

Performance of Three Innovative Levee Strengthening Systems under Full-Scale Overtopping Testing and Design Guidelines

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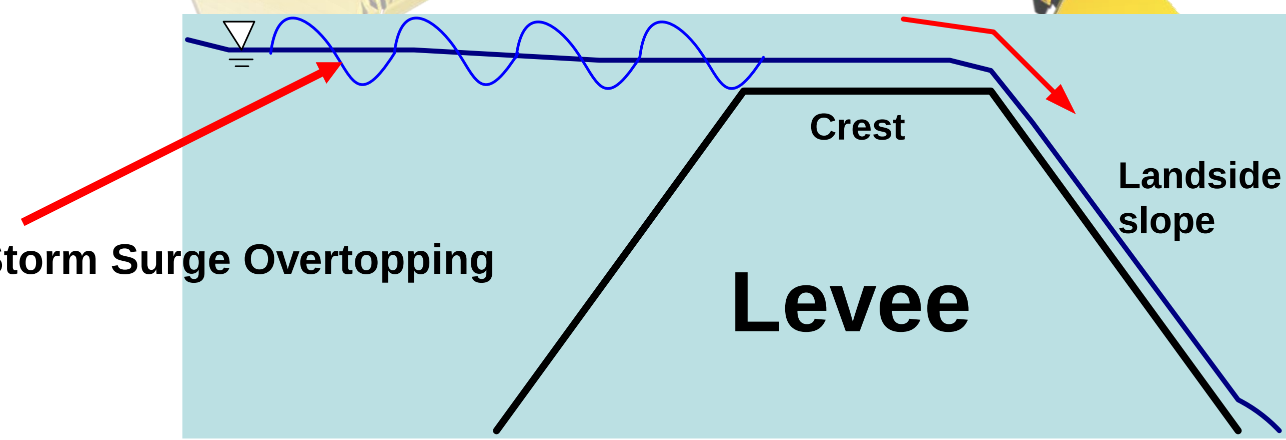
October 23, 2014

Congressional Delegation Visit

Problems Addressed

- Levees are subjected to overtopping, causing significant damage. Prevention methods against overtopping must be developed.
- This project addresses innovative methods to strengthen the crest and landside slope from erosive forces of overtopping flows.



SERRI
Southeast Region Research Initiative

Research Objectives

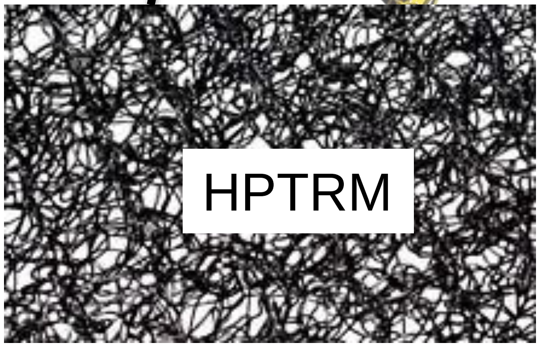
- To determine the effectiveness of three innovative levee strengthening systems during full-scale overtopping conditions simulating waves or combined wave and storm surge.
  - High performance turf reinforcement mat
  - Articulated concrete block system
  - Roller compacted concrete

Capabilities

- JSU is the leader in the area of Levee Overtopping with more than 40 publications, many in top engineering journals.
- Received 1.45 M from DHS for research
- Full Scale Testing
- Numerical Modeling
- Slope Stability Analysis

High Performance Turf Reinforcement Mats (HPTRM)

- The HPTRMs have extremely high tensile strengths, and use a unique matrix of polypropylene yarns and fiber technology specially created to lock soil in place.



Articulated Concrete Block System (ACB)

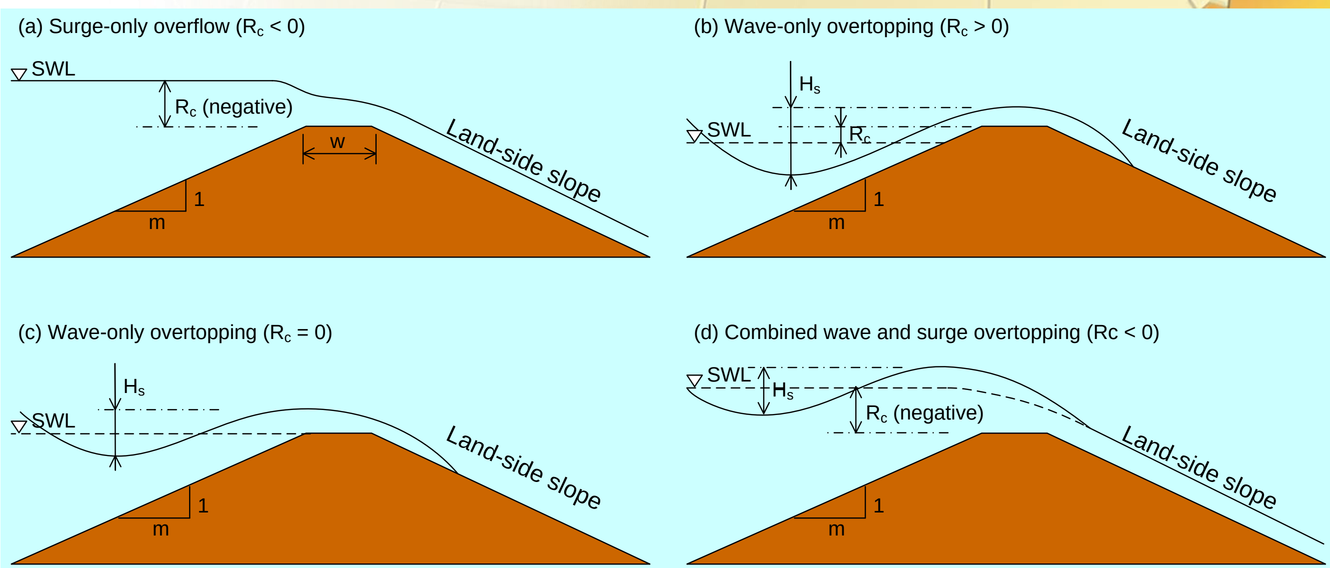
- An ACB system is a matrix of machine compressed individual concrete blocks assembled to form a large mat.
- Blocks are 10 to 23 cm thick and 929 to 1858 cm^2 in plan with openings penetrating the entire block.

Roller Compacted Concrete

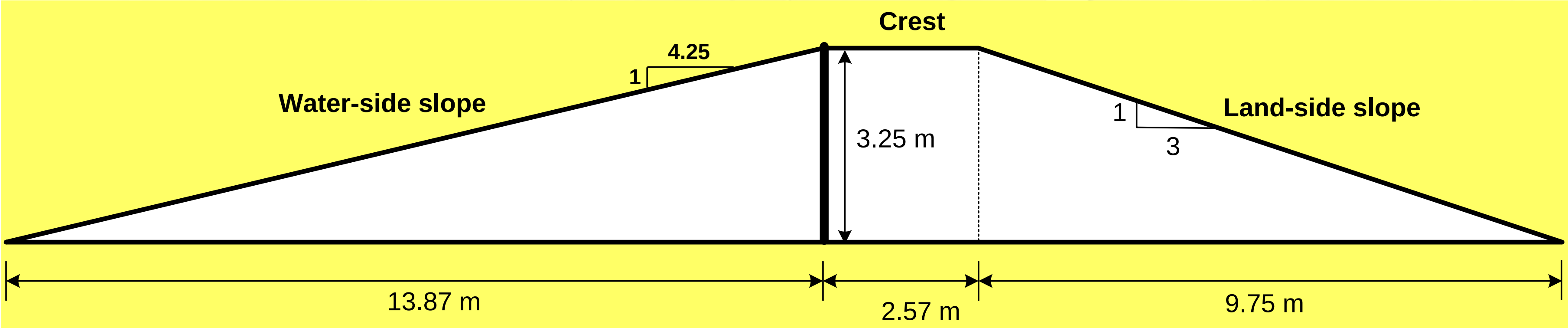
- RCC is formed by mixture of controlled-gradation aggregate, Portland cement, mixed with water and then compacted by a roller.

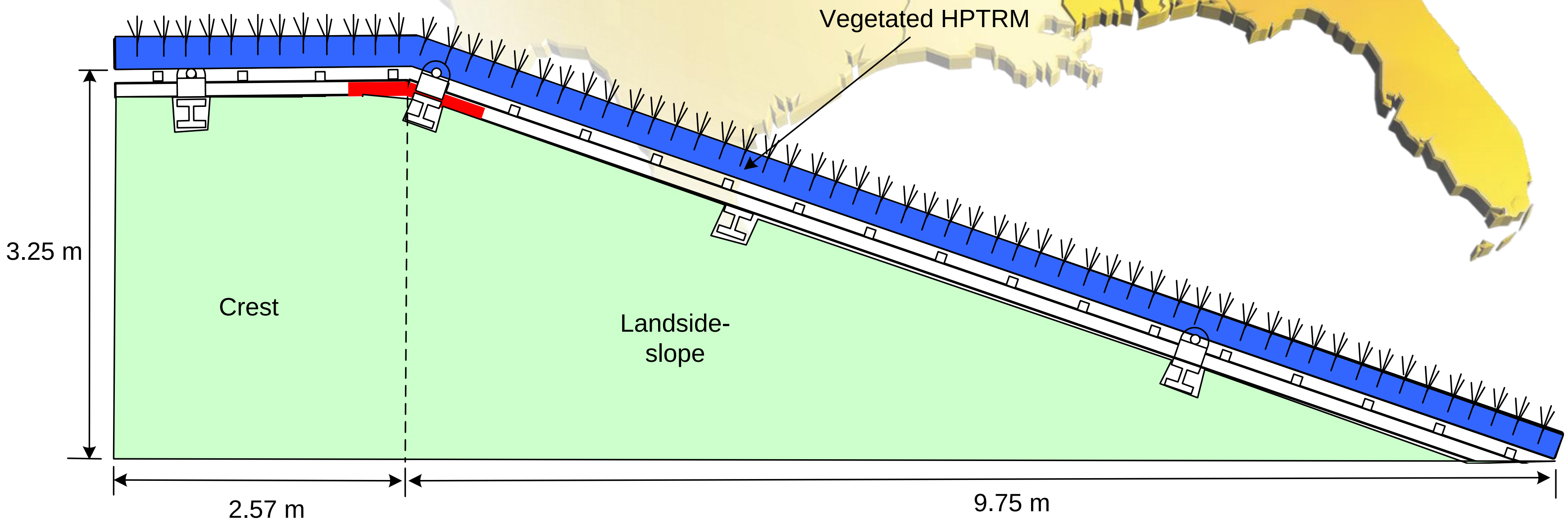
Full Scale Testing at OSU

- Full-scale overtopping test bed in 104-m wave flume
- Unsteady flow consisting of wave and/or combined wave and surge.



