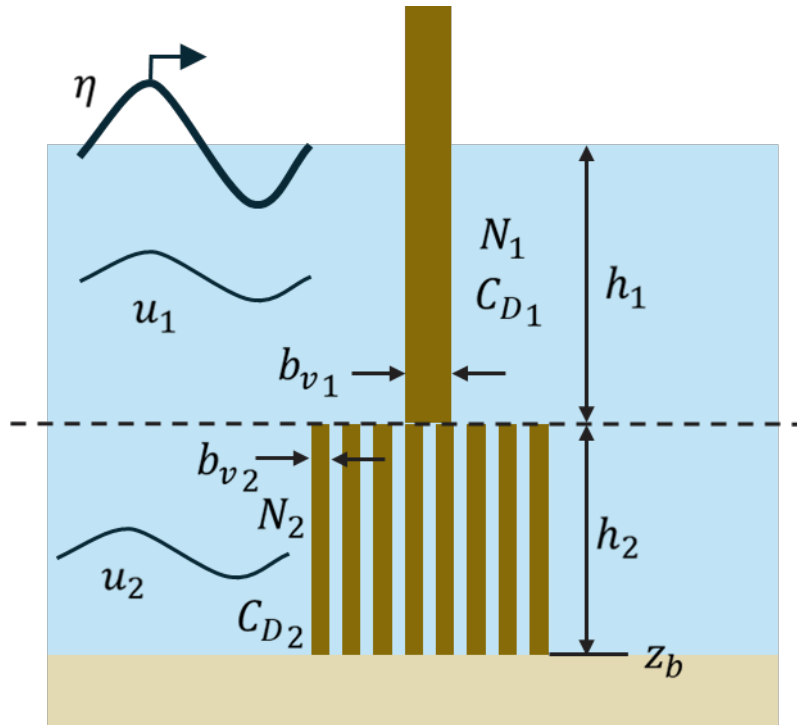
$$= \frac{\rho}{2} \overline{\int_{z_b}^{z_b+h_2} C_{D_2} b_{v_2} N_2 |u_2| u_2 \cdot u_2 \, dz} + \frac{\rho}{2} \overline{\int_{z_b+h_2}^{\eta} C_{D_1} b_{v_1} N_1 |u_1| u_1 \cdot u_1 \, dz}$$

$$= \frac{\rho}{2} C_{D_2} b_{v_2} N_2 \overline{|u_2^3|} h_2 + \frac{\rho}{2} C_{D_1} b_{v_1} N_1 \overline{|u_1^3|} (\eta + h_1)$$

If $u_2 \approx u_1, C_{D_2} \approx C_{D_1}$

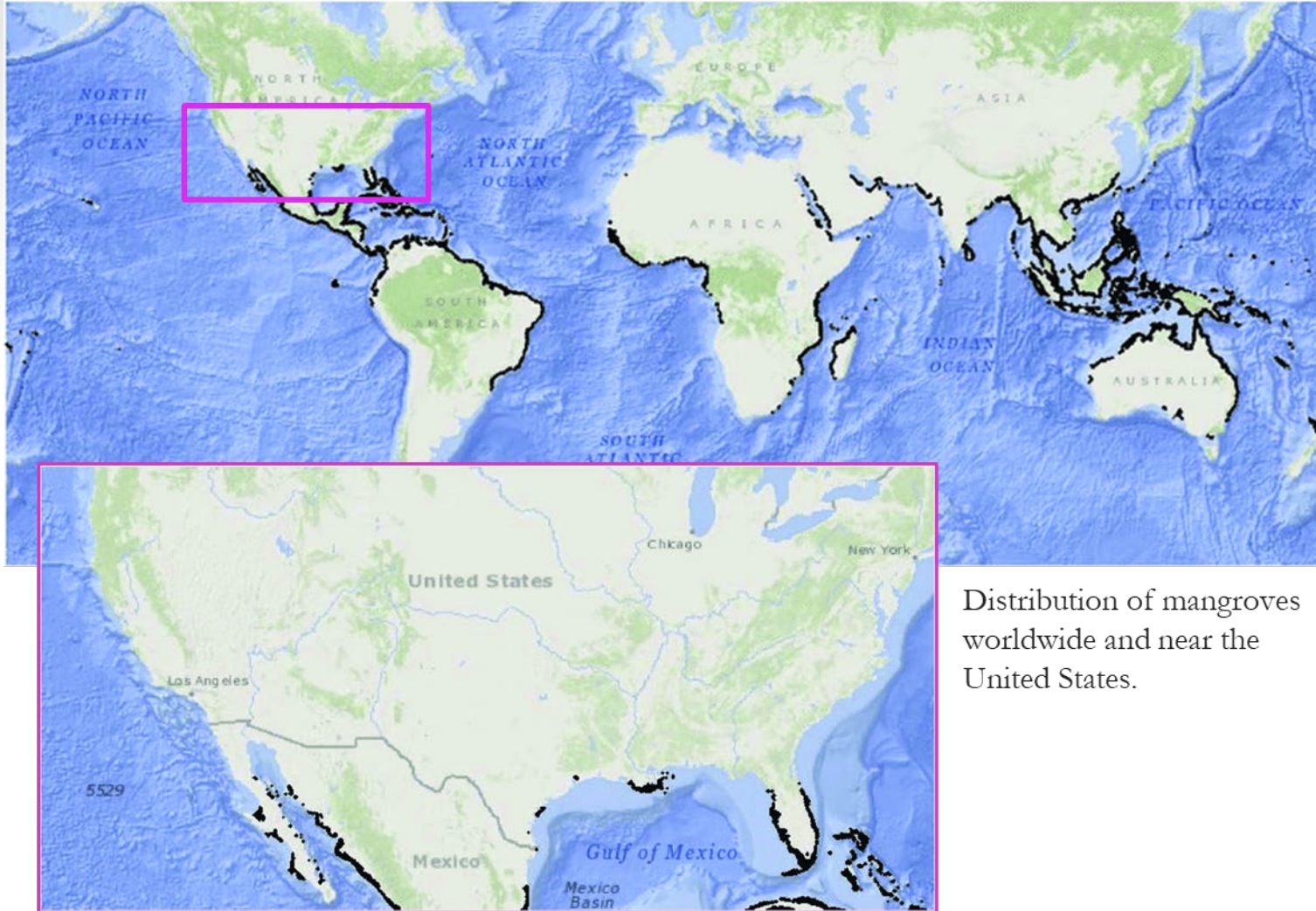
$$= \frac{\rho}{2} C_D \overline{|u^3|} (N_2 h_2 b_{v_2} + b_{v_1} N_1 (\eta + h_1))$$

$$= \frac{\rho}{2} C_D \overline{|u^3|} \overline{N b_v} (\bar{\eta} + h) = \frac{\rho}{2} C_D \overline{|u^3|} \overline{A_v} (\bar{\eta} + h)$$

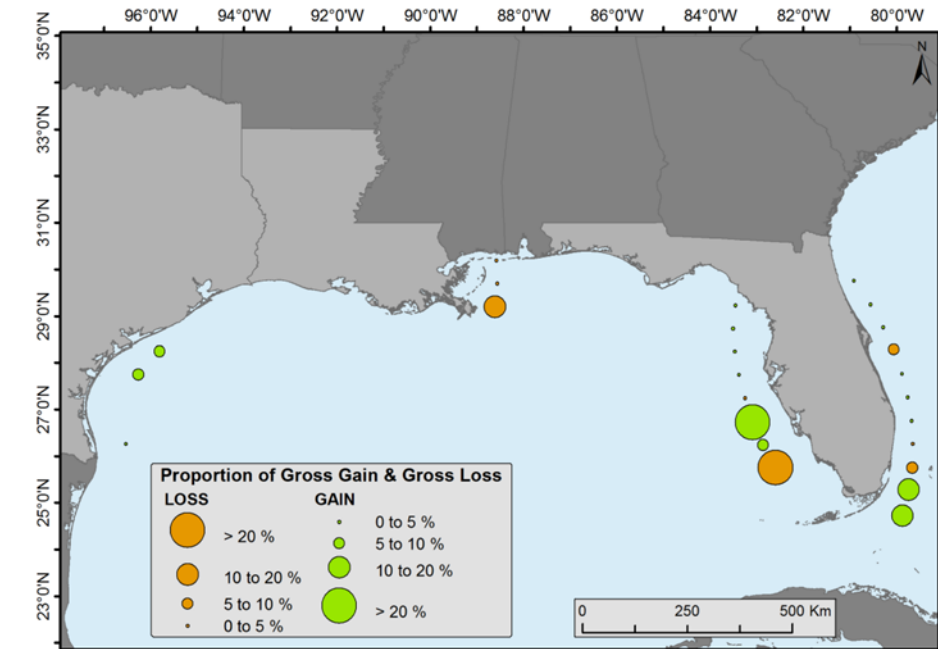




Location of Mangroves



Distribution of mangroves worldwide and near the United States.



Mangrove forest cover gain and loss 1980–2020.



Types of Mangroves

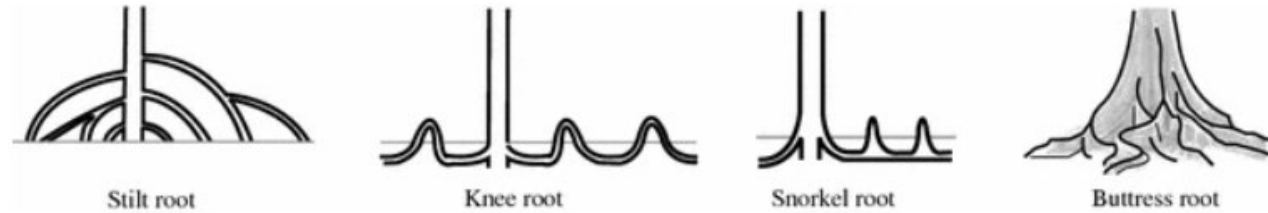


Table 2-1 Summary table of mangrove laboratory studies with scale, study type, mangrove data location, species type modeled, model and prototype diameter at breast height D_{BH} , and model and prototype tree density, N .

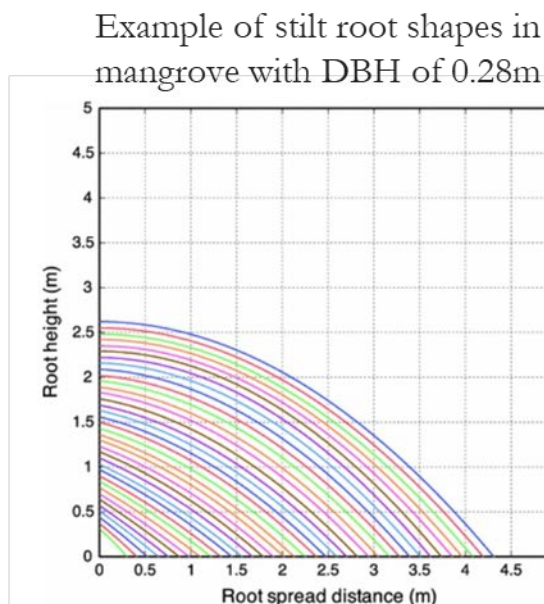
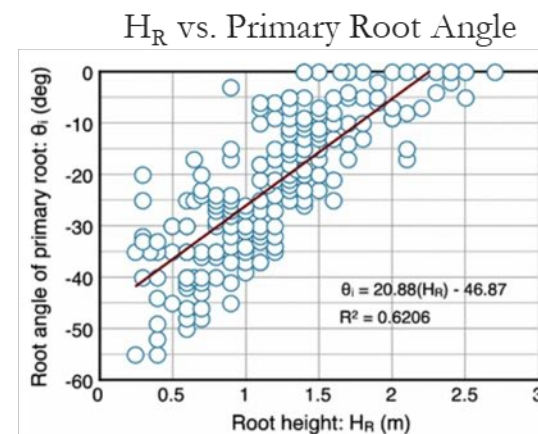
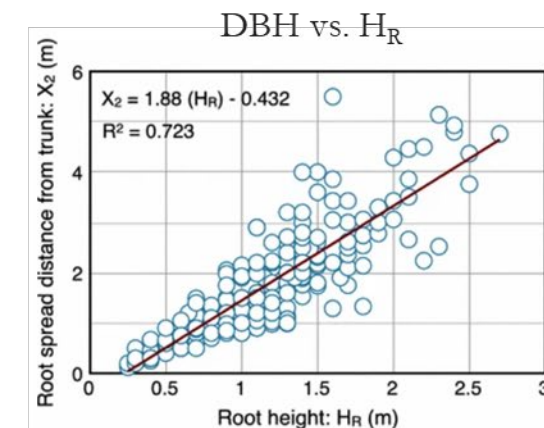
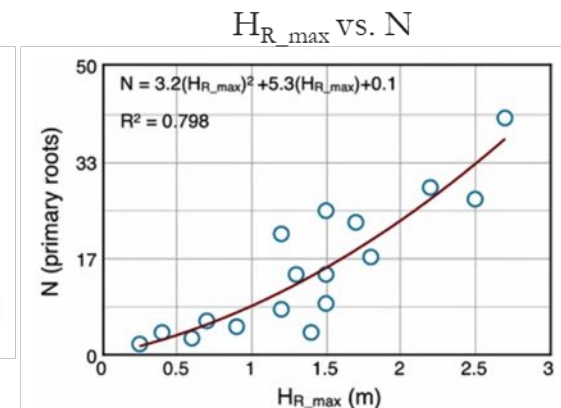
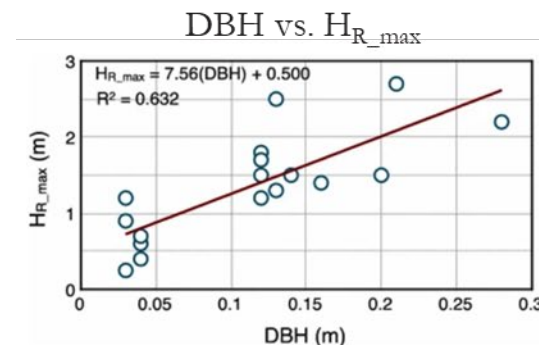
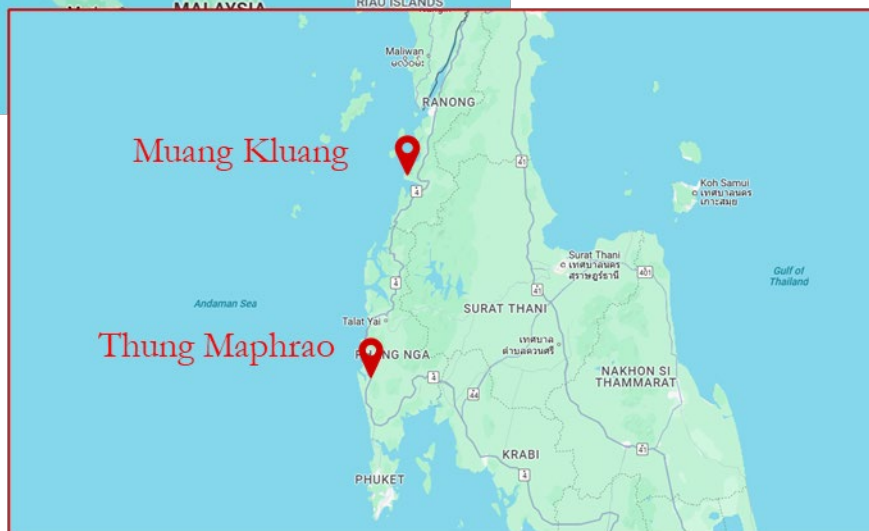
Study	Scale	Study Type	Mangrove Data Location	Species	D_{BH} [prototype]	N [model]	N [prototype]
(-)	(1:X)	(-)	(-)	(-)	(m)	(stems/m ²)	(stems/m ²)
Chang et al. (2019)	7	Regular Waves	V, 19 yr. old tree	<i>k</i>	0.07	29.40	0.6
Strusińska-Correia et al. 2014	25	Tsunami	JP, AUS, and ID	<i>p</i>	0.20	44	0.07
Hashim and Catherine, 2013	10	Waves/ Tsunami	JP, AUS	<i>p</i>	—	11-22	0.11 - 0.22
Maza et al. (2017)	12	Unidirectional Flow	Southwestern FL, USA, Ranong, TH	<i>p</i>	0.20	10.40	0.072
Maza et al. (2019)	6	Regular/Random Waves	Southwestern FL, USA, Ranong, TH	<i>p</i>	0.20	2.25	0.063
Tomiczek et al. (2020)	16	Transient Waves	Key West, FL, USA, Ranong, TH Cuddalore, IN	<i>m</i>	0.203	43.00	0.17
Zhang et al. (2015)	7.5	Unidirectional Flow	Pasir Ris Park and Kranji Natural Trail, SG	<i>p</i>	0.06	12.20	0.217