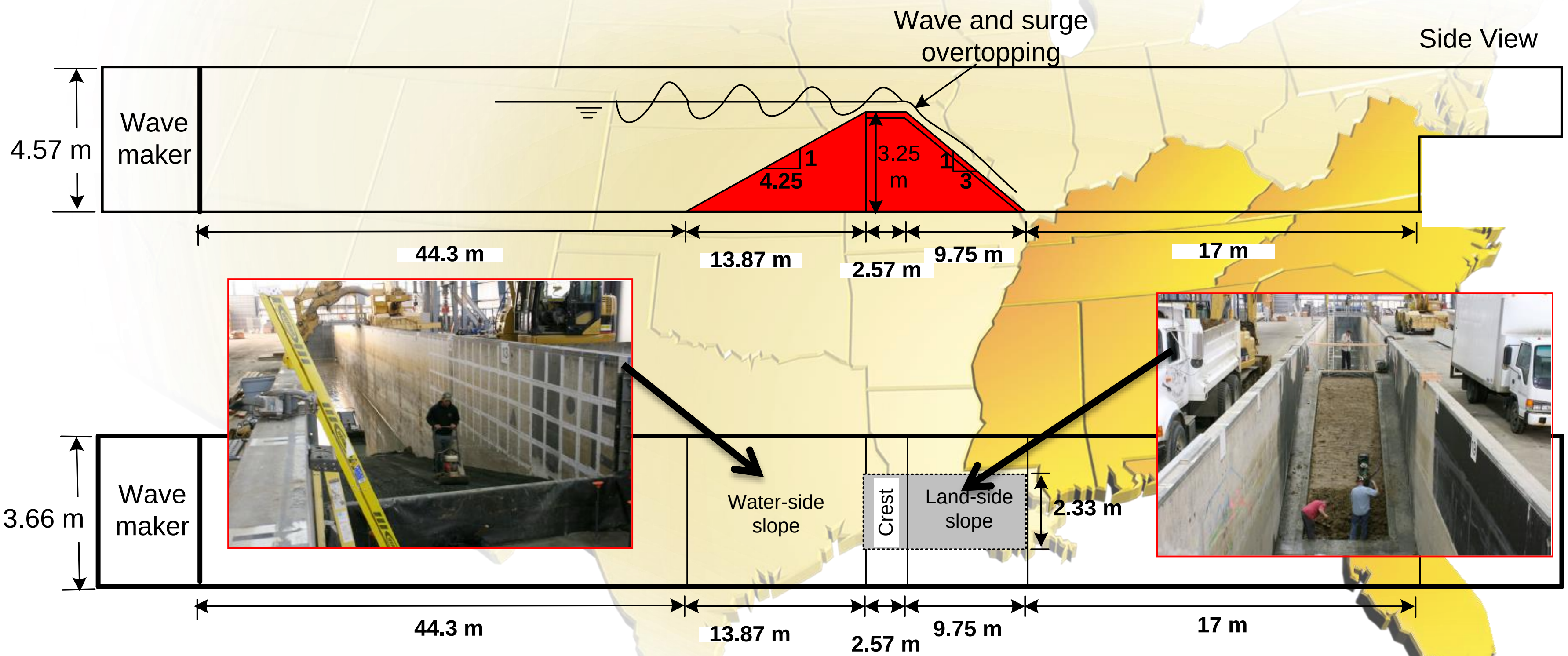
Levee Embankment Section





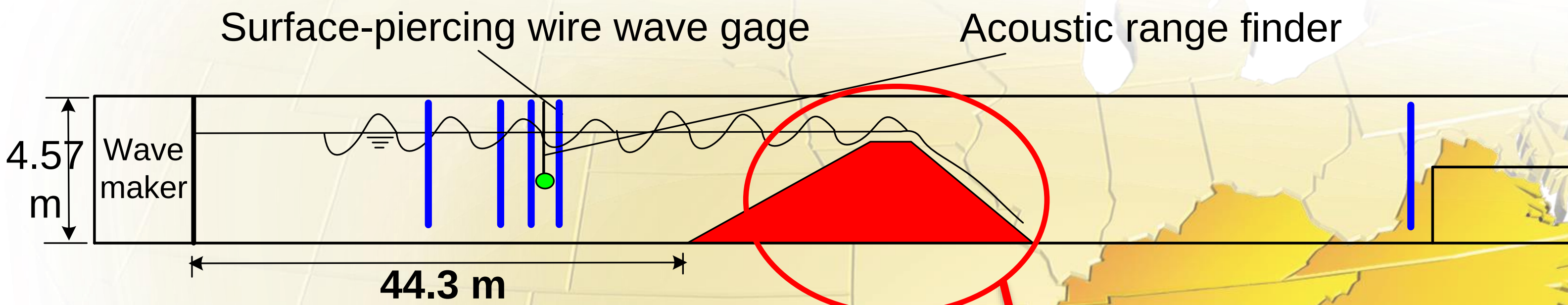
Vegetated HPTRM Setup and Maintenance

Levee Embankment in Large Wave Flume at OSU



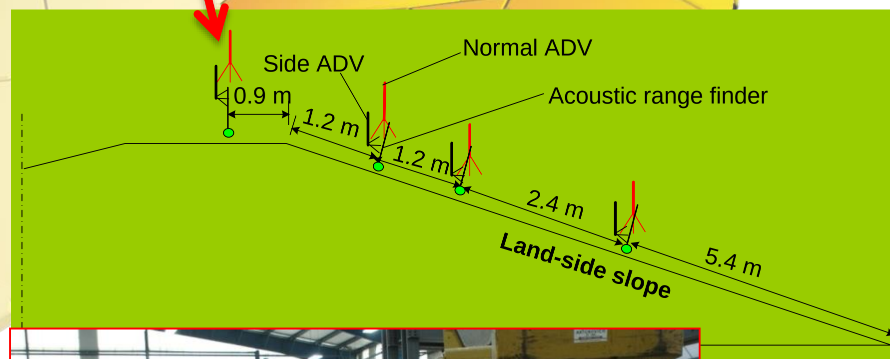
- Physical model was set up at full scale (1:1)
- LWF is 104 m (L) x 3.66 m (W) x 4.57 m (H) with a unidirectional piston wave maker for up to 1.6 m wave height.

Setup of Hydraulic Instrumentation



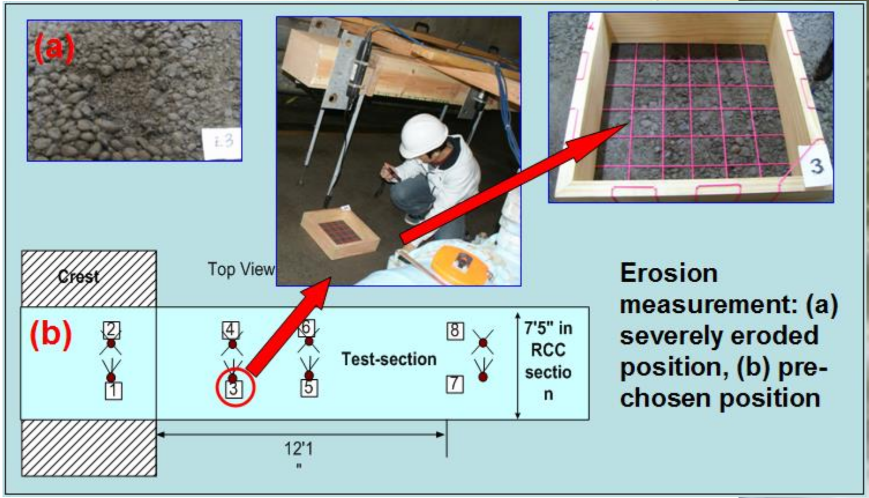
Sampling at 50 Hz

- 5 wave gages,
- 6 acoustic range finders,
- 8 ADV



Hydraulic Tests at RCC Test Section

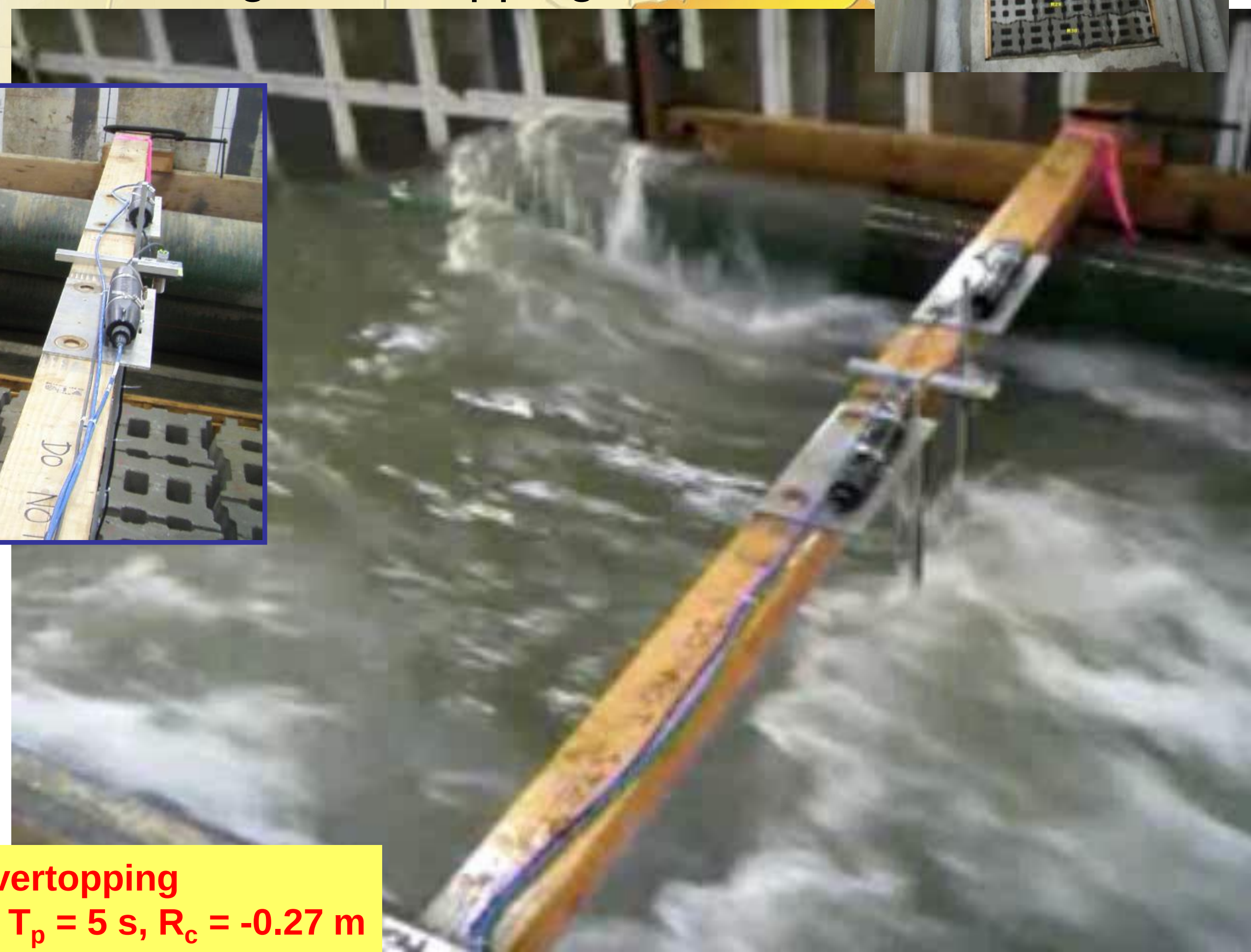
- Nine Surge-Only Overtopping Tests
- Six Wave-Only Overtopping Tests
- Seven Combined Wave and Surge Overtopping Tests



Combined overtopping
(H_{m0} = 0.7 m, T_p = 7 s, R_c = -0.24 m

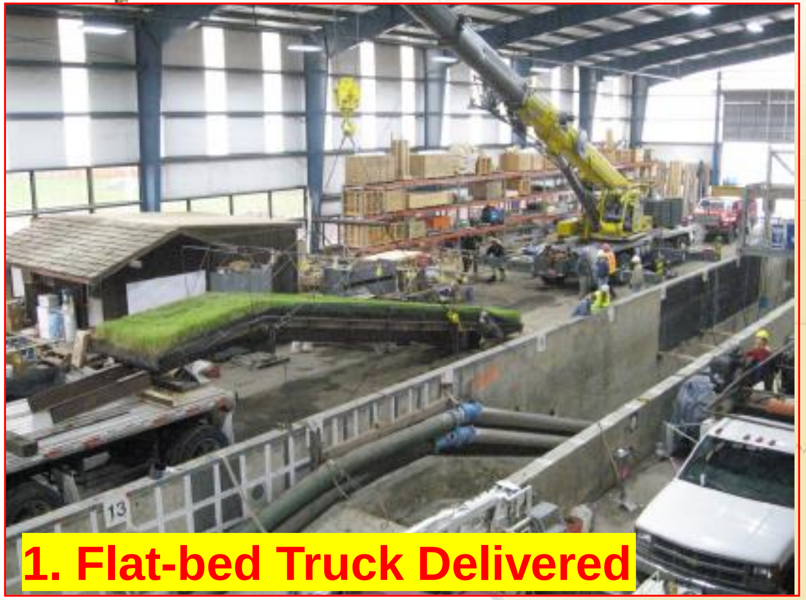
Hydraulic Tests at ACB Test Section

- One Surge-Only Overtopping Test
- Three Wave-Only Overtopping Tests
- Four Combined Wave and Surge Overtopping Tests