k *Rhizophora apiculata*, **m** *Rhizophora mangle*, **p** *Rhizophora sp.*

Kelty (2021)



Mangrove Models Ohira et al. (2013)

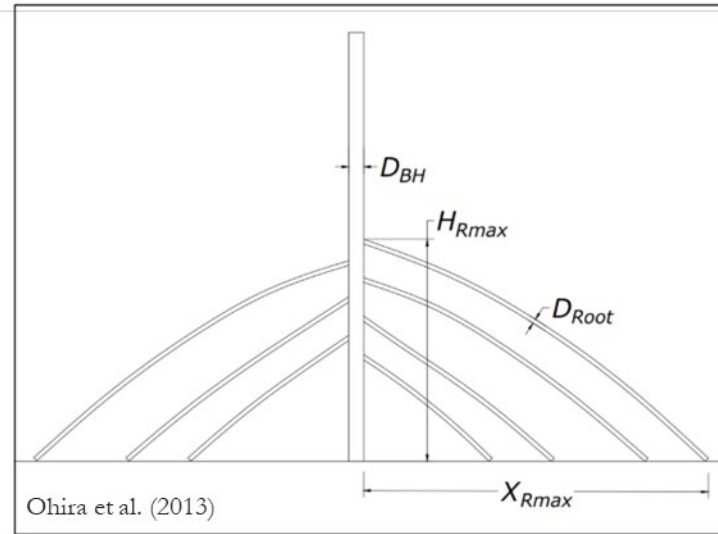




Kelty Physical Mangrove Models



Example of intertwined *Rhizophora* mangrove root system.
03/09/2020 St. Lucie Inlet State Park, Stuart FL



Ohira et al. (2013)

Example of idealized Ohira et al. (2013) mangrove tree root system.



Kelty (2021)

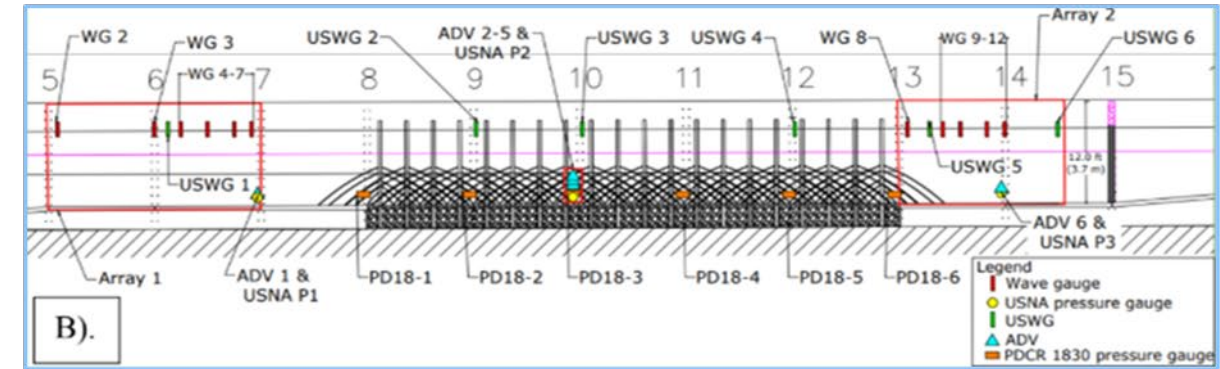
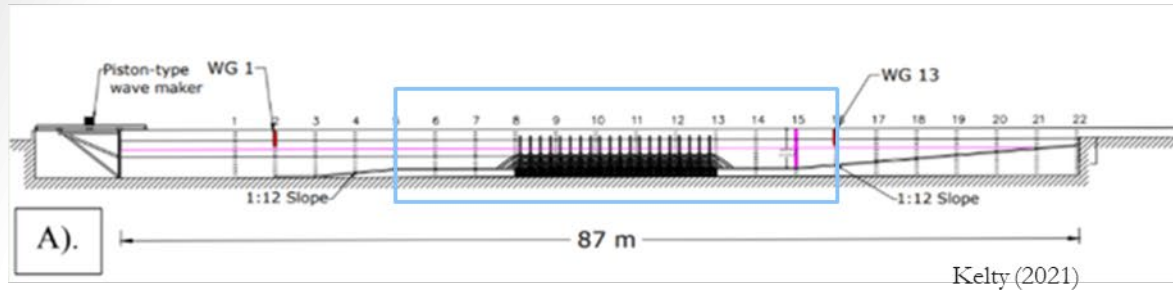
Kelty prototype-scale mangroves made of PVC.
Oregon State University

D_{BH}	N_R	D_{Root}	H_{Rmax}	X_{Rmax}
(m)	(-)	(m)	(m)	(m)
0.1143	14	0.0286	1.35	2.10

Summary table of model mangrove tree dimensions
 N_R = number of roots



Kelty Wave Flume

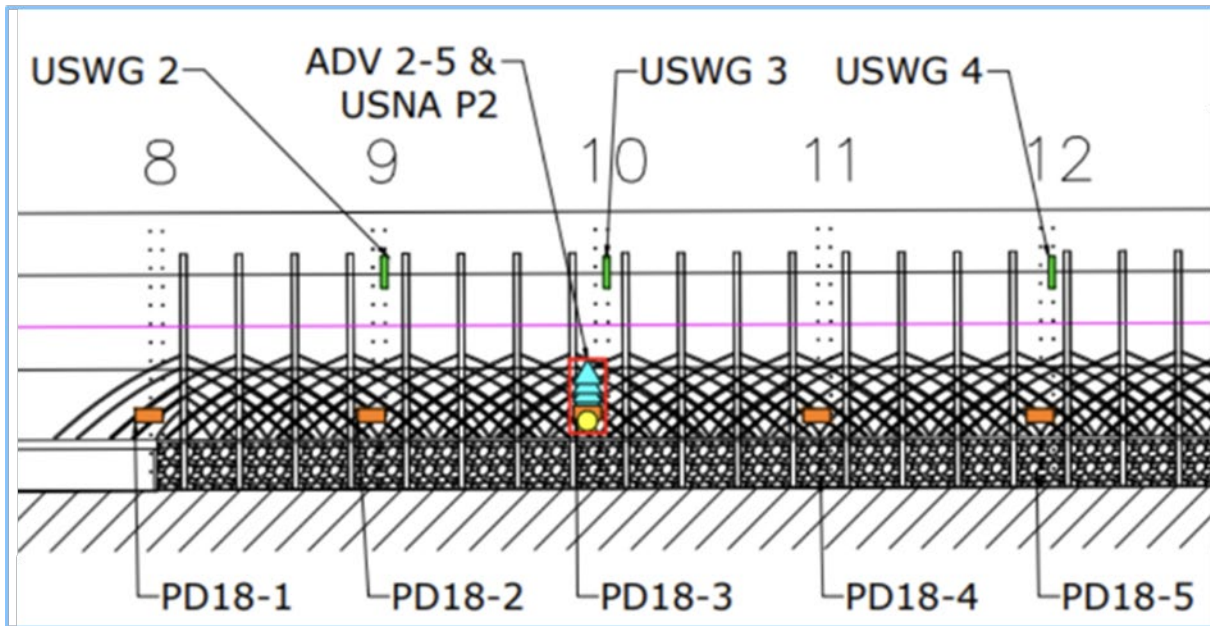
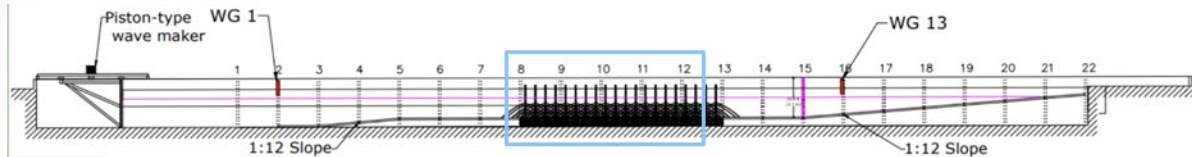


Layout		Wave Types	h _v [m] water height relative to false floor		T _p *[s]	H _{rmsi} *[m]	Wave Energy Flux* [W/m per width]
Baseline		Regular Random	0.8 1.0	1.5 1.8	1.55–7.65	0.125–0.990	10–3089
High Density		Regular Random	0.8 1.0	1.5 1.8	1.55–7.65	0.18–1.25	23–5917
Low Density		Regular Random	0.8 1.0	1.5 1.8	1.55–7.65	0.125–0.990	10–3478

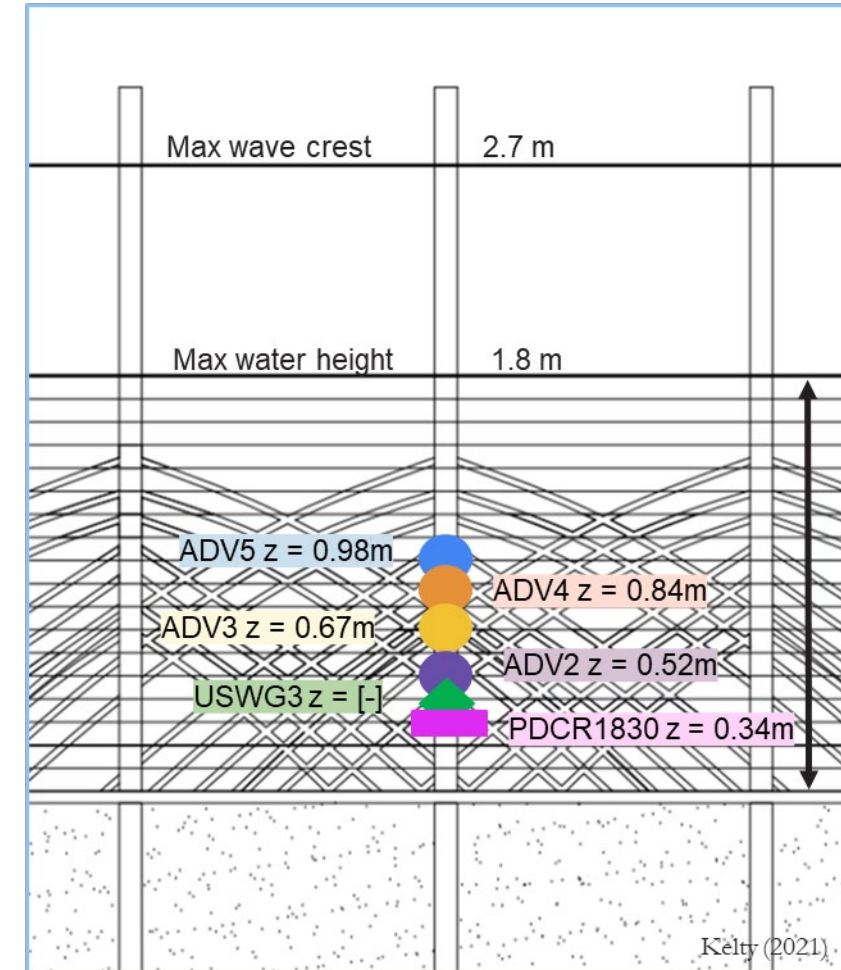
*only trials without a wall present are considered.



Kelty Data Collection, vertical stack



Kelty (2021)

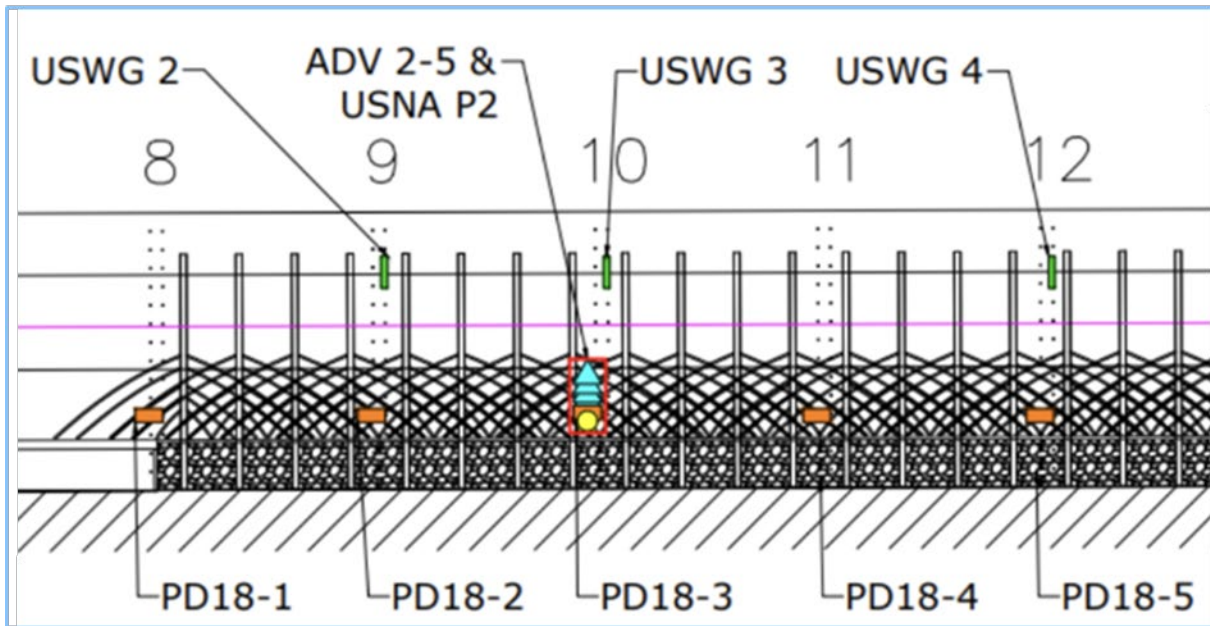
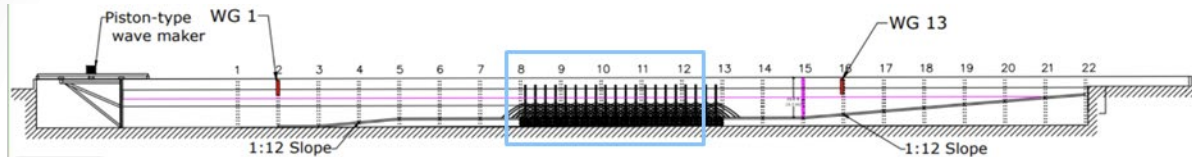


Kelty (2021)

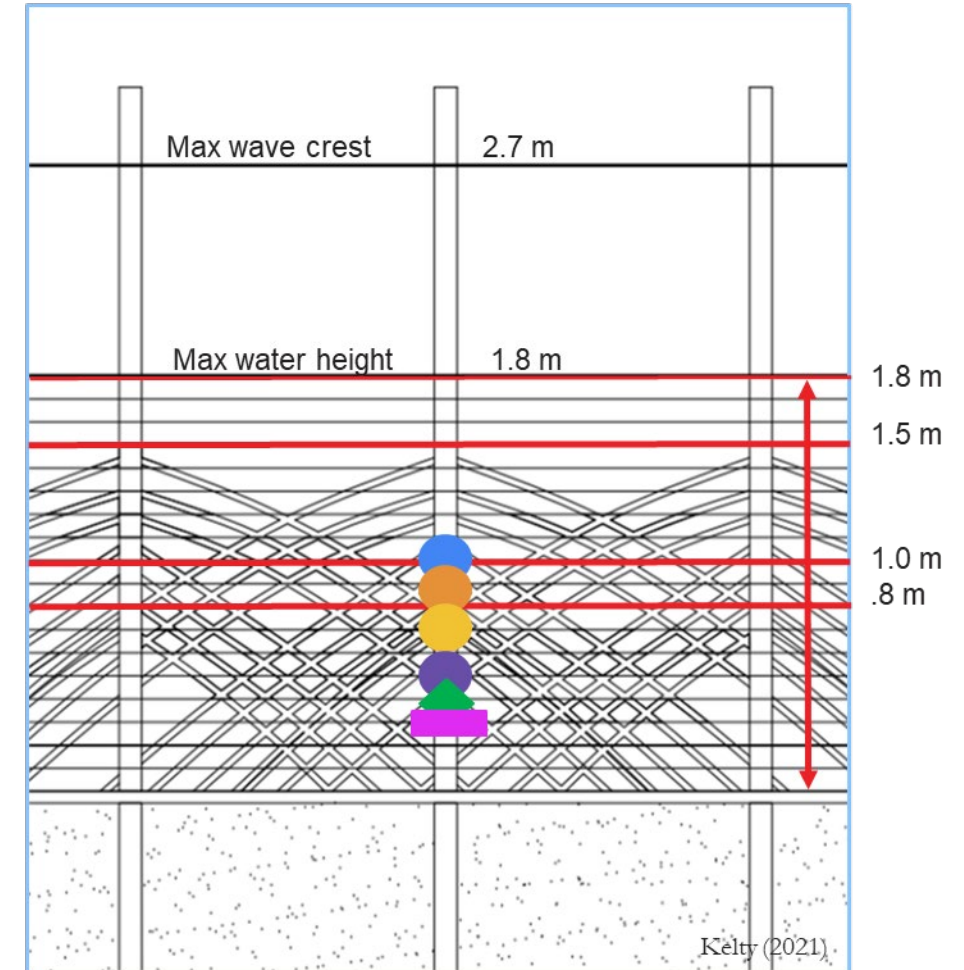
Elevations relative to false floor of max water level, max wave crest, acoustic doppler velocimeters, wave gauges, and pressure gauges.



Kelty Data Collection, water level



Kelty (2021)

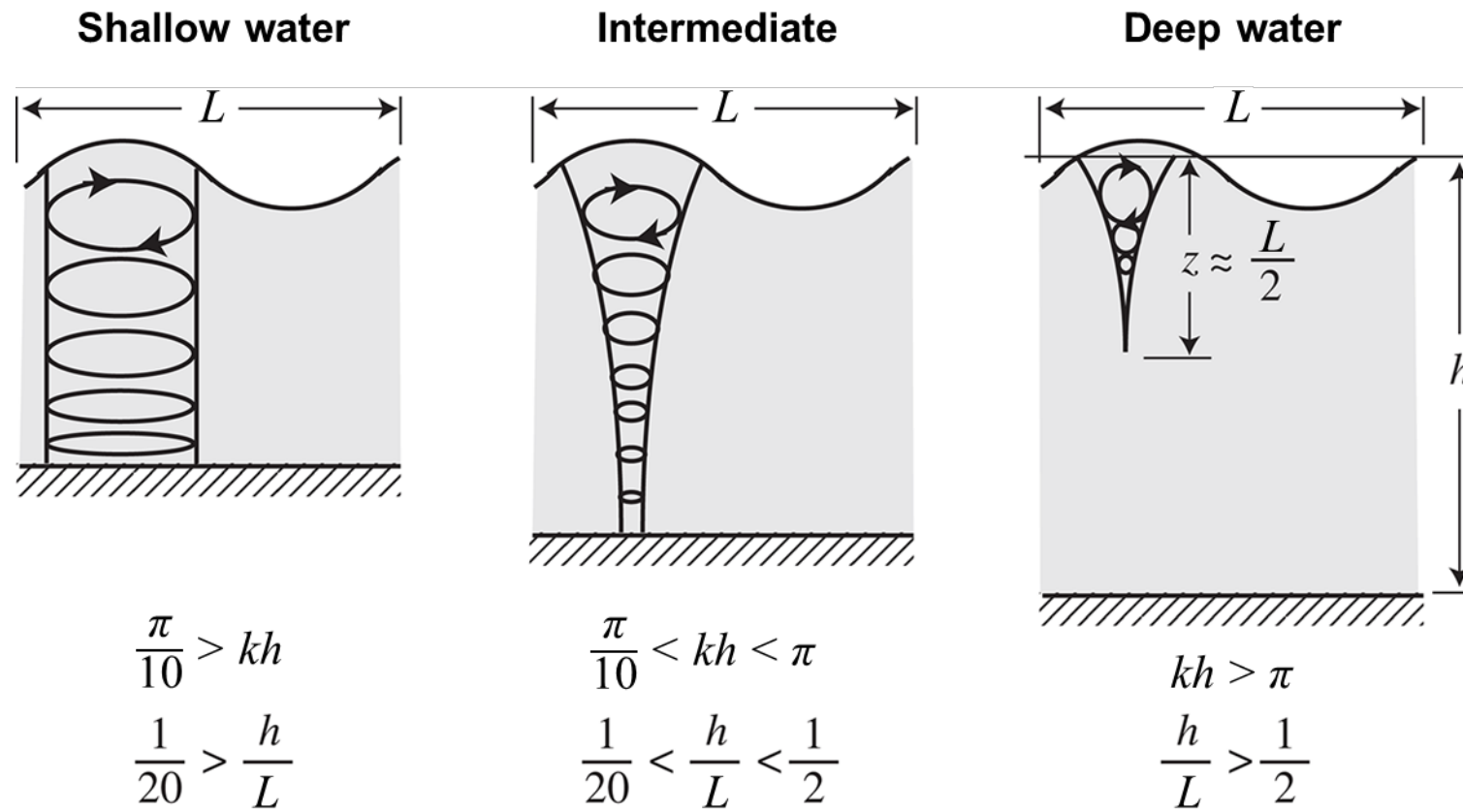


Elevations relative to false floor of max water level, max wave crest, acoustic doppler velocimeters, wave gauges, and pressure gauges.



Wave Orbital Velocities

- Some variation in horizontal velocity u expected, per linear wave theory
- Relative wavenumber kh ranges between 0.35 and 1.60 for mangrove laboratory studies



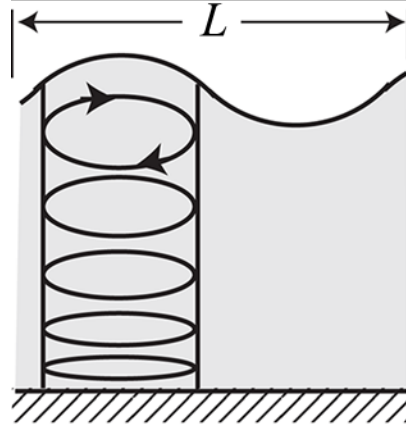


Wave Orbital Velocities, cont.

$$\eta = \frac{H}{2} \cos(kx - \sigma t)$$

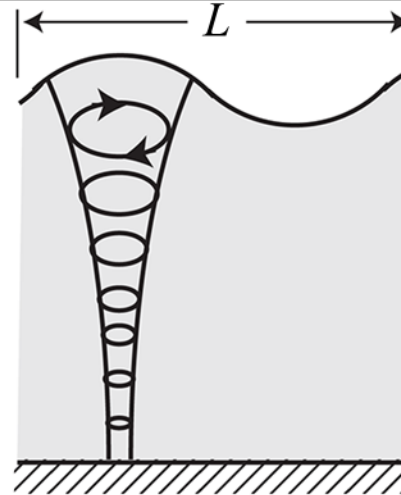
$$u = \frac{H}{2} \frac{\sigma \cosh(k(h+z))}{\sinh(kh)} \cos(kx - \sigma t) = \eta \frac{\sigma \cosh(k(h+z))}{\sinh(kh)}$$

Shallow water



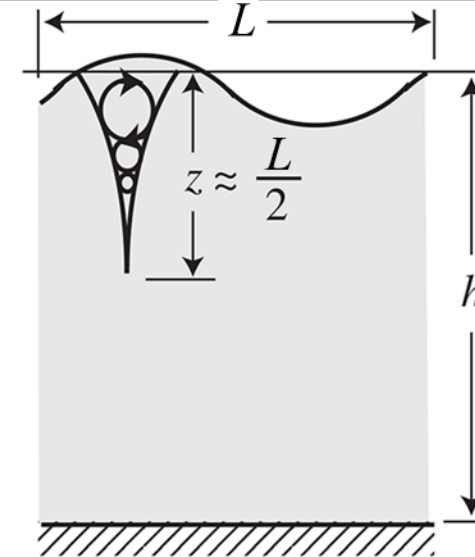
$$\frac{\pi}{10} > kh$$
$$\frac{1}{20} > \frac{h}{L}$$