Combined overtopping
(H_{m0} = 0.6 m, T_p = 5 s, R_c = -0.27 m

HPTRM Metal Tray Installation



1. Flat-bed Truck Delivered

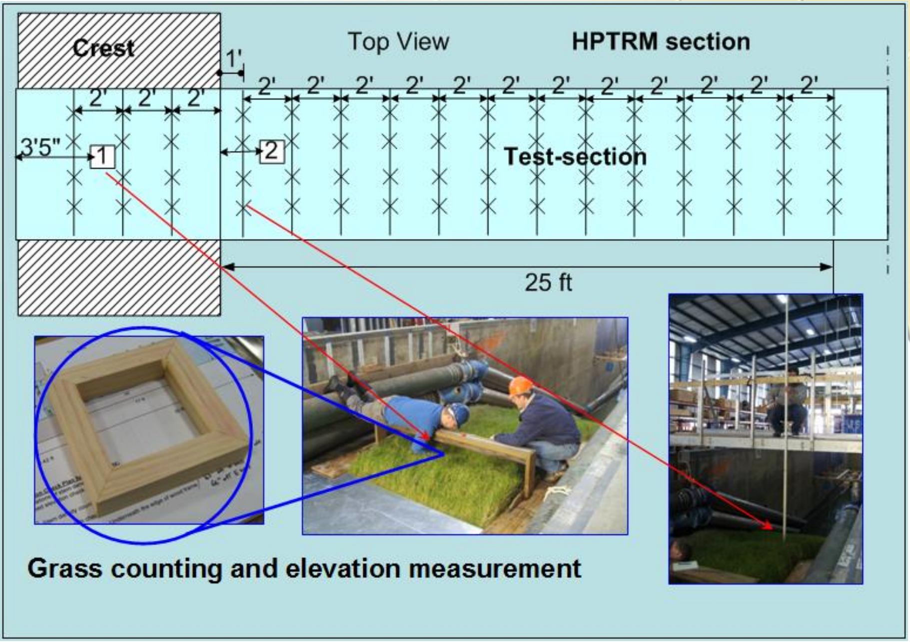
3. Installed in LWF

2. Crane Lift

4. Light & Heat Controlled

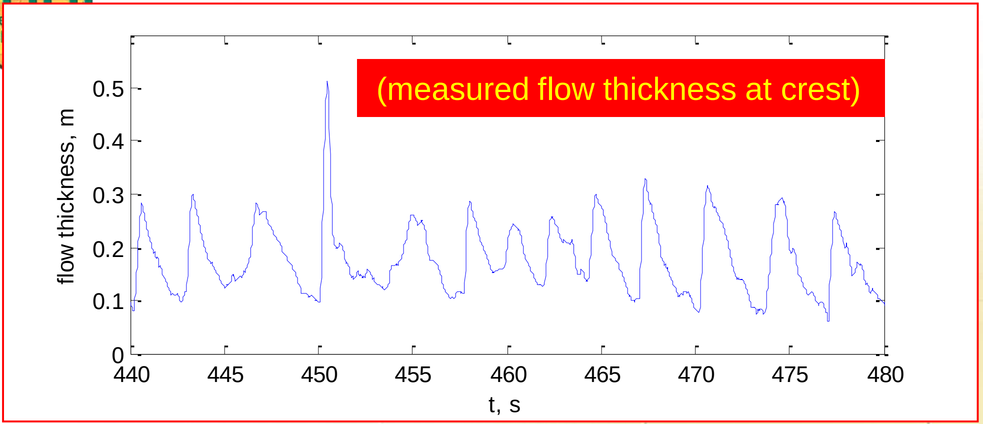
Hydraulic Tests at HPTRM Test Section

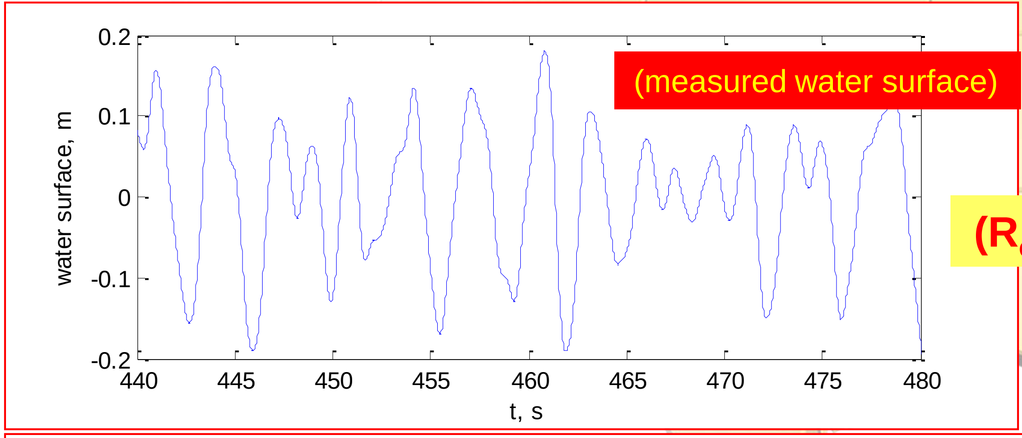
- One Surge-Only Overtopping Test
- Three Wave-Only Overtopping Tests
- Five Combined Wave and Surge Overtopping Tests

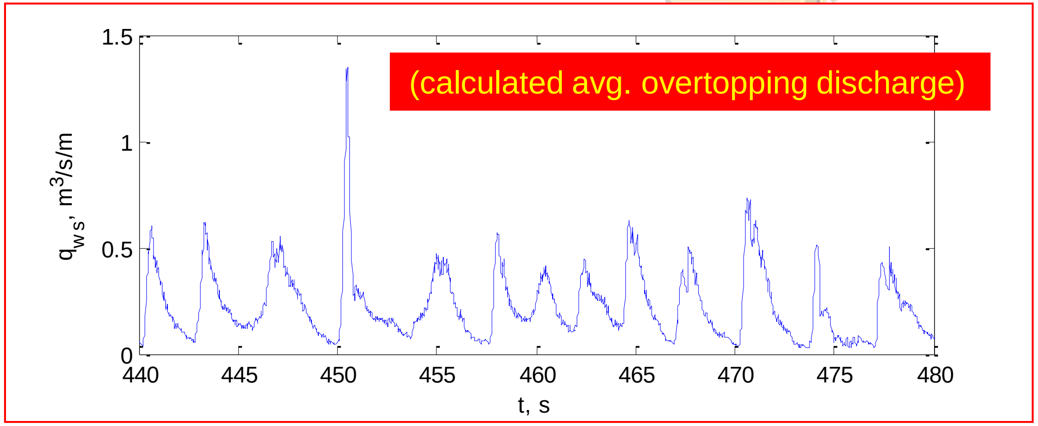


Combined overtopping
(H_{m0} = 0.85 m, T_p = 5 s, R_c = -0.26 m

Hydraulic Data Analysis



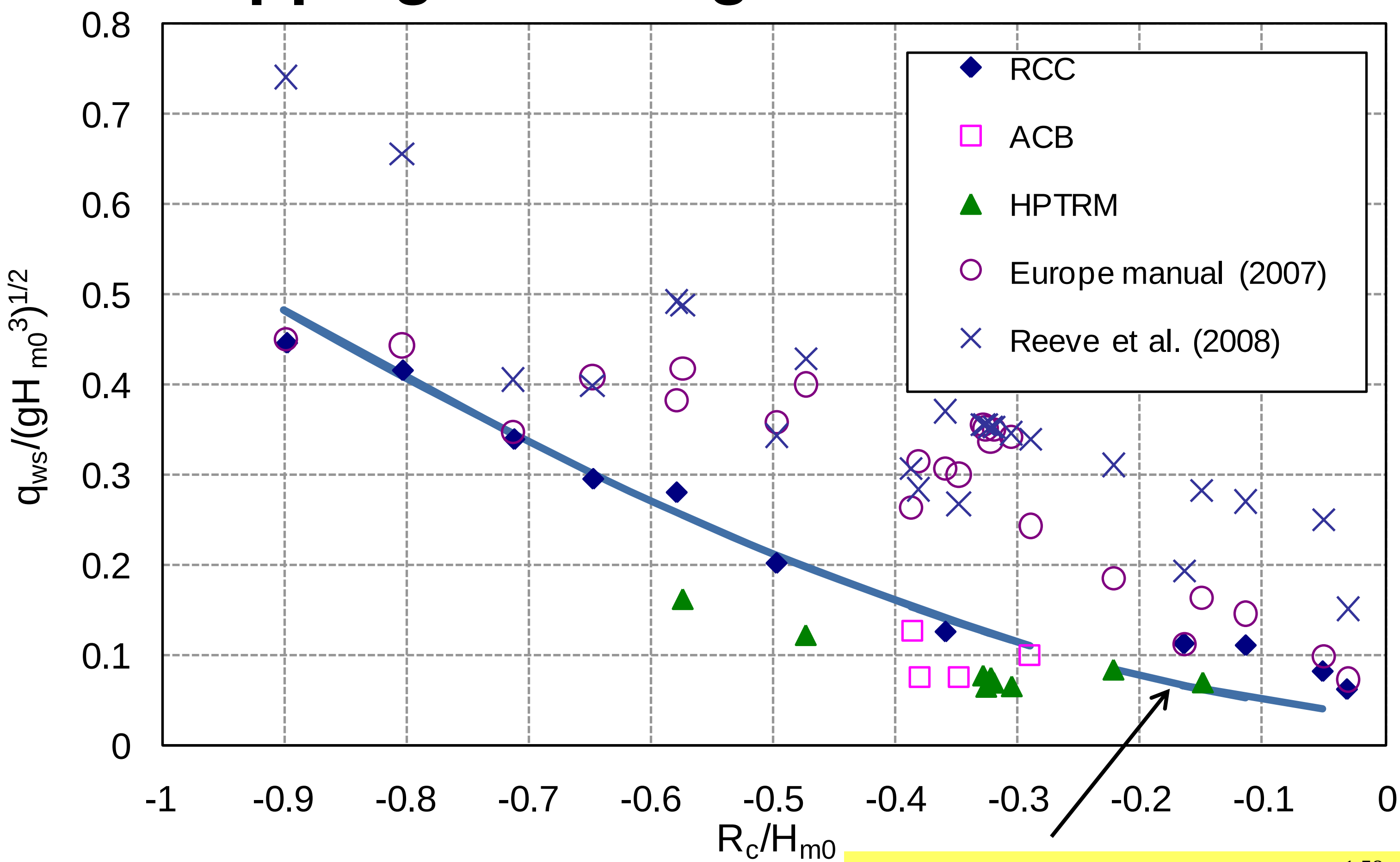




Combined wave and surge overtopping Trial1 of RCC tests

(R_c = -0.29 m, H_{m0} = 0.41 m, T_p = 3.4 s)

Dimensionless Average Wave/Surge Overtopping Discharge vs. Relative Freeboard

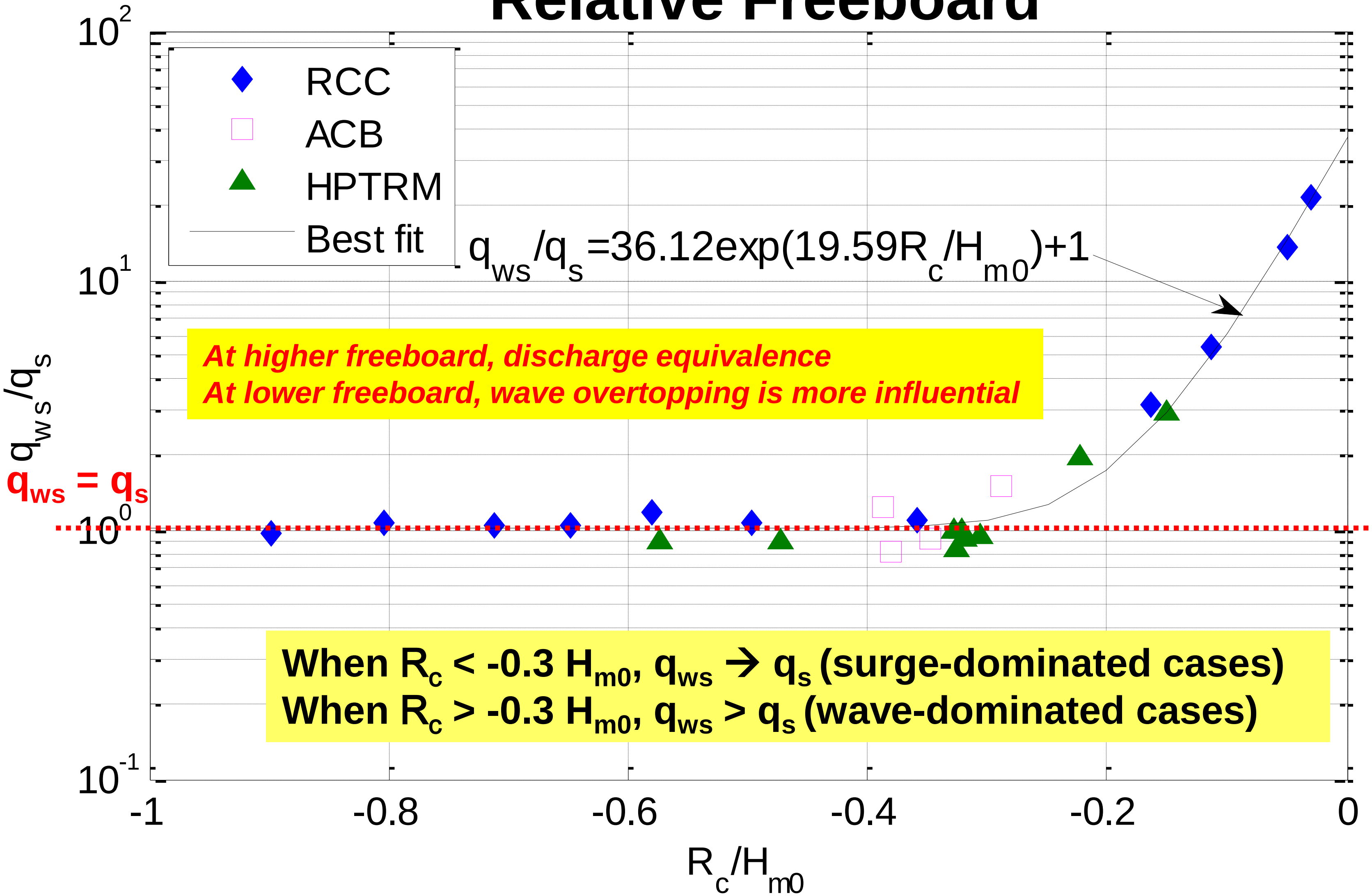


(Hughes and Nadal 2009)