Intermediate



$$\frac{\pi}{10} < kh < \pi$$
$$\frac{1}{20} < \frac{h}{L} < \frac{1}{2}$$

Deep water



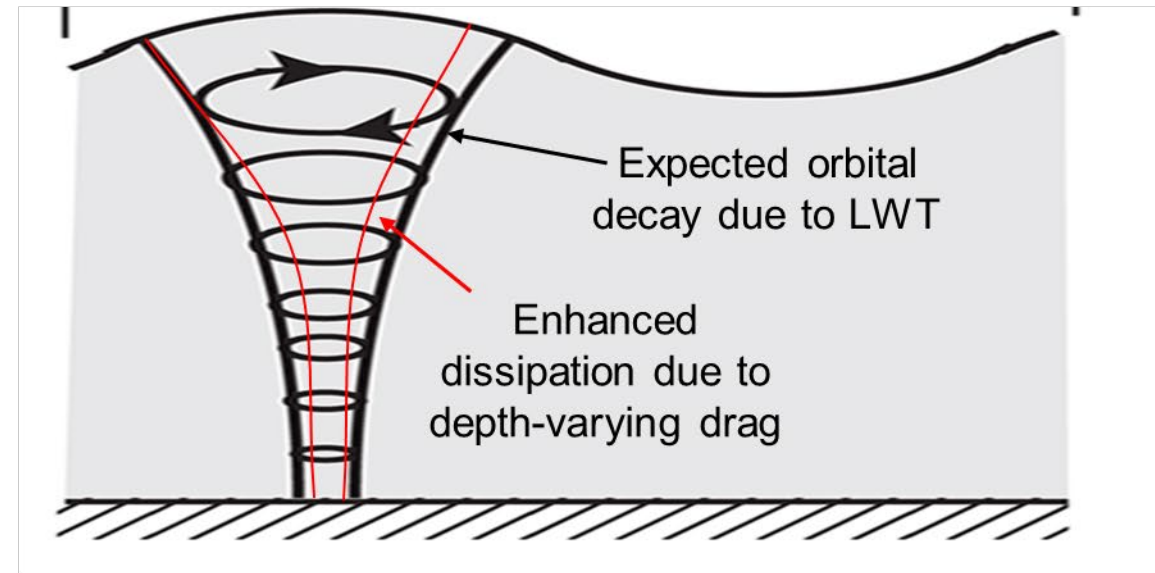
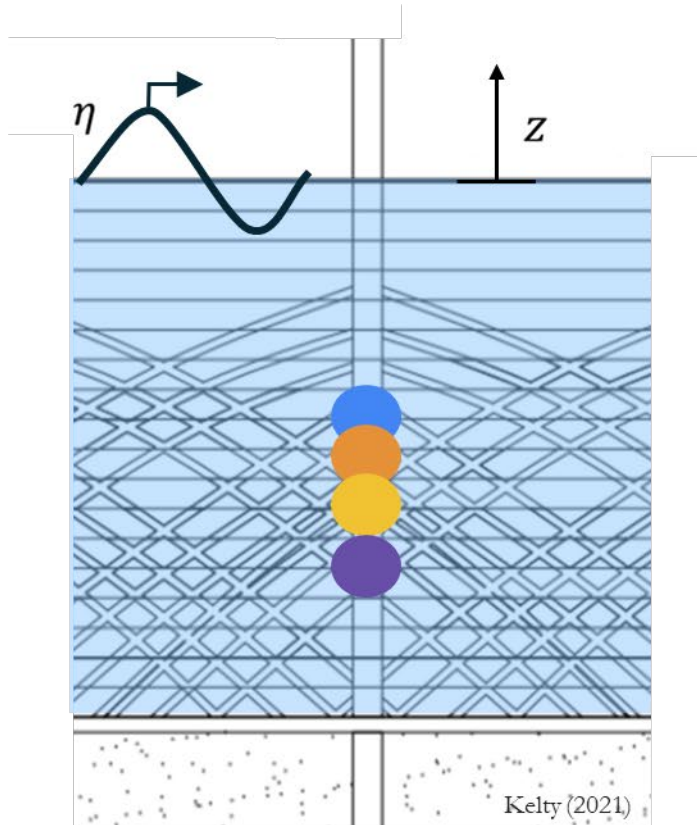
$$kh > \pi$$
$$\frac{h}{L} > \frac{1}{2}$$



Wave Orbital Velocities, additional

$$\eta = \frac{H}{2} \cos(kx - \sigma t)$$

$$u = \frac{H}{2} \frac{\sigma \cosh(k(h+z))}{\sinh(kh)} \cos(kx - \sigma t) = \eta \frac{\sigma \cosh(k(h+z))}{\sinh(kh)}$$



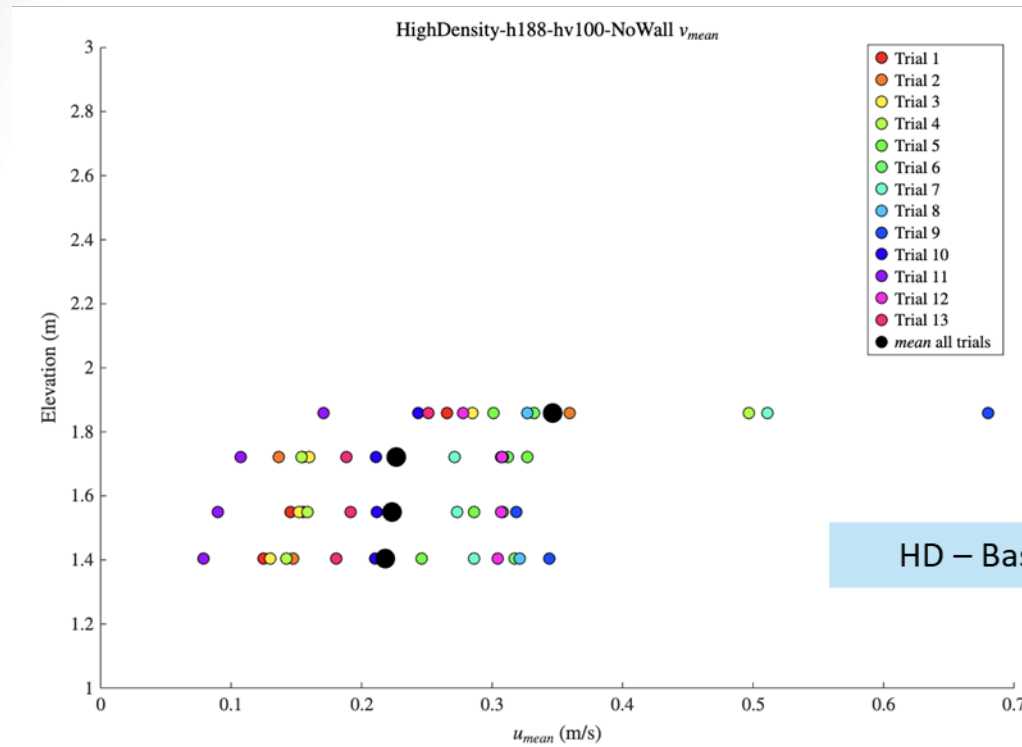
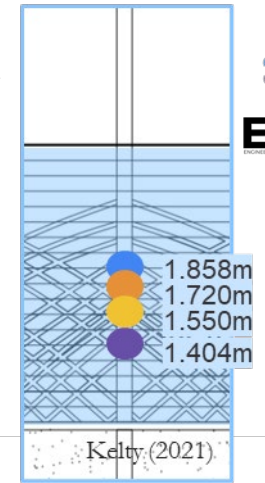


Velocities within ADV stack – High Density

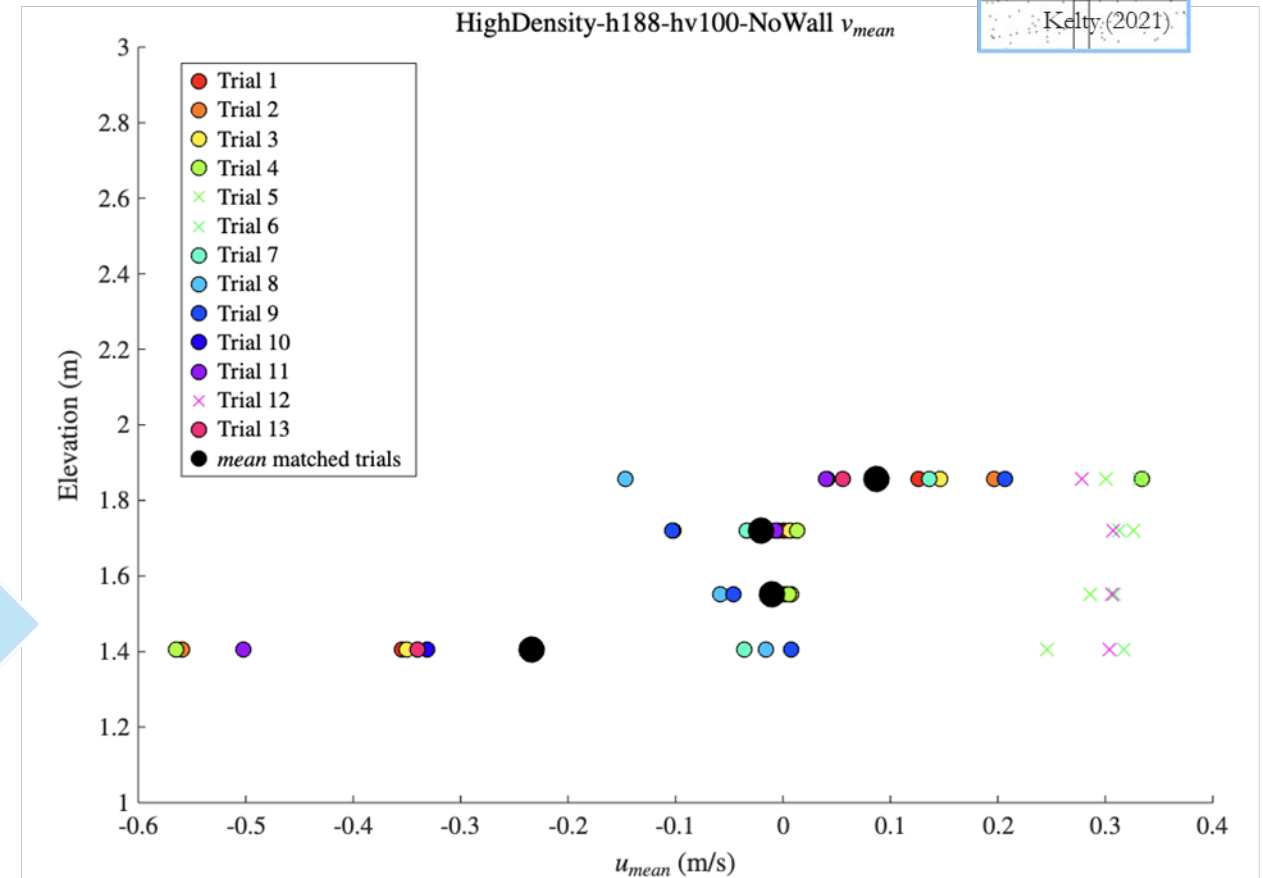
High-Density and Low-Density trials were matched with a Baseline trial.

random vs. regular wave $T_p \leq 0.5$ s

$H_{rms} \leq 5$ cm



HD – Baseline



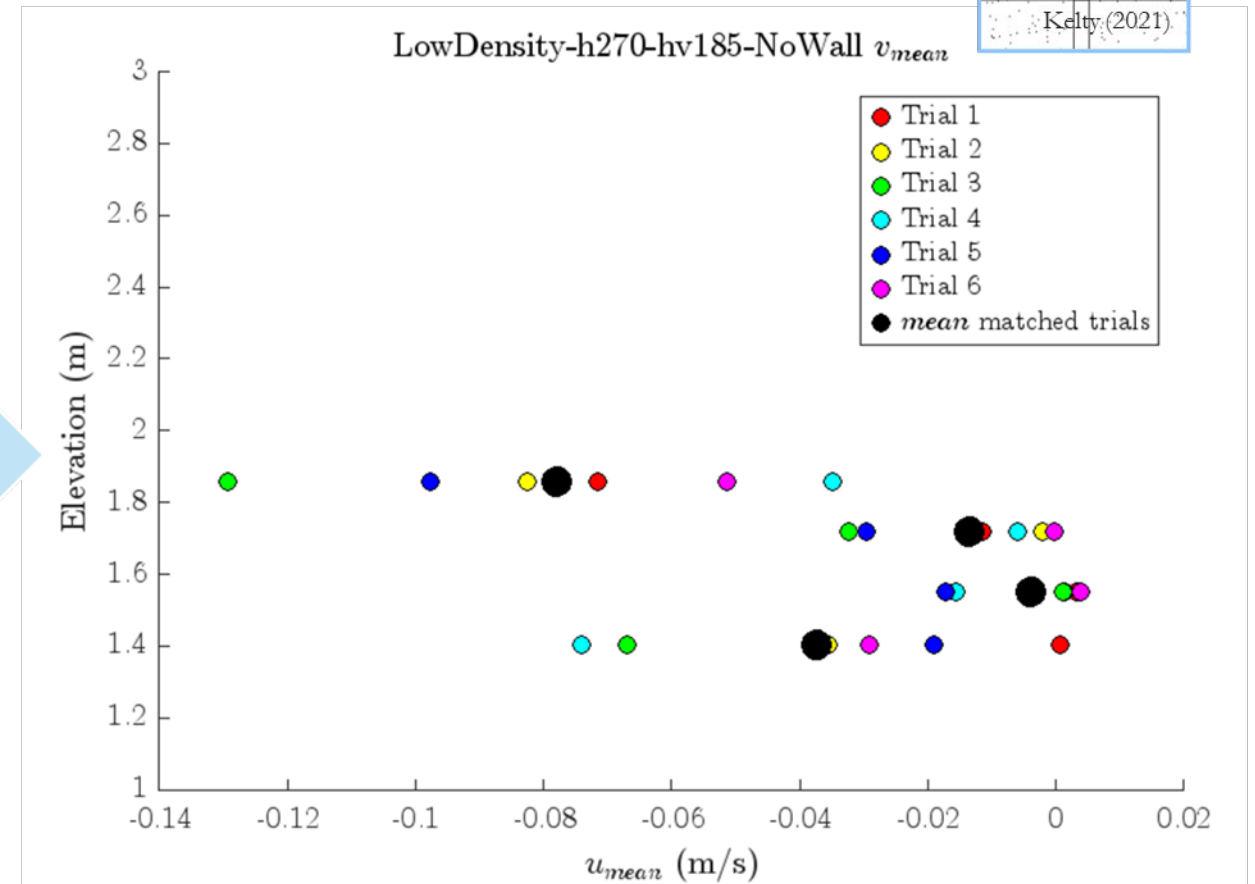
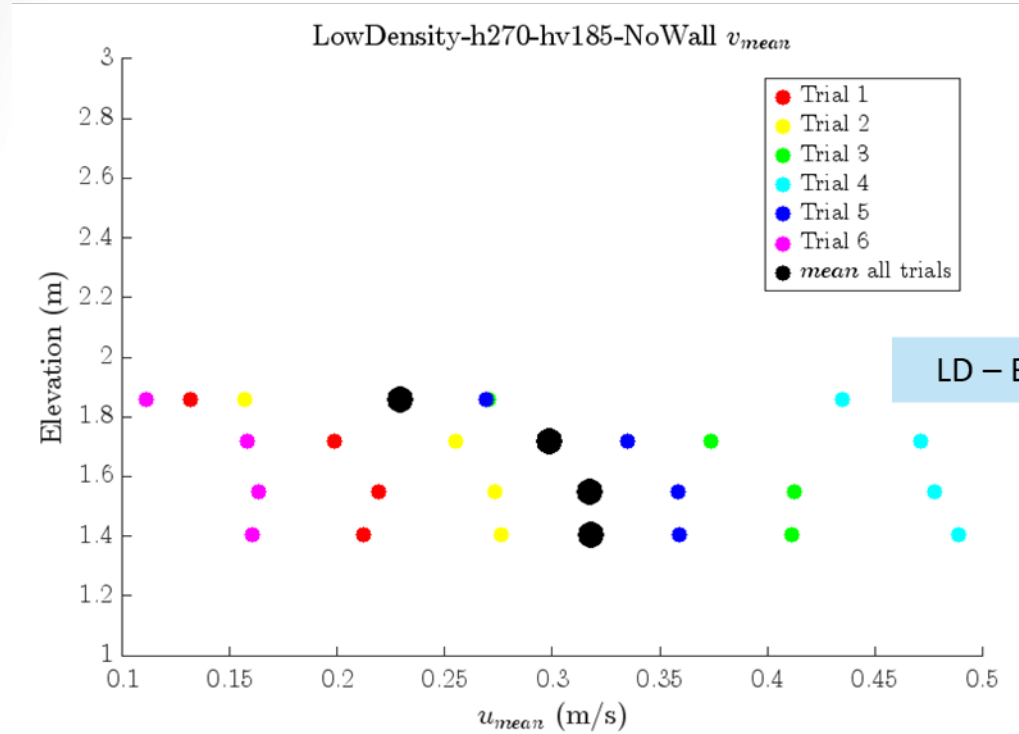
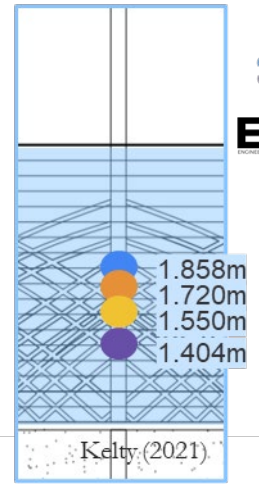


Velocities within ADV stack – Low Density

High-Density and Low-Density trials were matched with a Baseline trial.

random vs. regular wave $T_p \leq 0.5$ s

$H_{rms} \leq 5$ cm





Correlation Calculations

Cross Correlation

`[x, y] = xcorr(η*cosh, u, 'normalized')`

$$\hat{R}_{xy, \text{coeff}}(m) = \frac{1}{\sqrt{\hat{R}_{xx}(0)\hat{R}_{yy}(0)}} \hat{R}_{xy}(m)$$

term to normalize output

cross correlation at lag m

Coherence

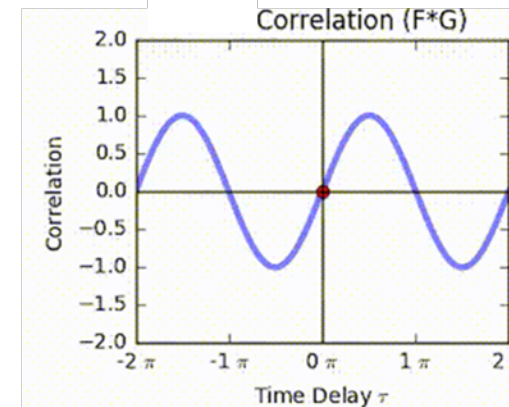
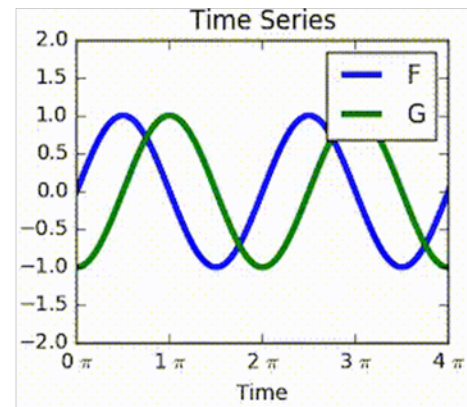
`[x, y] = mscohere(η*cosh, u)`

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}$$

cross power spectral density between x and y

power x has at frequency f

power y has at frequency f



<https://en.wikipedia.org/wiki/Cross-correlation#>

x - calculated correlation

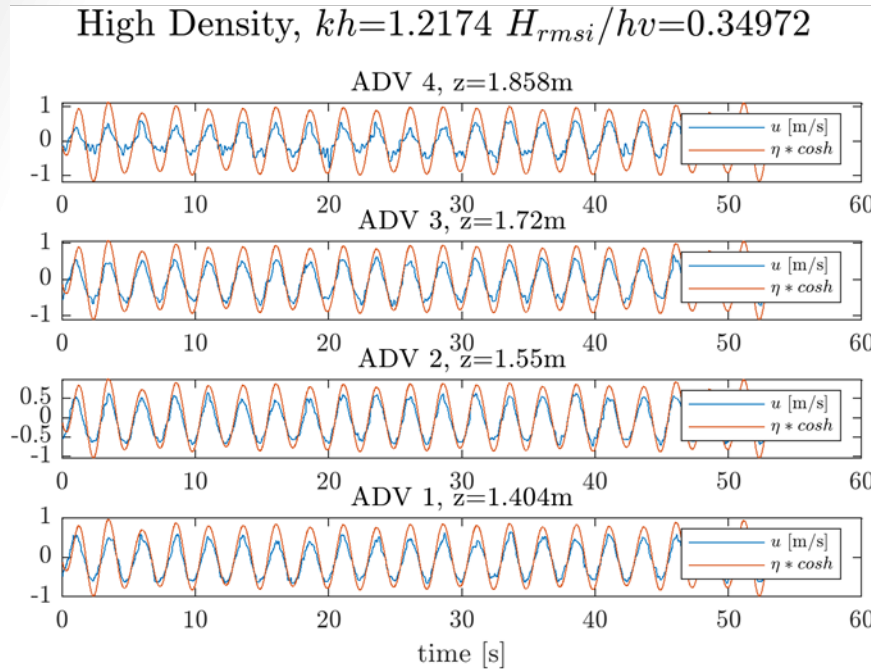
y - lag

normalized - normalizes the sequence so that the autocorrelations at zero lag equal 1



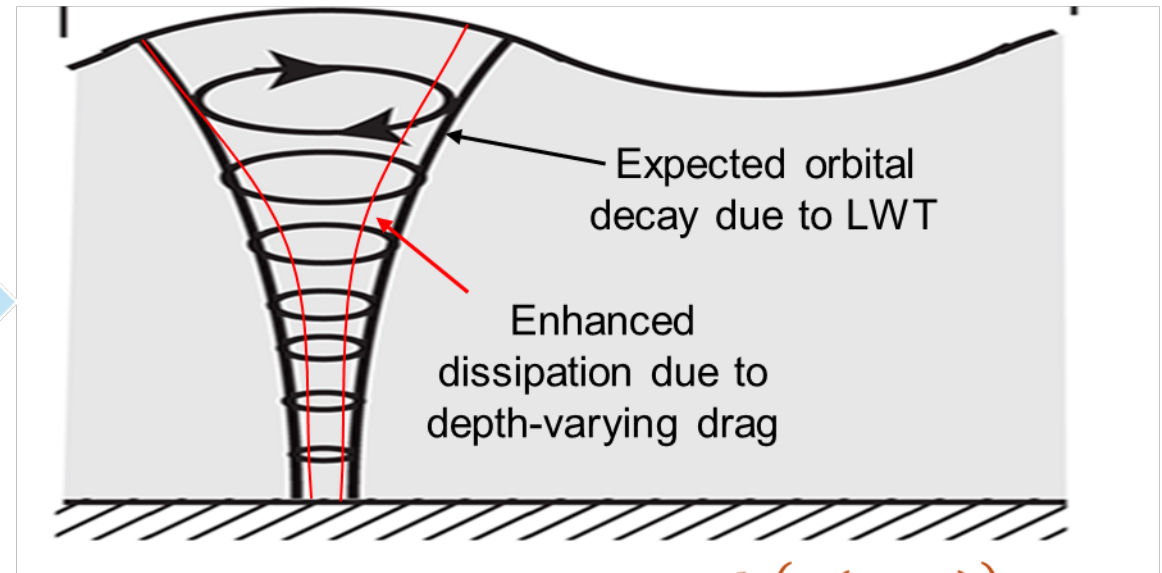
Correlation u and $\eta^* \cosh$

$$u = \frac{H \cosh(k(h+z))}{2 \sigma \sinh(kh)} \cos(kx - \sigma t) = \eta \frac{\cosh(k(h+z))}{\sigma \sinh(kh)}$$



Example plot depicting velocity and water height * cosh term over time.

Coherence

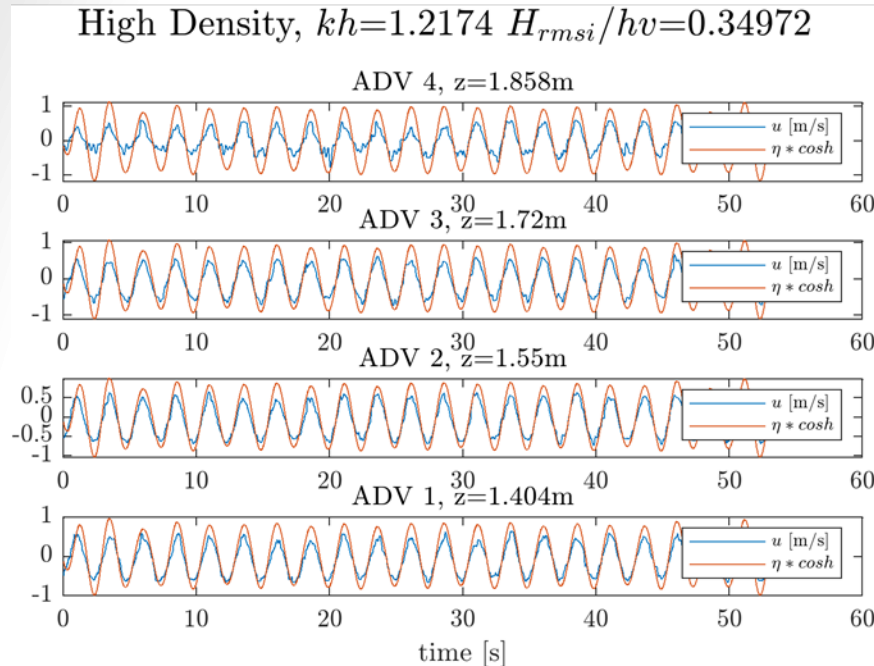


low coherence $\rightarrow u \propto \eta \frac{\sigma \cosh(k(h+z))}{\sinh(kh)}$

high coherence $\rightarrow u \propto \eta \frac{\sigma \cosh(k(h+z))}{\sinh(kh)}$