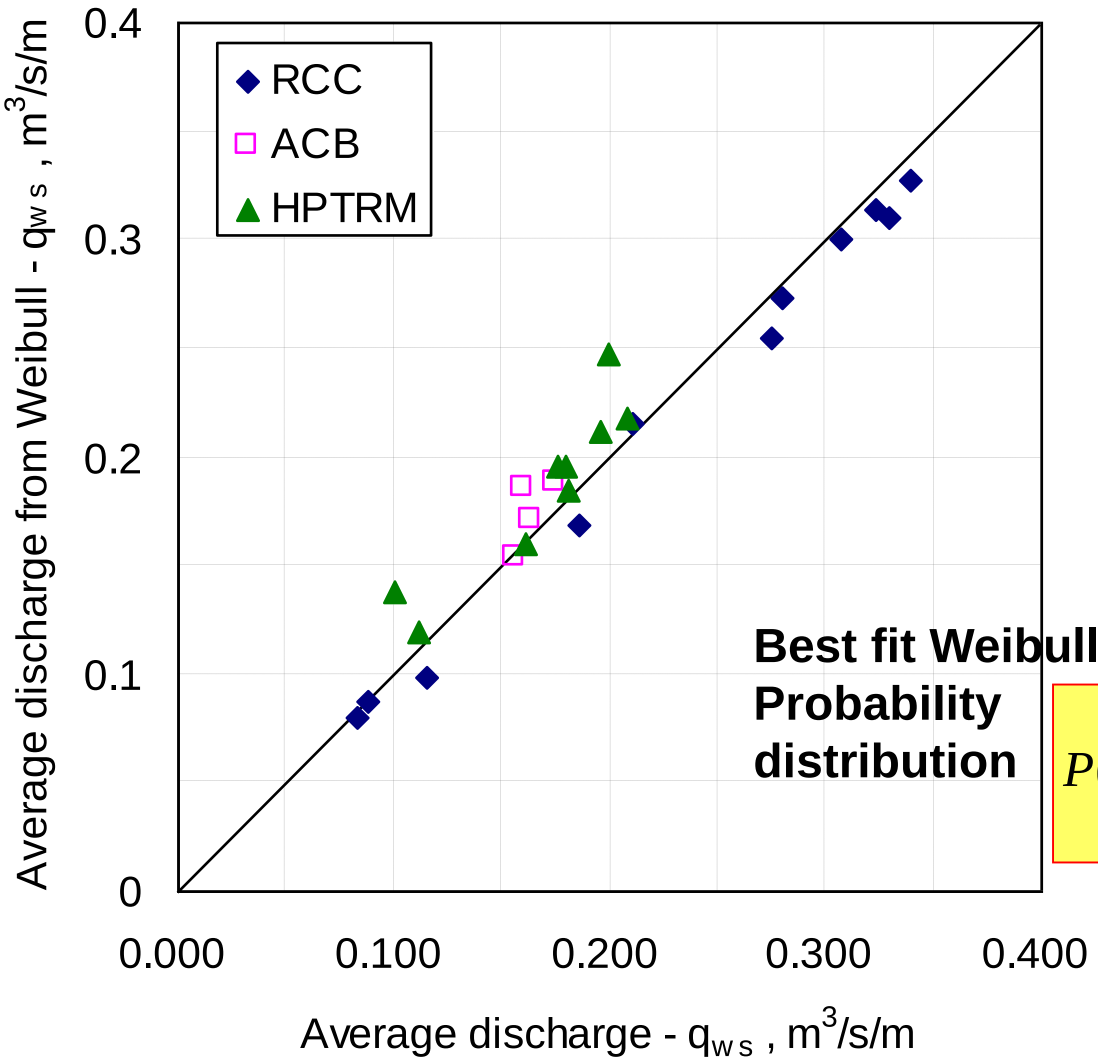
$$\frac{q_{ws}}{\sqrt{gH_{m0}^3}} = 0.034 + 0.53 \cdot \left(\frac{-R_c}{H_{m0}}\right)^{1.58} \qquad for\ R_c < 0$$

Peak wave period (T_p) had negligible influence on the determination of q_{ws}

Relative Average Wave/Surge Overtopping Discharge to Surge-Only Discharge vs. Relative Freeboard



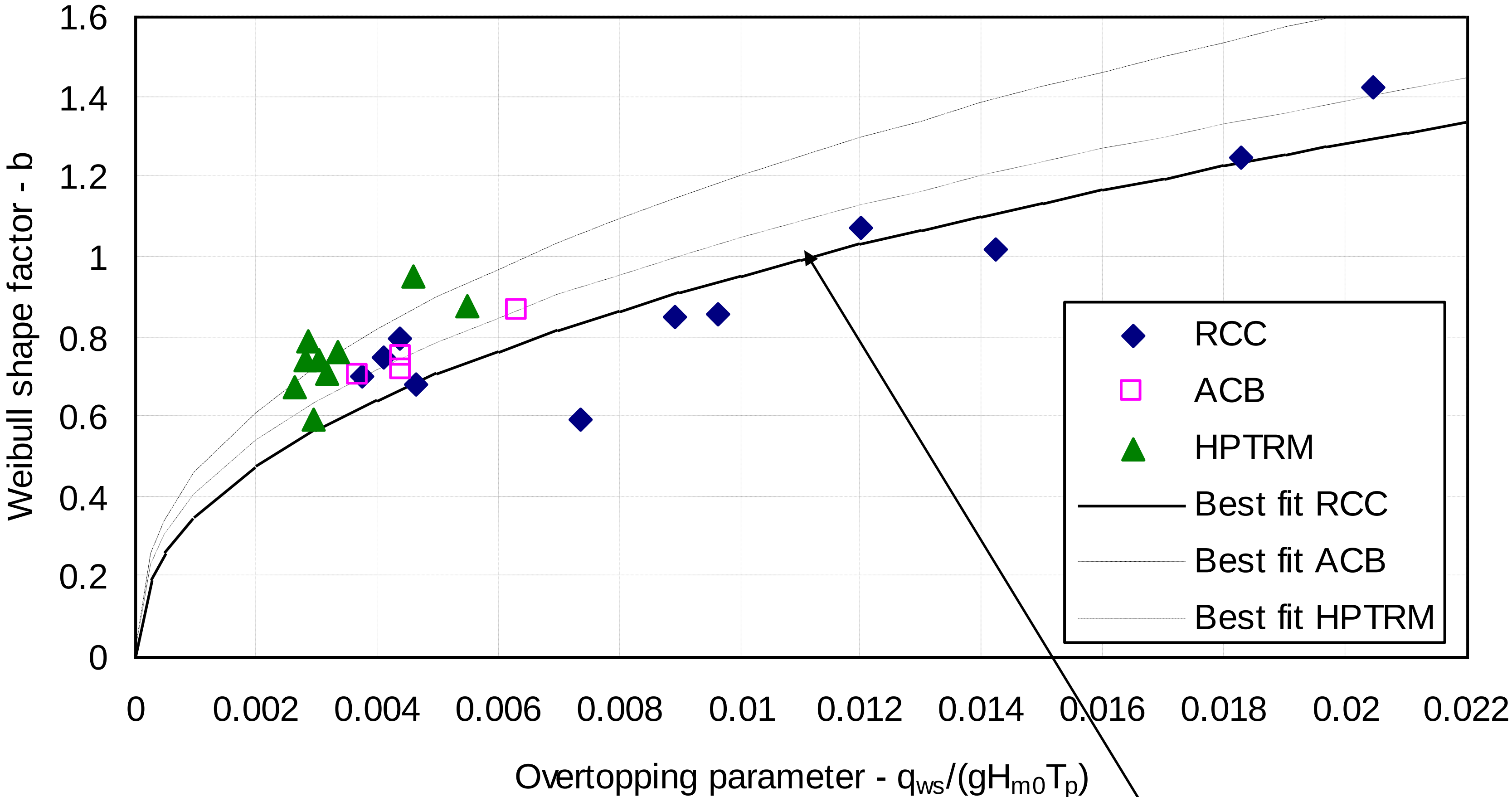
Distribution of Individual Wave/Surge Overtopping Discharge



Best fit Weibull cumulative Probability distribution

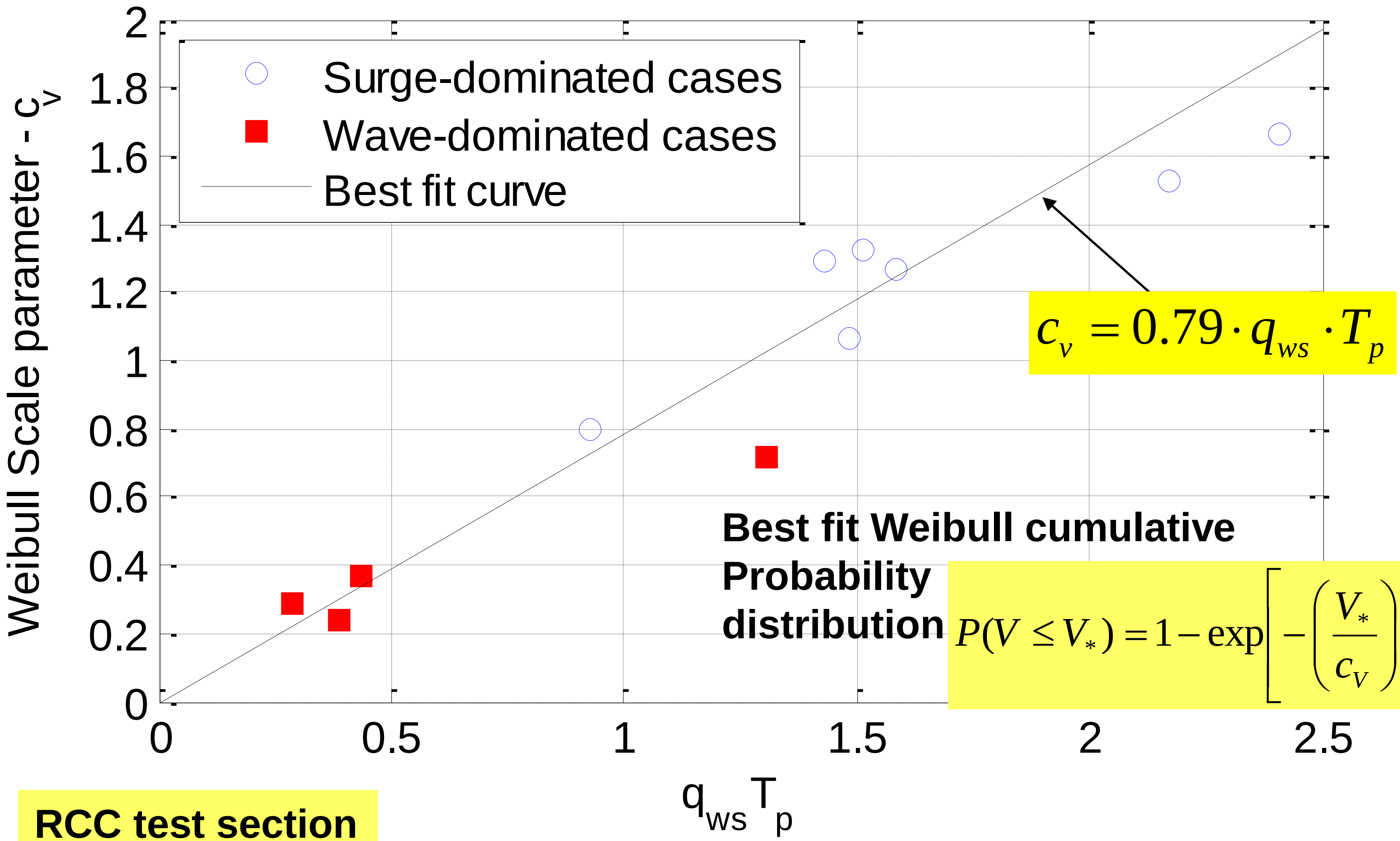
$$P(q \le q_*) = 1 - \exp\left[-\left(\frac{q_*}{c}\right)^b\right]$$