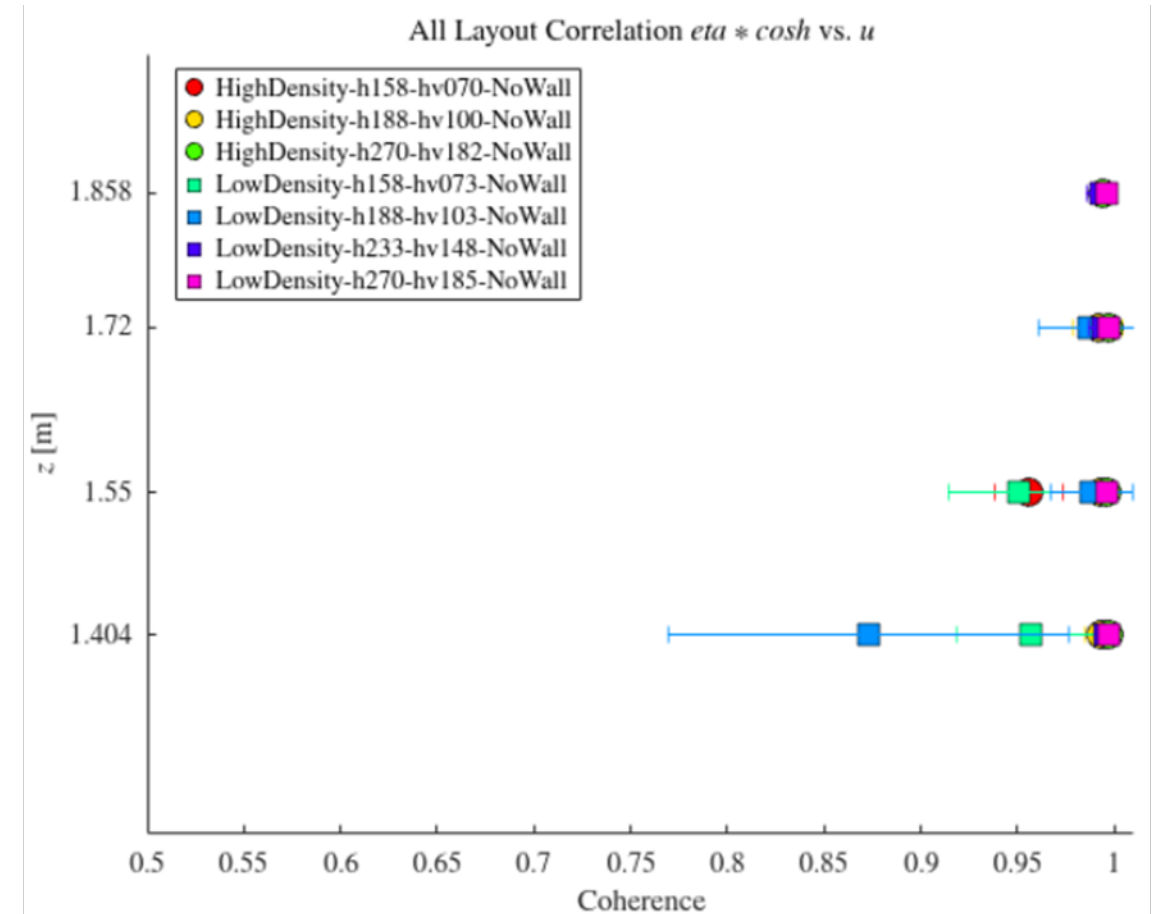


Correlation u and η^*cosh , cont.



Example plot depicting velocity and water height* $cosh$ term over time.

Coherence

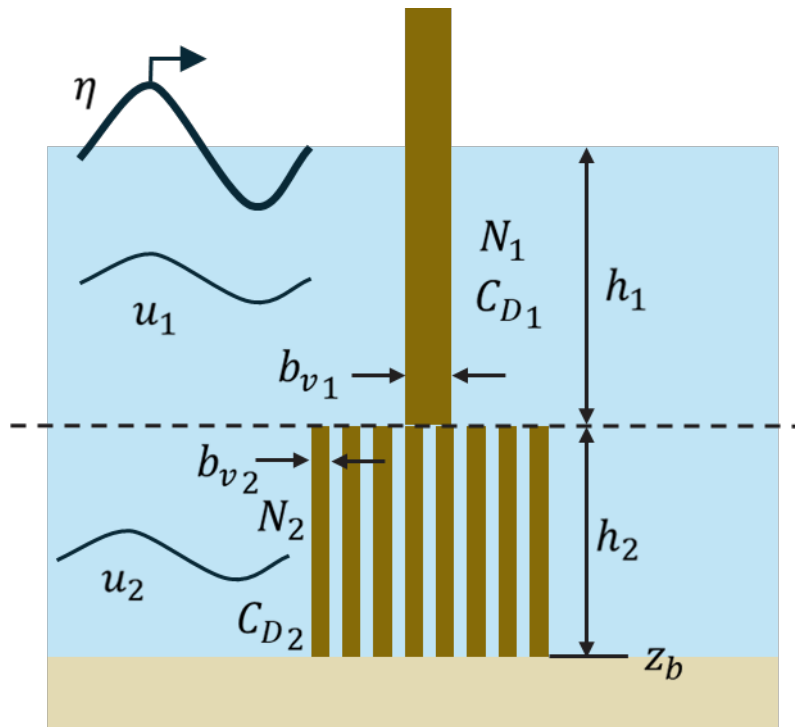


$$\text{high coherence} \rightarrow u \propto \eta \frac{\sigma \cosh(k(h+z))}{\sinh(kh)}$$



Research Question #2

$$\frac{\partial E_f}{\partial x} = -\varepsilon_f - \varepsilon_v = -\overline{\tau_b u} - \overline{\int_{z_b}^{\eta} f_v \cdot u \, dz} = -\overline{\rho c_f u^2 |u|} - \overline{\int_{z_b}^{\eta} \frac{\rho}{2} C_D b_v N |u| u \cdot u \, dz}$$



Research question: What is the most (1) practical, (2) physically meaningful method of predicting dissipation over vegetation with strong vertical variation?

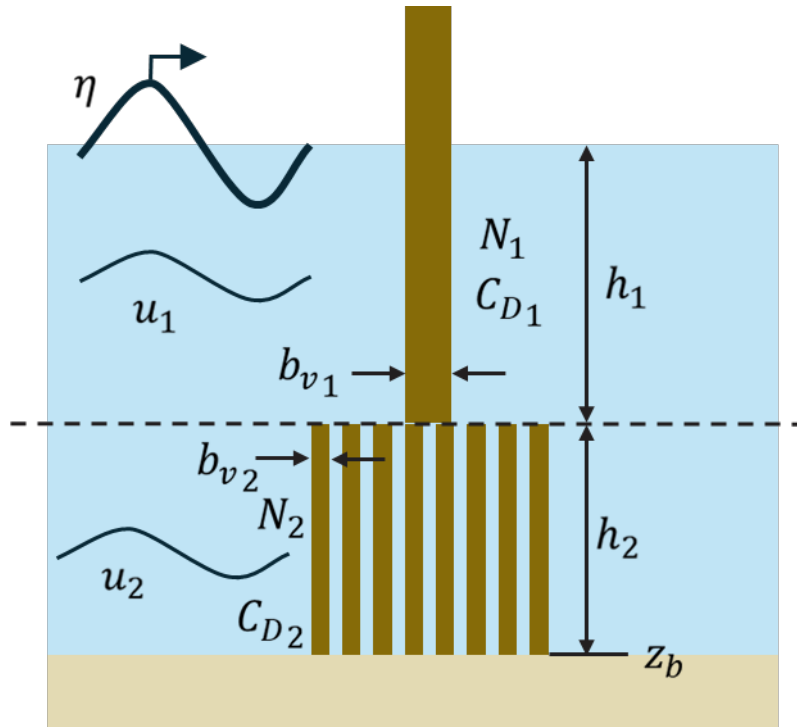


RQ #2 – discussion

$$\frac{\partial E_f}{\partial x} = -\varepsilon_f - \varepsilon_v = -\overline{\tau_b u} - \overline{\int_{z_b}^{\eta} f_v \cdot u \, dz} = -\overline{\rho c_f u^2 |u|} - \overline{\int_{z_b}^{\eta} \frac{\rho}{2} C_D b_v N |u| u \cdot u \, dz}$$

$$= \overline{\frac{\rho}{2} \int_{z_b}^{z_b+h_2} C_{D_2} b_{v_2} N_2 |u_2| u_2 \cdot u_2 \, dz} + \overline{\frac{\rho}{2} \int_{z_b+h_2}^{\eta} C_{D_1} b_{v_1} N_1 |u_1| u_1 \cdot u_1 \, dz}$$

$$= \frac{\rho}{2} C_{D_2} b_{v_2} N_2 \overline{|u_2^3|} h_2 + \frac{\rho}{2} C_{D_1} b_{v_1} N_1 \overline{|u_1^3|} (\eta + h_1)$$



If $u_2 \approx u_1$

$$= \frac{\rho}{2} C_D \overline{|u^3|} (N_2 h_2 b_{v_2} + b_{v_1} N_1 (\eta + h_1))$$

$$= \frac{\rho}{2} C_D \overline{|u^3|} \overline{N b_v} (\bar{\eta} + h) = \frac{\rho}{2} C_D \overline{|u^3|} \overline{A_v} (\bar{\eta} + h)$$



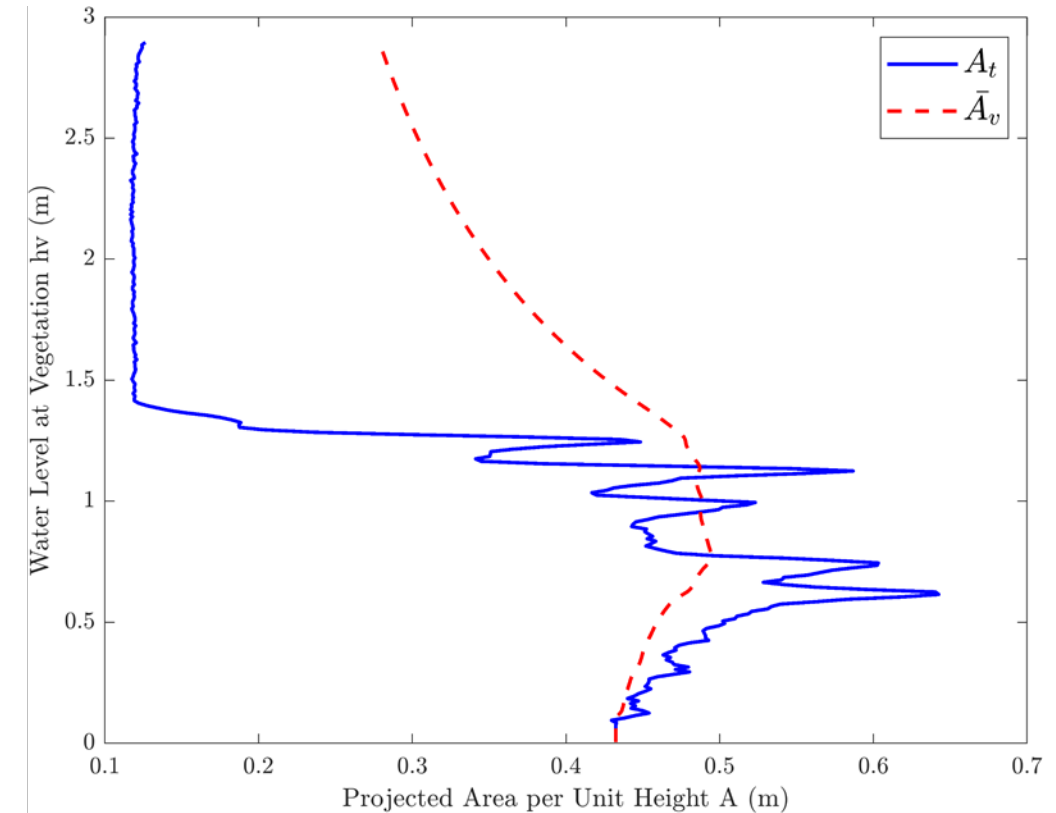
Proposed Method of Wave Attenuation Calculation

If $u_2 \approx u_1$

$$\begin{aligned}
 &= \frac{\rho}{2} C_D \overline{|u^3|} (N_2 h_2 b_{v_2} + b_{v_1} N_1 (\bar{\eta} + h_1)) \\
 &= \frac{\rho}{2} C_D \overline{|u^3|} \overline{N b_v} (\bar{\eta} + h) = \frac{\rho}{2} C_D \overline{|u^3|} \overline{A_v} (\bar{\eta} + h)
 \end{aligned}$$



Image of LiDAR scan of HD prototype mangrove forest from Kelty case study.



Plot showing Kelty collected prototype mangrove area data and depth averaged area.



Proposed Method of Wave Attenuation Calculation, cont.