Best-fit equation for Weibull shape factor b for all the tests



RCC	ACB	HPTRM
$b = 6.93\left(\frac{q_{ws}}{gH_{m0}T_p}\right)^{0.43}$	$b = 6.90\left(\frac{q_{ws}}{gH_{m0}T_p}\right)^{0.41}$	$b = 8.30\left(\frac{q_{ws}}{gH_{m0}T_p}\right)^{0.42}$

Distribution of Individual Wave Volume for Combined Wave and Surge Overtopping

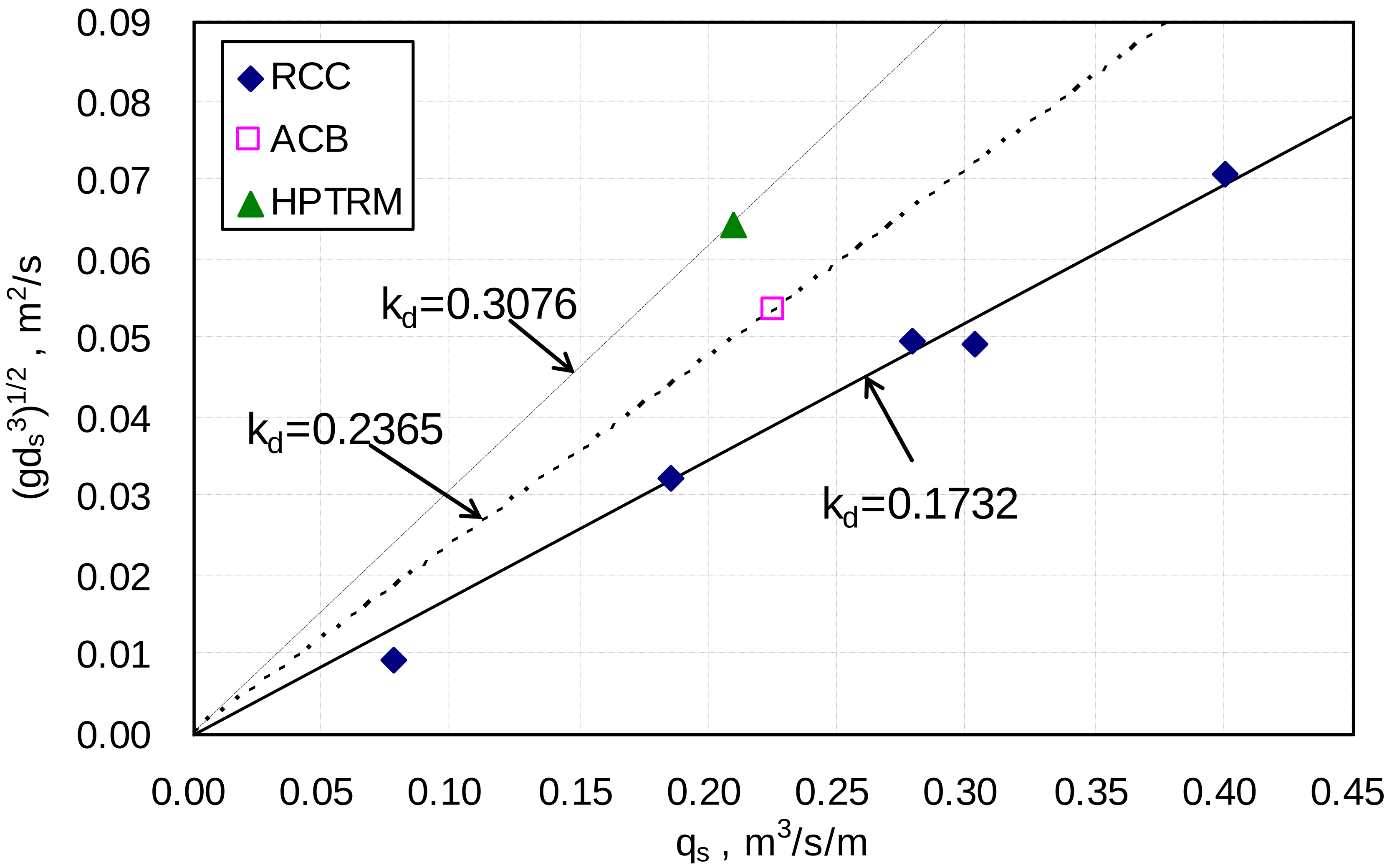


Best fit Weibull cumulative Probability distribution

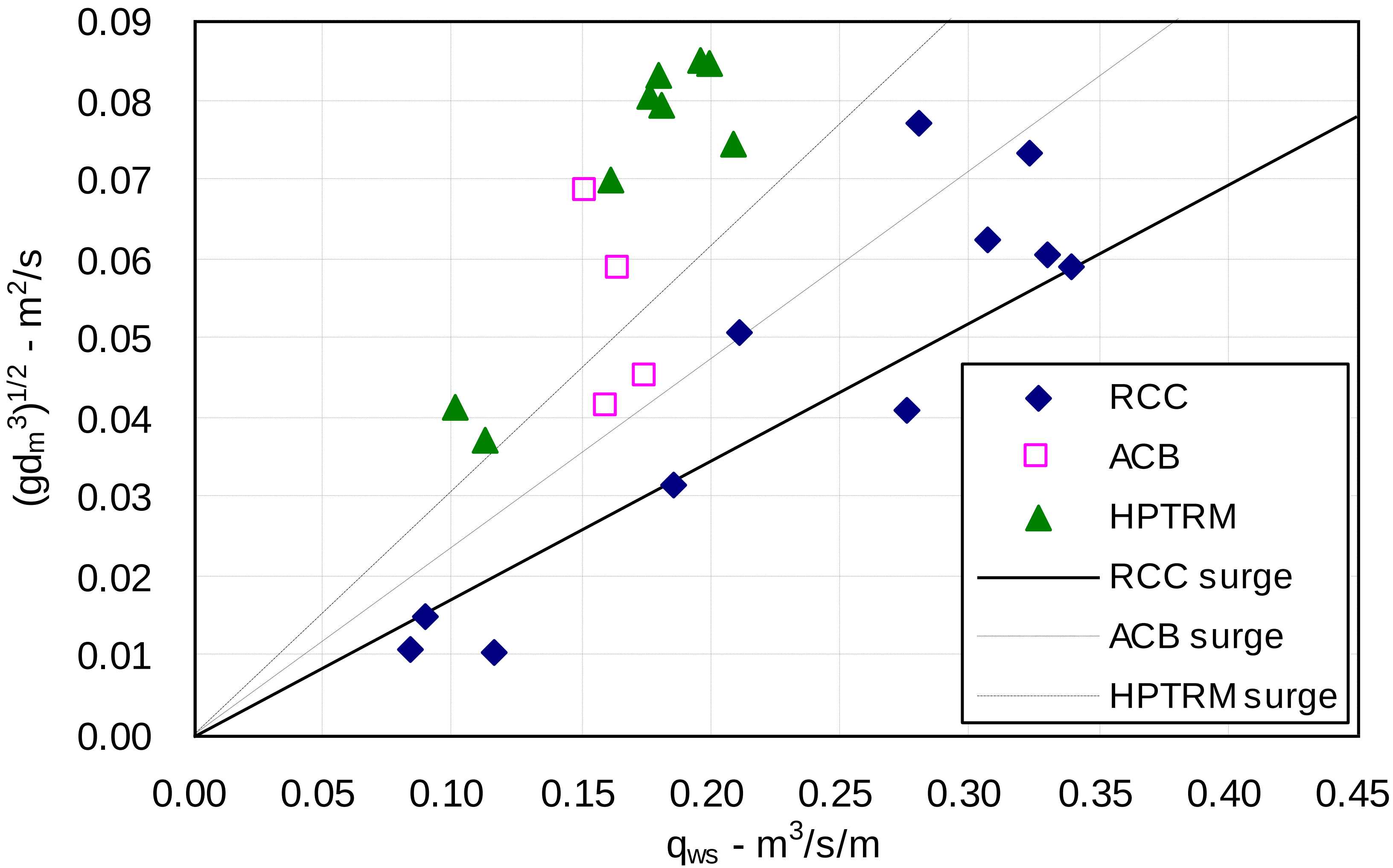
$$P(V \le V_*) = 1 - \exp\left[- \left(\frac{V_*}{c_V} \right)^{b_V} \right]$$

RCC test section

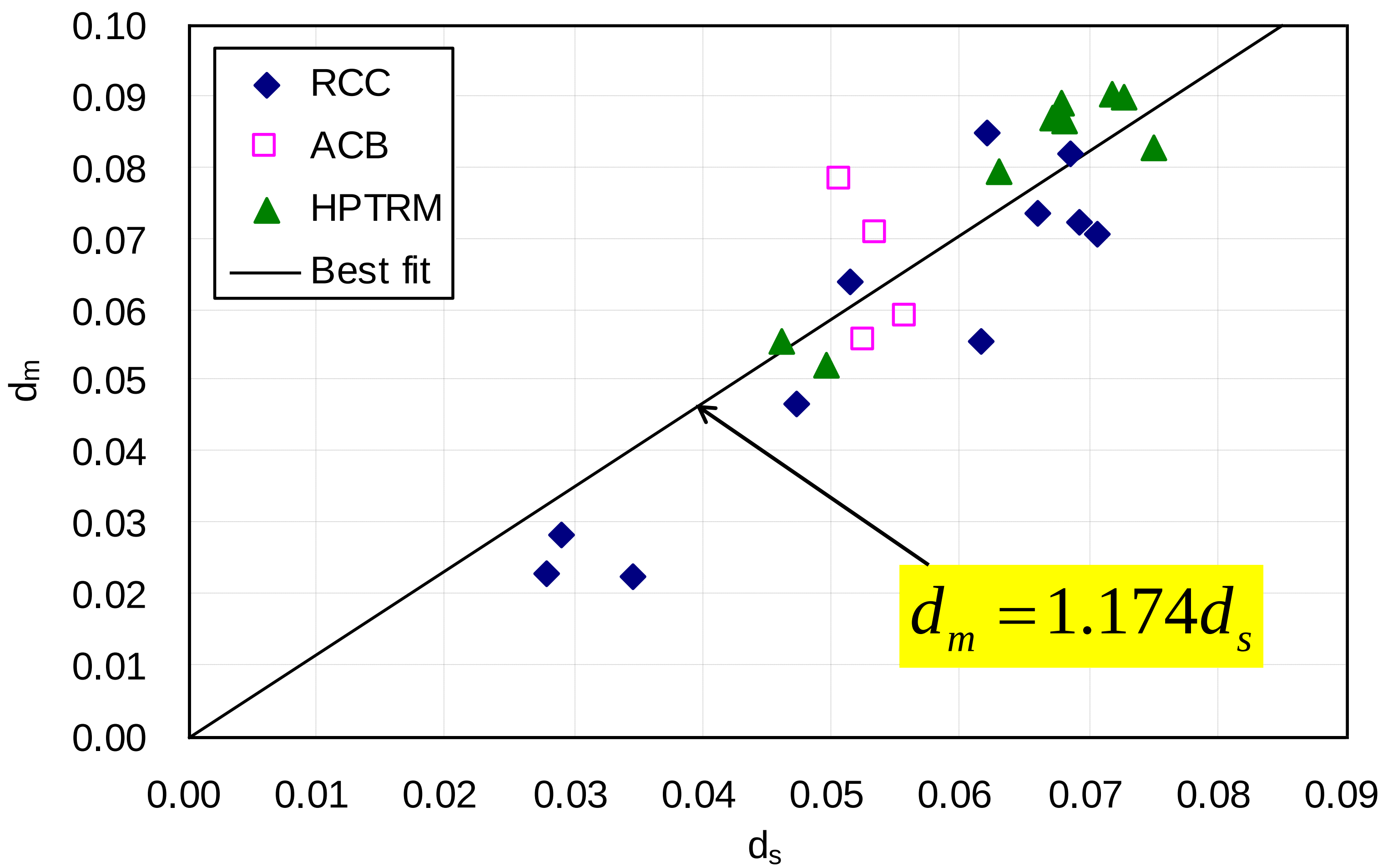
Steady Flow Thickness on Landward-side Slope for Surge-only Overflow



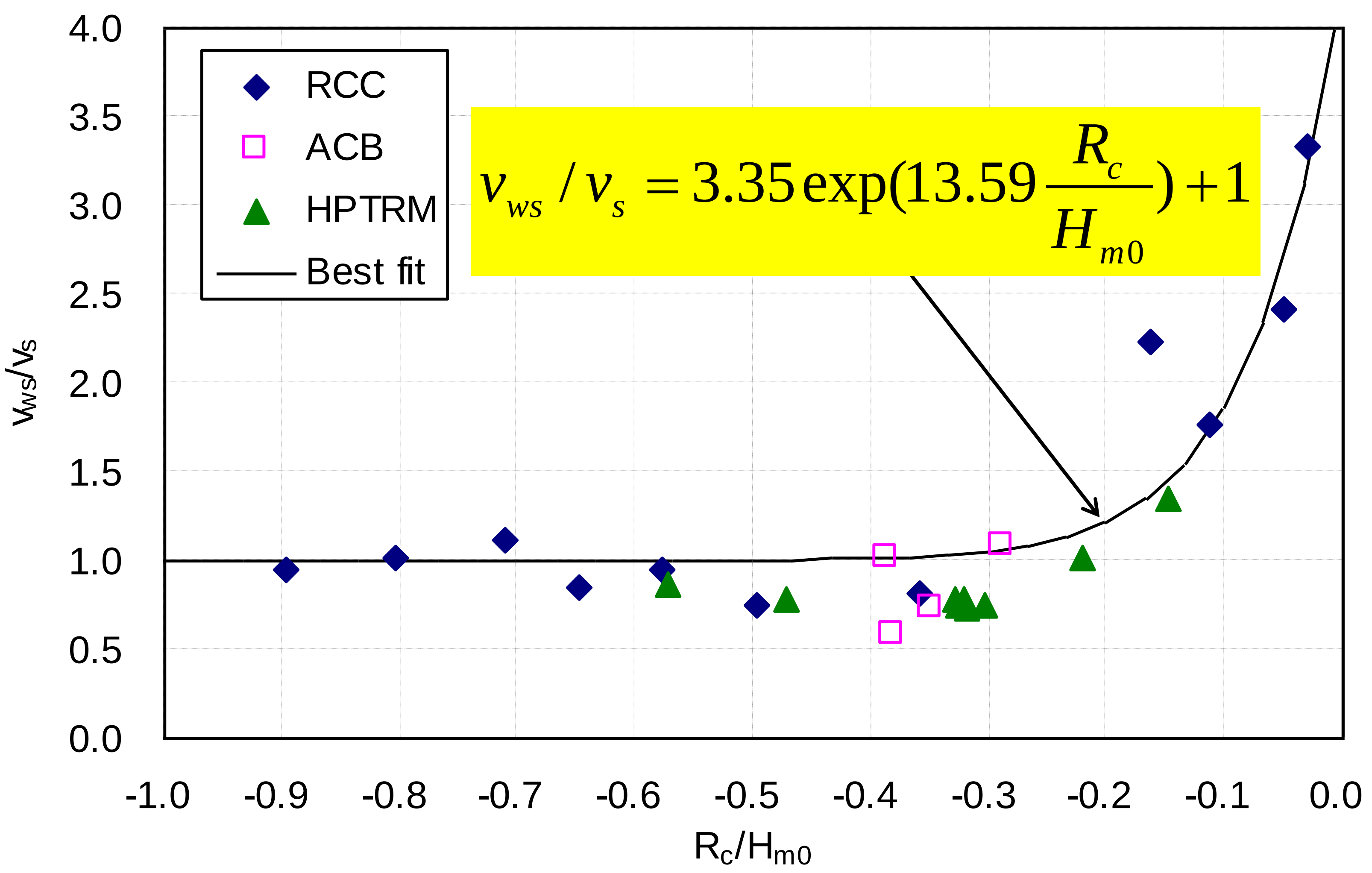
Average Flow Thickness on Landward-side Slope for Combined Wave and Surge Overtopping



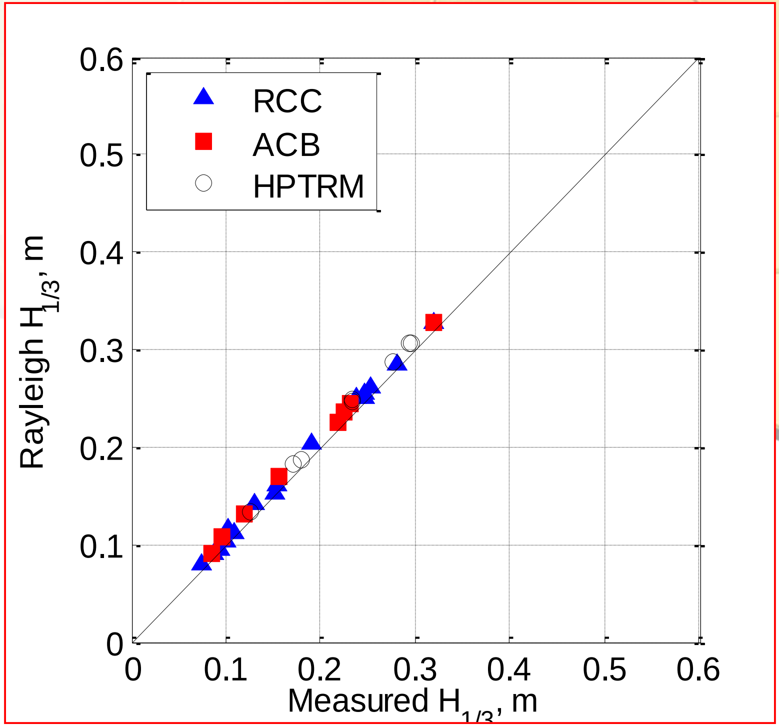
Average Flow Thickness Equivalency between Surge-only Overflow and Combined Wave and Surge Overtopping

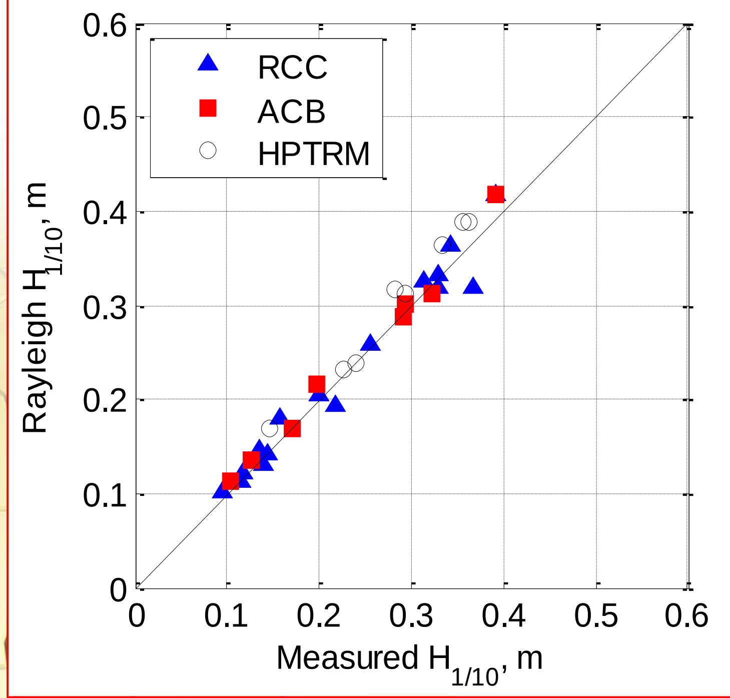


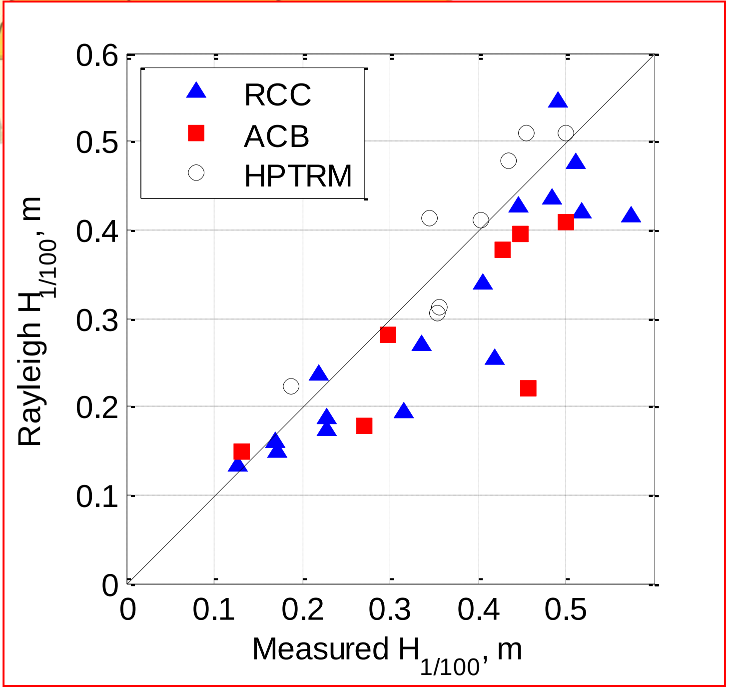
Average Flow Velocity Equivalency between Surge-only Overflow and Combined Wave and Surge Overtopping