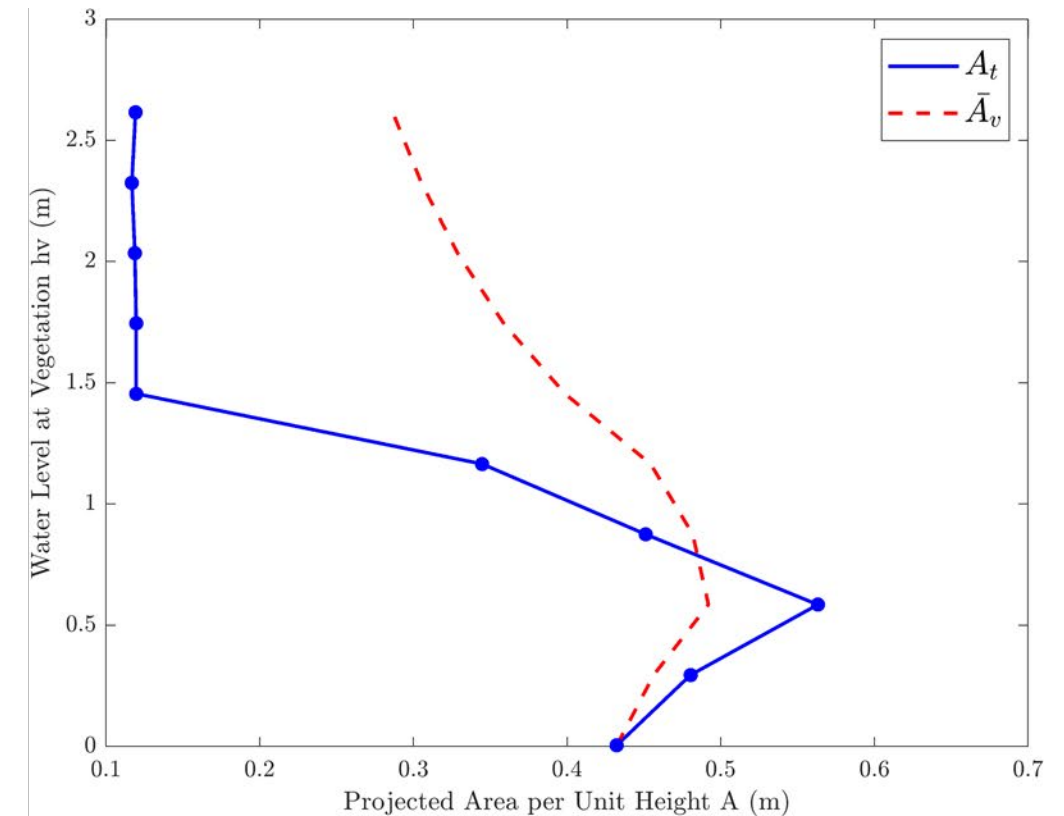
If $u_2 \approx u_1$, $C_{D2} \approx C_{D1}$

$$= \frac{\rho}{2} C_D \overline{|u^3|} (N_2 h_2 b_{v_2} + b_{v_1} N_1 (\bar{\eta} + h_1))$$

$$= \frac{\rho}{2} C_D \overline{|u^3|} \overline{Nb_v} (\bar{\eta} + h) = \frac{\rho}{2} C_D \overline{|u^3|} \overline{A_v} (\bar{\eta} + h)$$



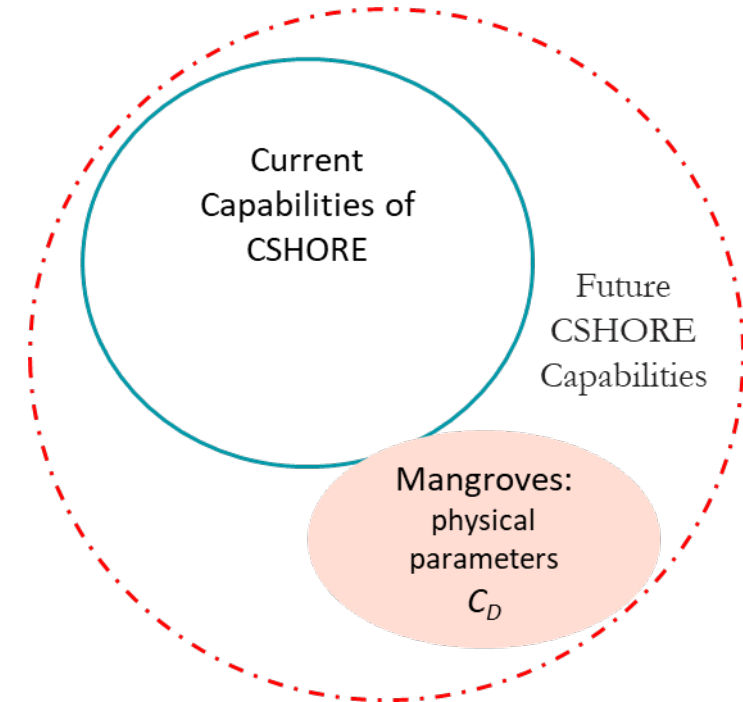
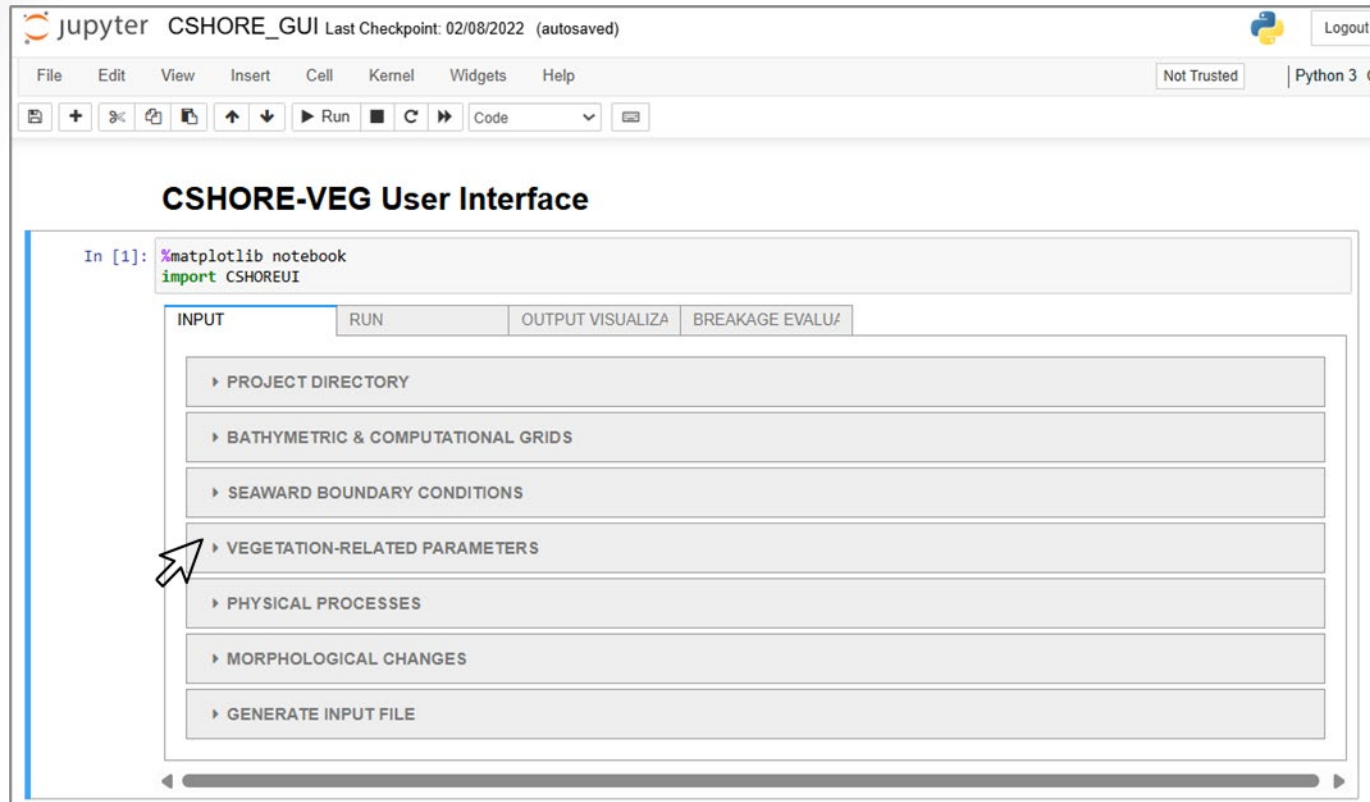
N and b_v can be found through physically measuring mangrove branches.



Simplified plot showing Kelty collected prototype mangrove area data and depth averaged area.



Future updates to the CSHORE-VEG GUI





Drag Coefficient Equations

$$f = \rho \frac{C_D}{2} b_v N |u| u = \beta |u| u$$

Johnson | Regular and Random Waves

$$\alpha = \frac{4 A_{t,m} N H_i C_D k}{9\pi} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Kelty | Regular Waves

$$\tilde{\alpha} = \frac{A_{t,m} N H_{rms,i} C_D k}{3\sqrt{\pi}} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Kelty | Random Waves



Drag Coefficient Equations, 2

CSHORE Drag Coefficient Code

```

F2overCd = N*1000/2*De*(hv+eta_p(:,3)).*udum.*abs(udum);
dissvegoverCd2 = mean(-F2overCd.*udum);
Cdexact2 = ((9810*n*c/8)*(Hrmsi(end)^2-Hrmsi(1)^2) - dissb*L)/(dissvegoverCd2*L);
if N==0;Cdexact = 1;Cdexact2 = 1;end
%Cd = Cdexact;
F2 = N*1000*Cdexact2/2*De*(hv+eta_p(:,3)).*udum.*abs(udum);
d = -(abs(F2).*abs(udum));
dissveg2 = -mean(abs(F2).*abs(udum));
  
```

$$\overline{F} = \overline{\int_{zb}^{\eta} f dz} = \beta h \overline{|u|u}$$

$$\overline{Fu} = \beta h \overline{|u|u^2}$$

Regular and Random Waves | Johnson et. al. (2024)

$$\frac{\partial E_f}{\partial x} = -\overline{\tau u} - \overline{\int_{zb}^{\eta} f u dz}$$

$$f = \rho \frac{C_D}{2} b_v N |u|u = \beta |u|u$$

Regular and Random Waves | Johnson (2024)

simplified
from



Drag Coefficient Equations, 3

CSHORE Drag Coefficient Calculation

F - depth integrated force
 f - incremental fluid force on veg per unit area
 ρ - density of water
 C_d - drag coefficient
 b_v - vegetation diameter
 N - plan-form density of vegetation
 u - velocity
 β - combination of all factors
 E_f - wave energy flux
 ρ - density of water
 g - gravitational acceleration
 h - instantaneous water depth
 H - wave height or rms wave height
 c_g - group velocity
 x - horizontal coordinate
 τ - bottom shear stress
 h_v - water depth at vegetation

Constants

Measured

Modeled

$$\overline{F} = \int_{z_b}^{\eta} f dz = \beta \overline{h|u|u}$$

$$\overline{Fu} = \beta \overline{h|u|u^2}$$

Regular and Random Waves | Johnson et. al. (2024)

$$\frac{\partial E_f}{\partial x} = -\overline{\tau u} - \int_{z_b}^{\eta} f u dz$$

$$f = \rho \frac{C_D}{2} b_v N |u|u = \beta |u|u$$

Regular and Random Waves | Johnson (2024)

simplified
from



Drag Coefficient Equations, 4

Kelty Drag Coefficient Calculation

Regular Waves :

$$\frac{H_t}{H_i} = \frac{1}{1 + \alpha x}$$

$$\alpha = \frac{4 A_{t,m} N H_i C_D k}{9\pi} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Random Wave

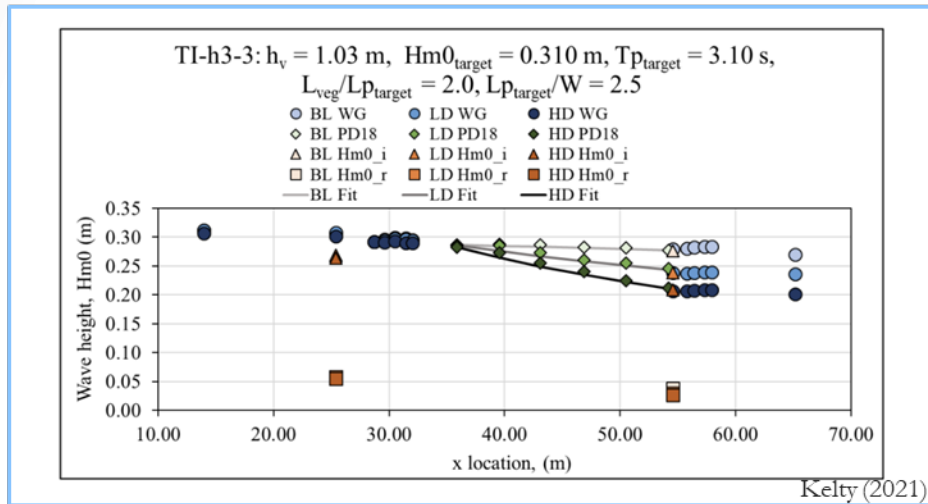
$$\frac{H_{rms,t}}{H_{rms,i}} = \frac{1}{1 + \tilde{\alpha} x}$$

$$\tilde{\alpha} = \frac{A_{t,m} N H_{rms,i} C_D k}{3\sqrt{\pi}} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$



Drag Coefficient Equations, 5

Kelty Drag Coefficient Calculation



Example calculation of α for Baseline, High Density, and Low Density layouts of random wave case TI-3-3. The wave height decay coefficient was found with the best fit line of each layout.

$$\alpha = \frac{4 A_{t,m} N H_i C_D k}{9\pi} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Regular Waves | Kelty et al. (2021)

$$\tilde{\alpha} = \frac{A_{t,m} N H_{rms,i} C_D k}{3\sqrt{\pi}} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Random Waves | Kelty et al. (2021)

calculated
based on T
and η



Drag Coefficient Equations, 6

Kelty Drag Coefficient Calculation

α - wave height decay coefficient

A_{tm} - ave projected area per height per tree

N - number of vegetation per area

H_{rmsiv} - rms wave height

C_d - drag coefficient

k - wave number ($2\pi/L$)

d - ave wetted height of veg (=water height)

h - average water depth at start of veg

Constants

Measured

Modeled

calculated
based on t
and η

$$\alpha = \frac{4 A_{t,m} N H_i C_D k}{9\pi} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Regular Waves | Kelty et al. (2021)

line of best
fit of H_{rmsi}
and x

$$\tilde{\alpha} = \frac{A_{t,m} N H_{rms,i} C_D k}{3\sqrt{\pi}} \frac{\sinh^3(kd) + 3\sinh(kd)}{\sinh(kh)(\sinh(2kh) + 2kh)}$$

Random Waves | Kelty et al. (2021)