Distribution of Waves on the Landside Slope

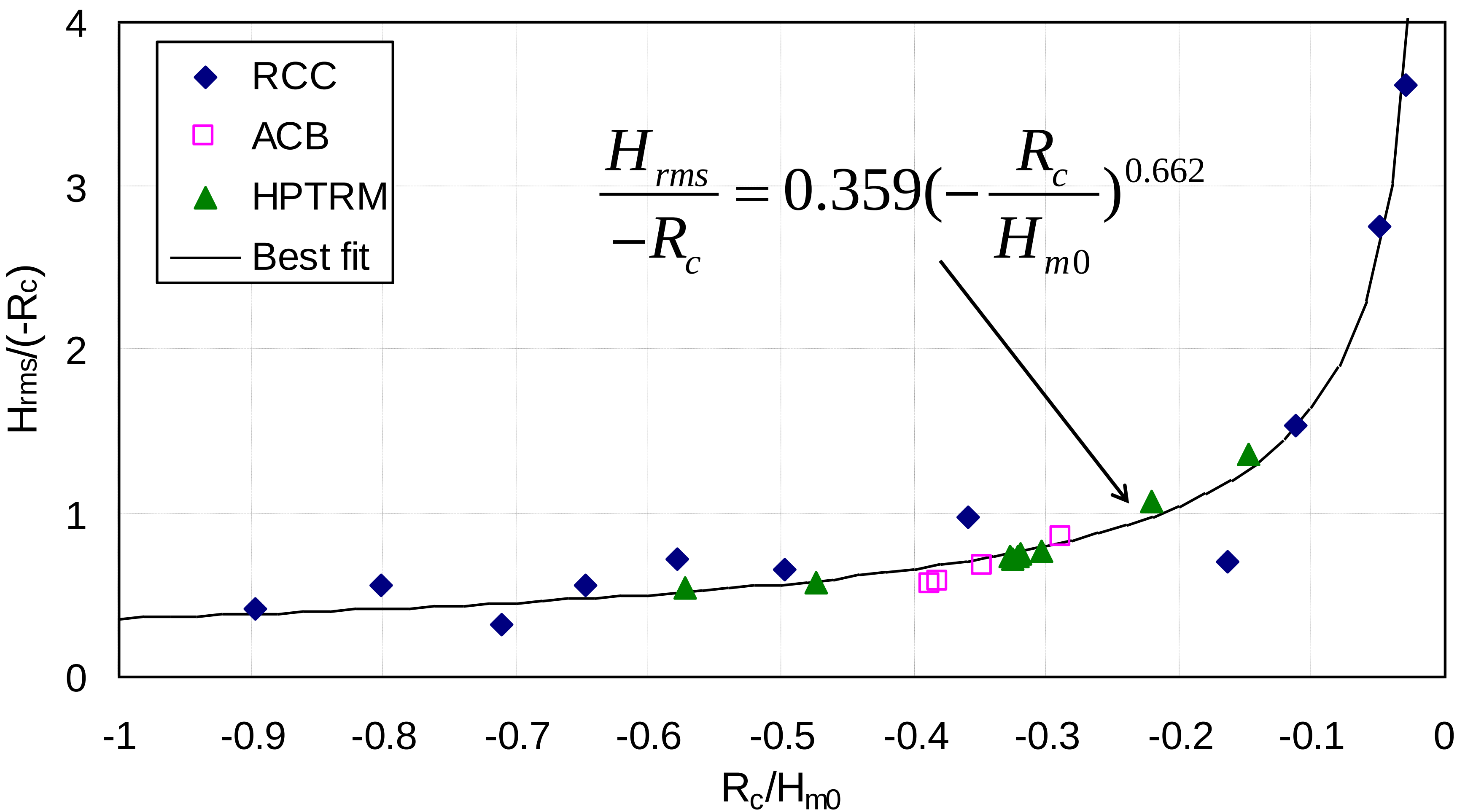




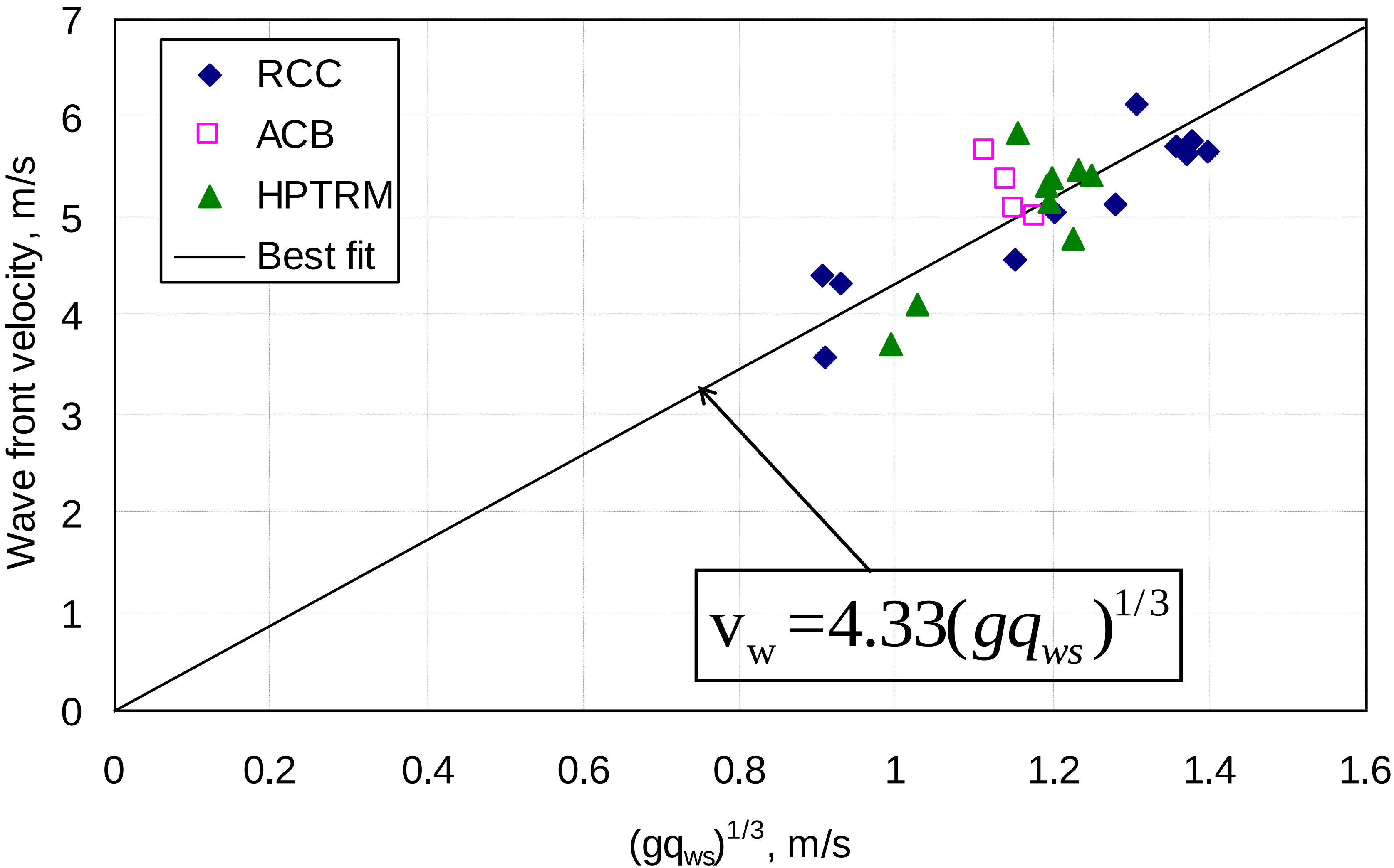


Rayleigh Distribution of characteristic wave heights

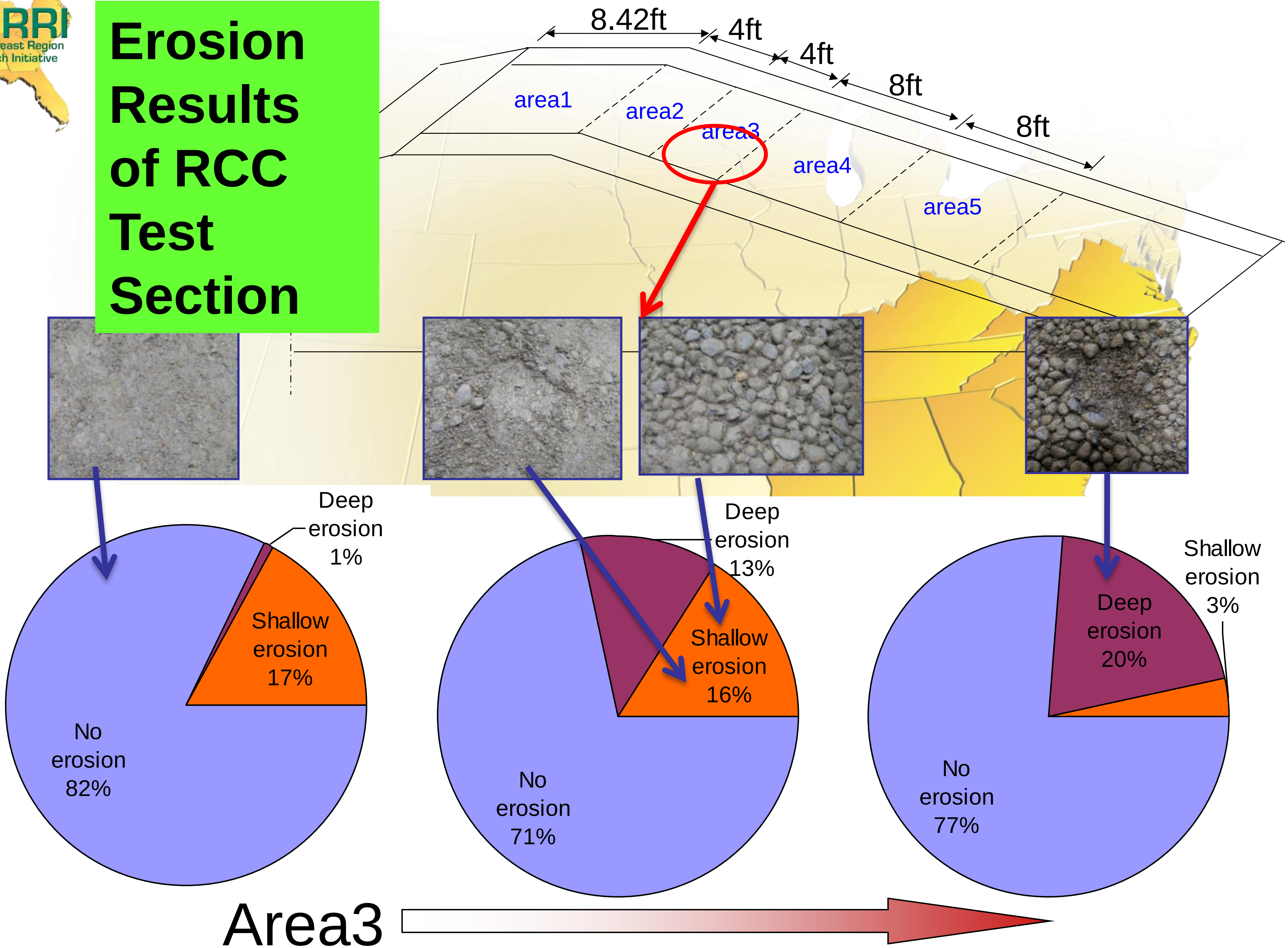
Estimation of H_{rms} on Landward-side Slope



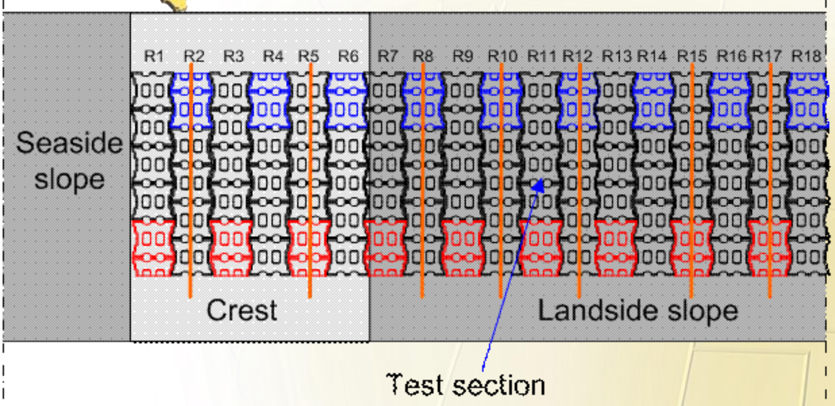
Wave Front Velocity on Landward-side Slope