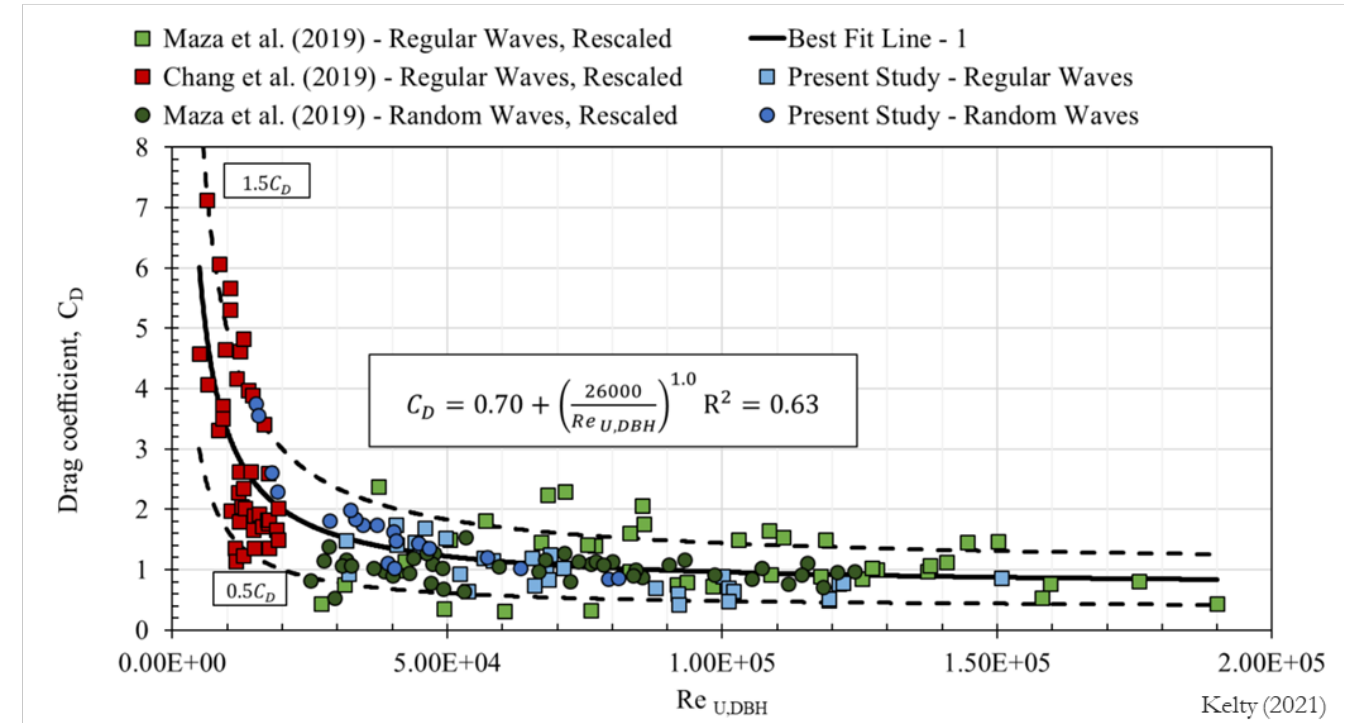
Drag Coefficient

Current

$$\begin{aligned} &= \frac{\rho}{2} C_D \overline{|u^3|} (N_2 h_2 b_{v_2} + b_{v_1} N_1 \overline{(\eta + h_1)}) \\ &= \frac{\rho}{2} C_D \overline{|u^3|} \overline{N b_v} (\bar{\eta} + h) = \frac{\rho}{2} C_D \overline{|u^3|} \overline{A_v} (\bar{\eta} + h) \end{aligned}$$

If $C_{D,Kelty} \approx C_{D,Johnson}$

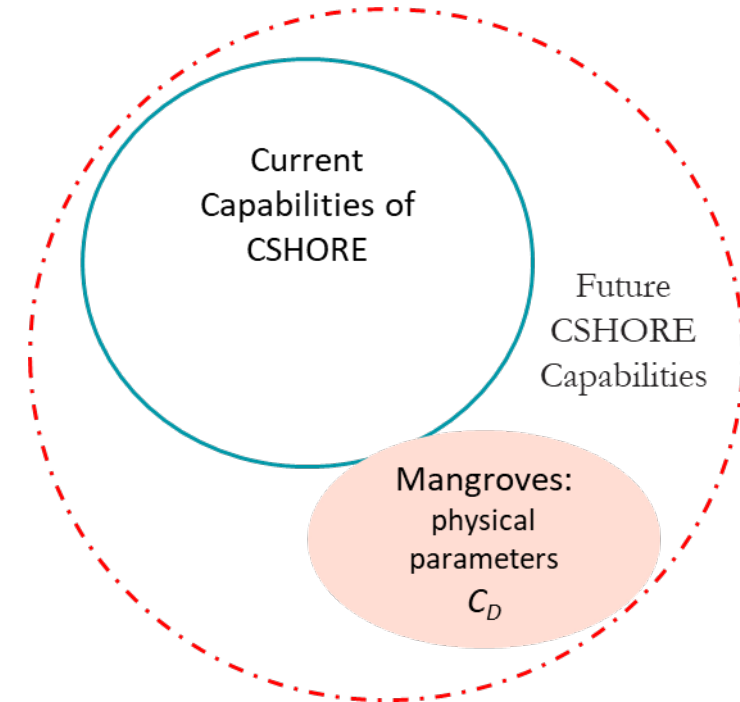
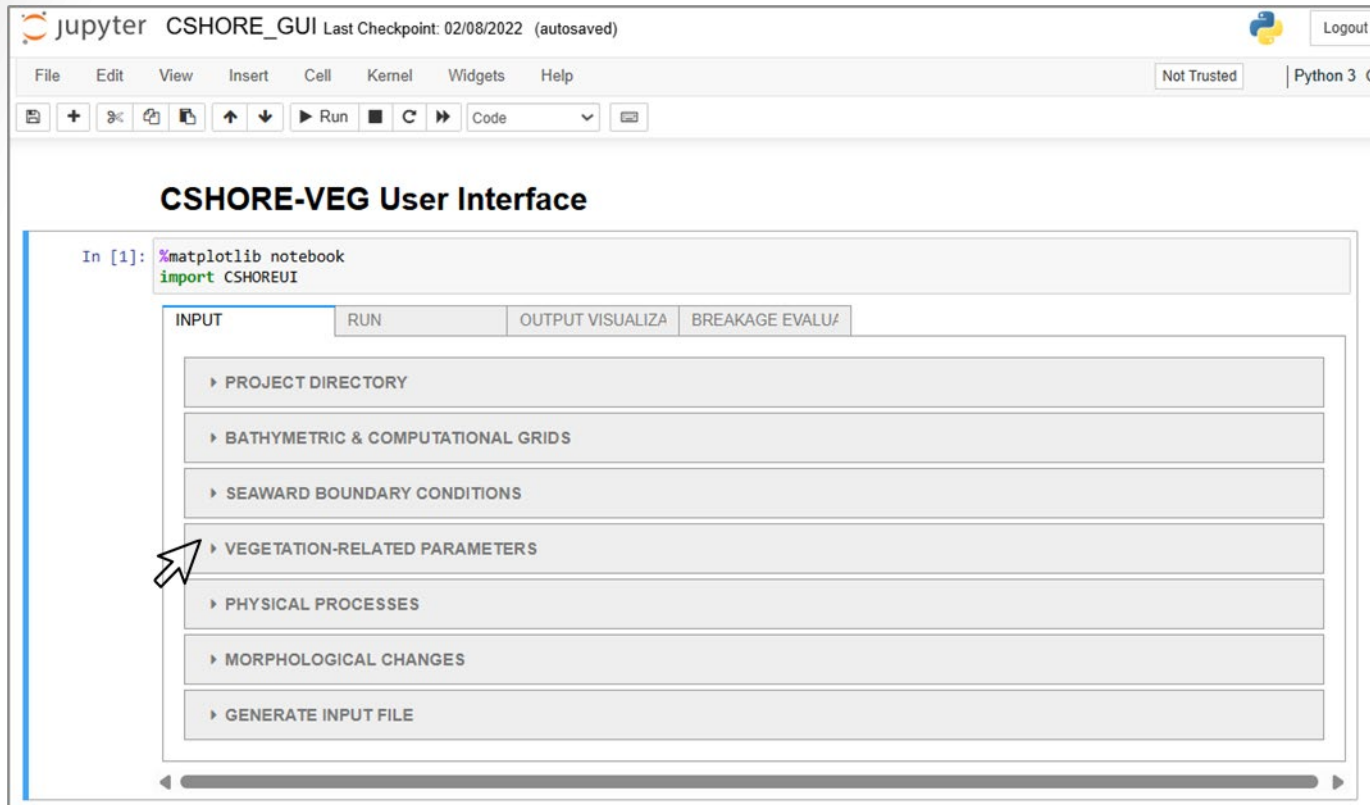
$$C_D = 0.70 + \left(\frac{26000}{Re_{U,DBH}} \right)^{1.0}$$



Kelty's proposed C_D equation for Kelty (2021), Maza et al. (2019) and Chang et al. (2019) data

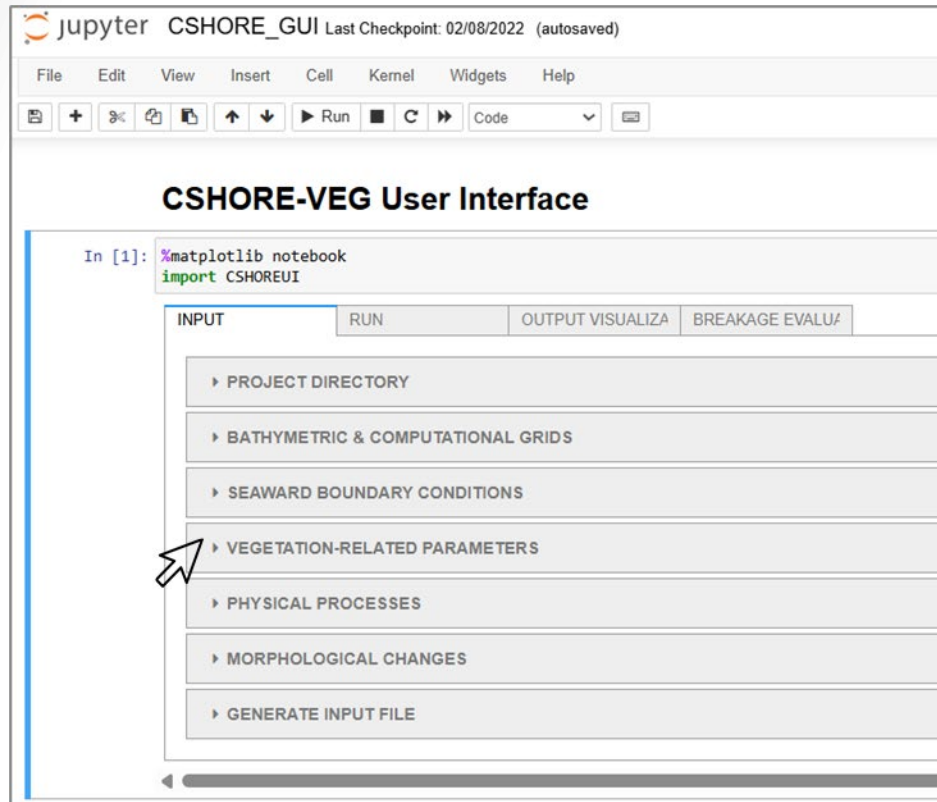


Future updates to the CSHORE-VEG GUI, revisited





Future updates to the CSHORE-VEG GUI, cont.



VEGETATION-RELATED PARAMETERS

Vegetation module: With vegetation

Consider spatially-varying C_D : no

Wave energy dissipation: Mendez and Losada (2004)

Vegetal flow-drag resistance: parametric model (Zhu and Chen 2019)

Veg. from $x =$ (m): 0

Veg. to $x =$ (m): 10

vegetation erosion limit (m): 0.3

Vegetation type: Mangrove,

Vegetal drag coefficient C_D : default

maximum allowed C_D : 45

Plant population density (plants/m²):

Diameter at breast height (m):

Number of roots per trunk (-):

Root diameter (m):

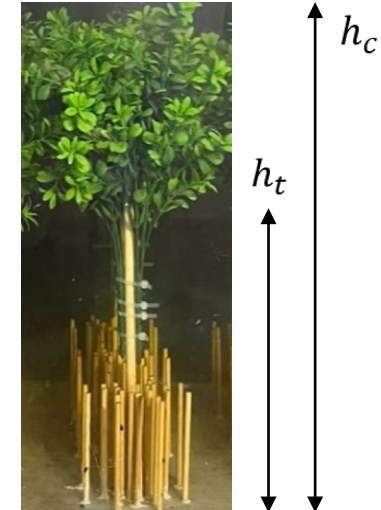
Height of primary roots (m):

Height of main trunk (m):

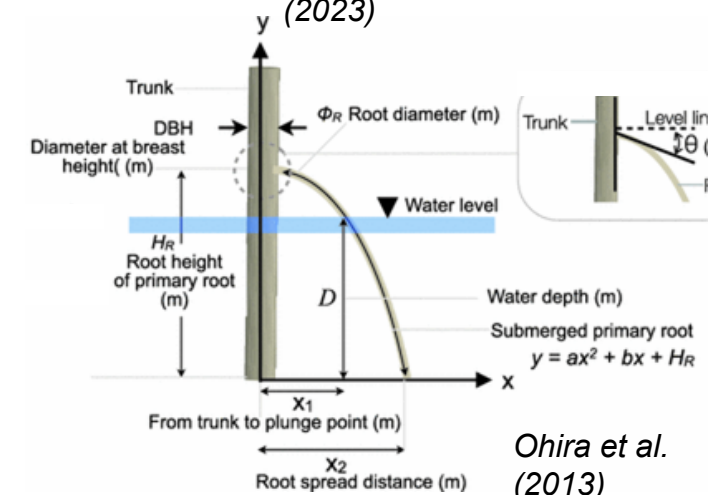
Height to top of canopy (m):

Canopy volume (m³):

...



Zhang et al.
(2023)



Ohira et al.
(2013)

CONTACT US:

Clara Zwolanek (ORISE Fellow)

Liz Holzenthal (PI)

Yan Ding (PI)

c.zwolo@gmail.com

elizabeth.r.holzenthal@usace.army.mil

yan.ding@usace.army.mil



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