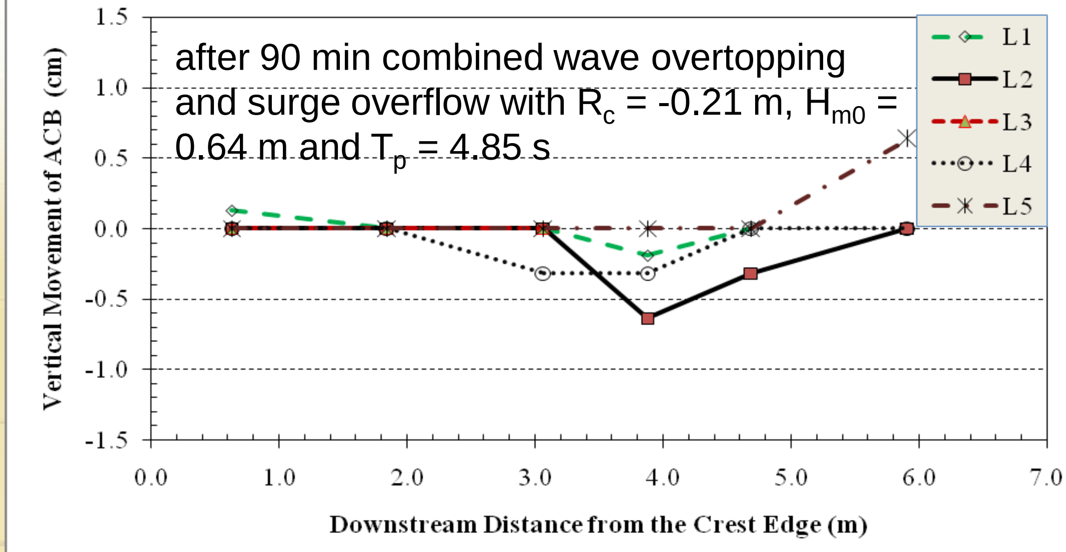


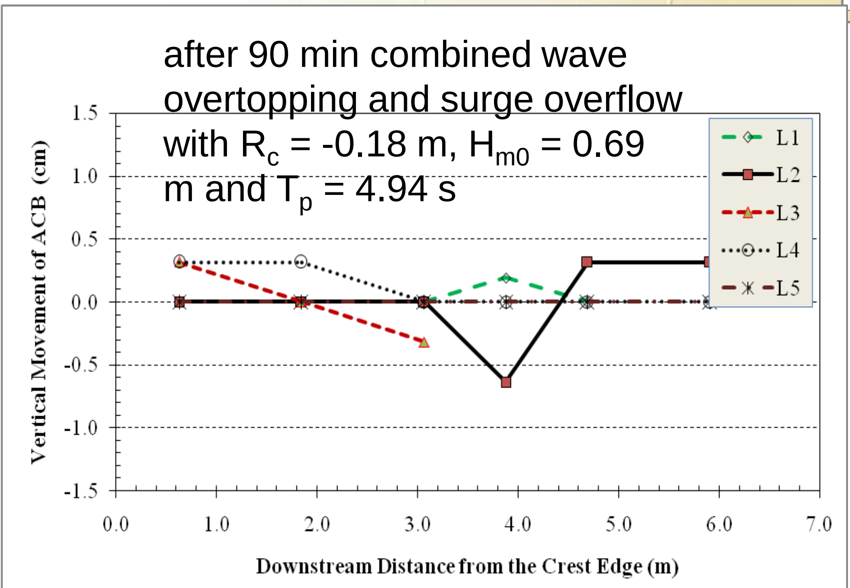
Erosion Results of RCC Test Section

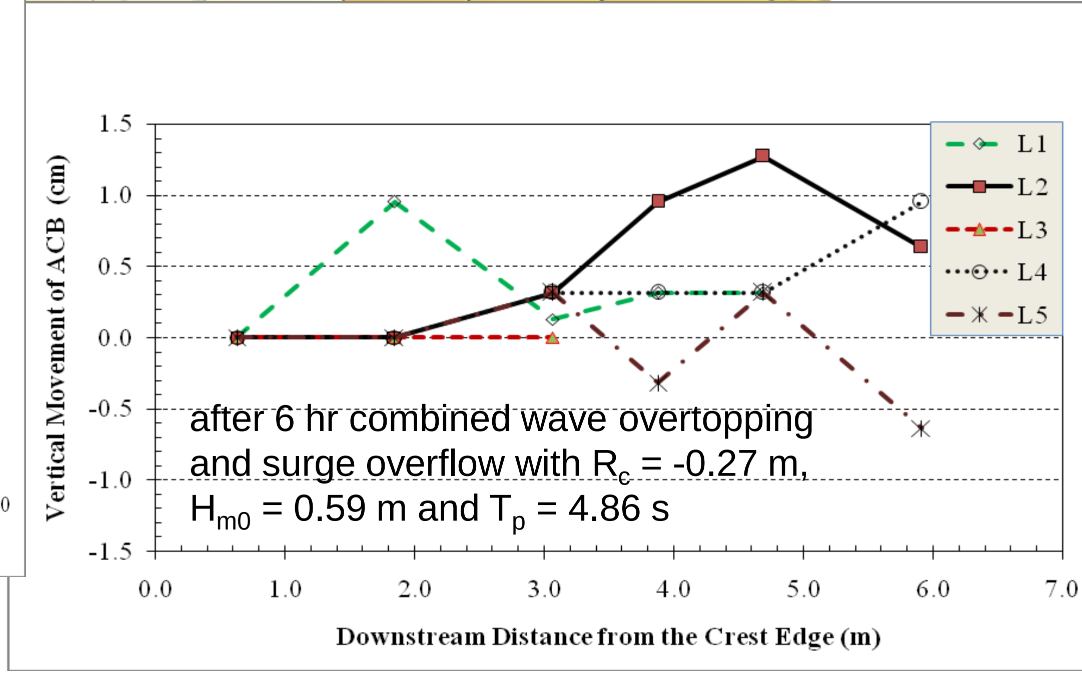


Settlement or Uplift Data for ACB Tests



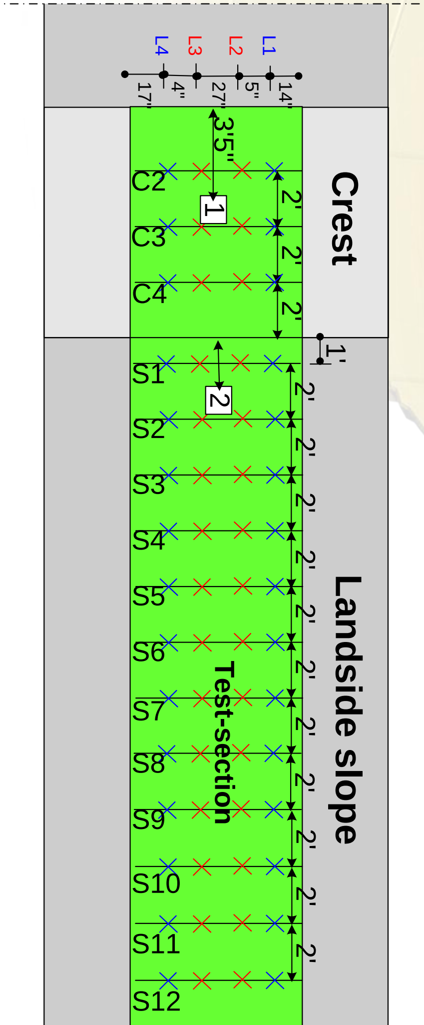


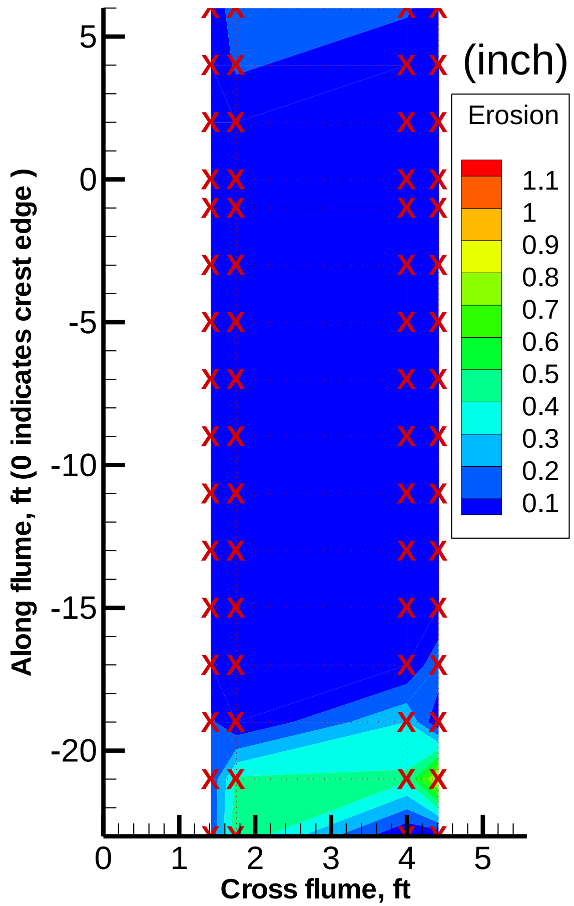




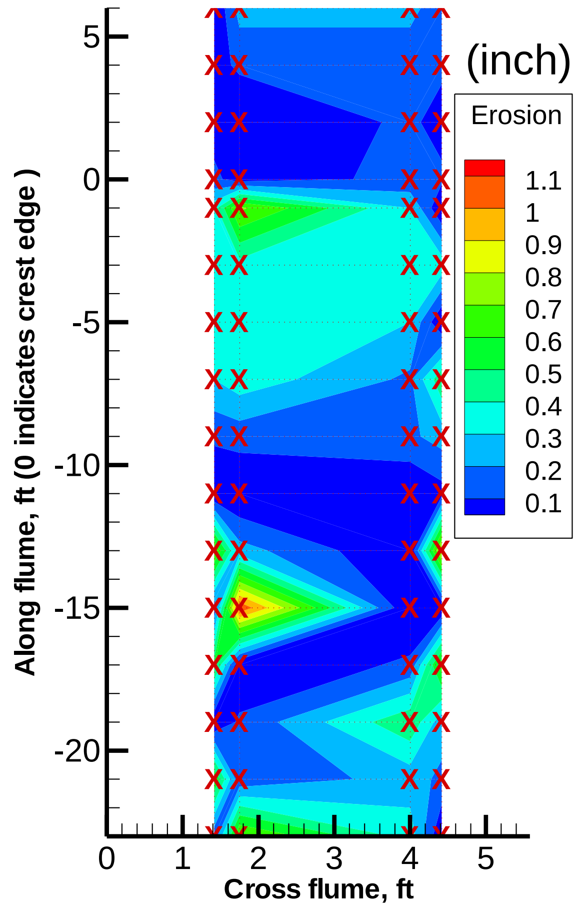
Erosion Data of HPTRM Tests

(1) Elevation measurement



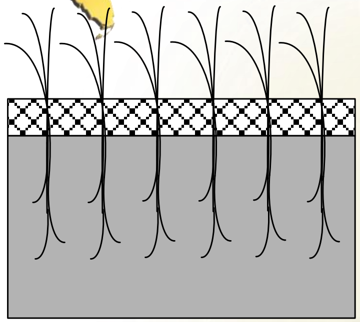


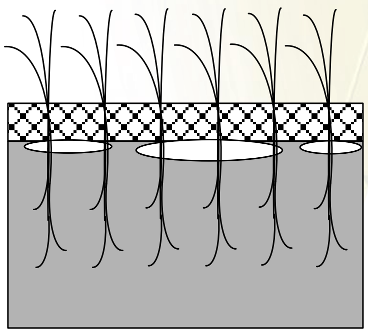
12.25 After wave test2

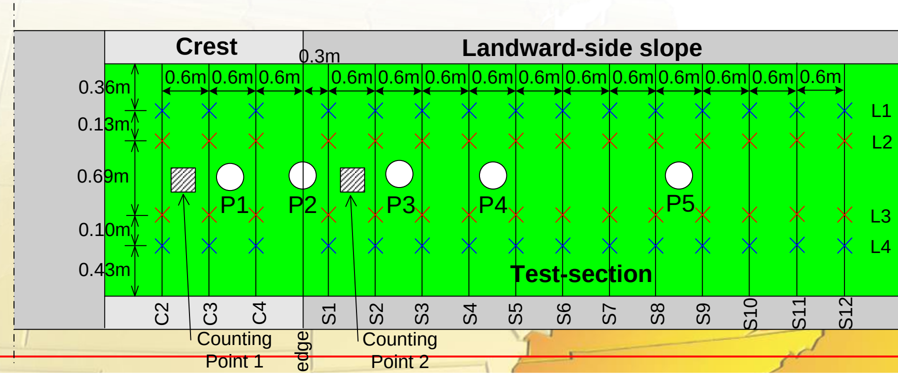


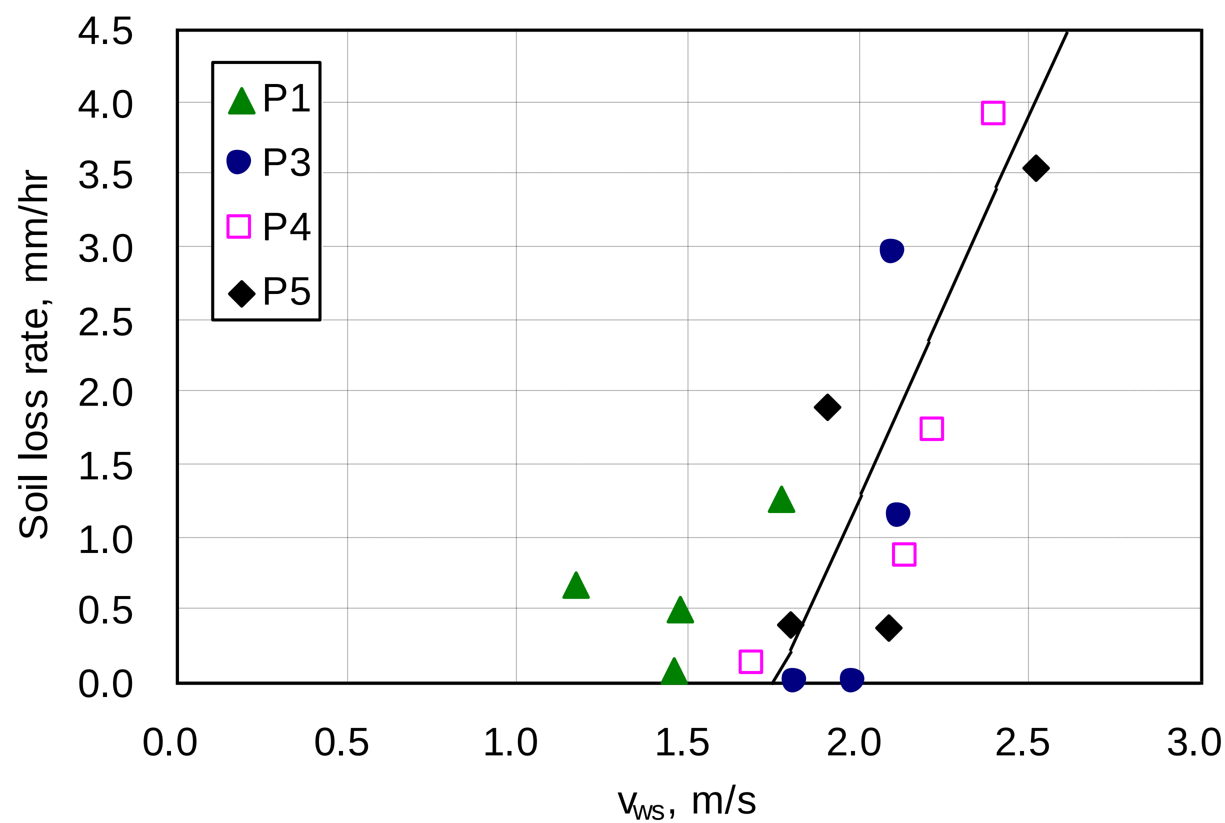
12.25 After combined test1

Soil erosion rate versus overtopping velocity

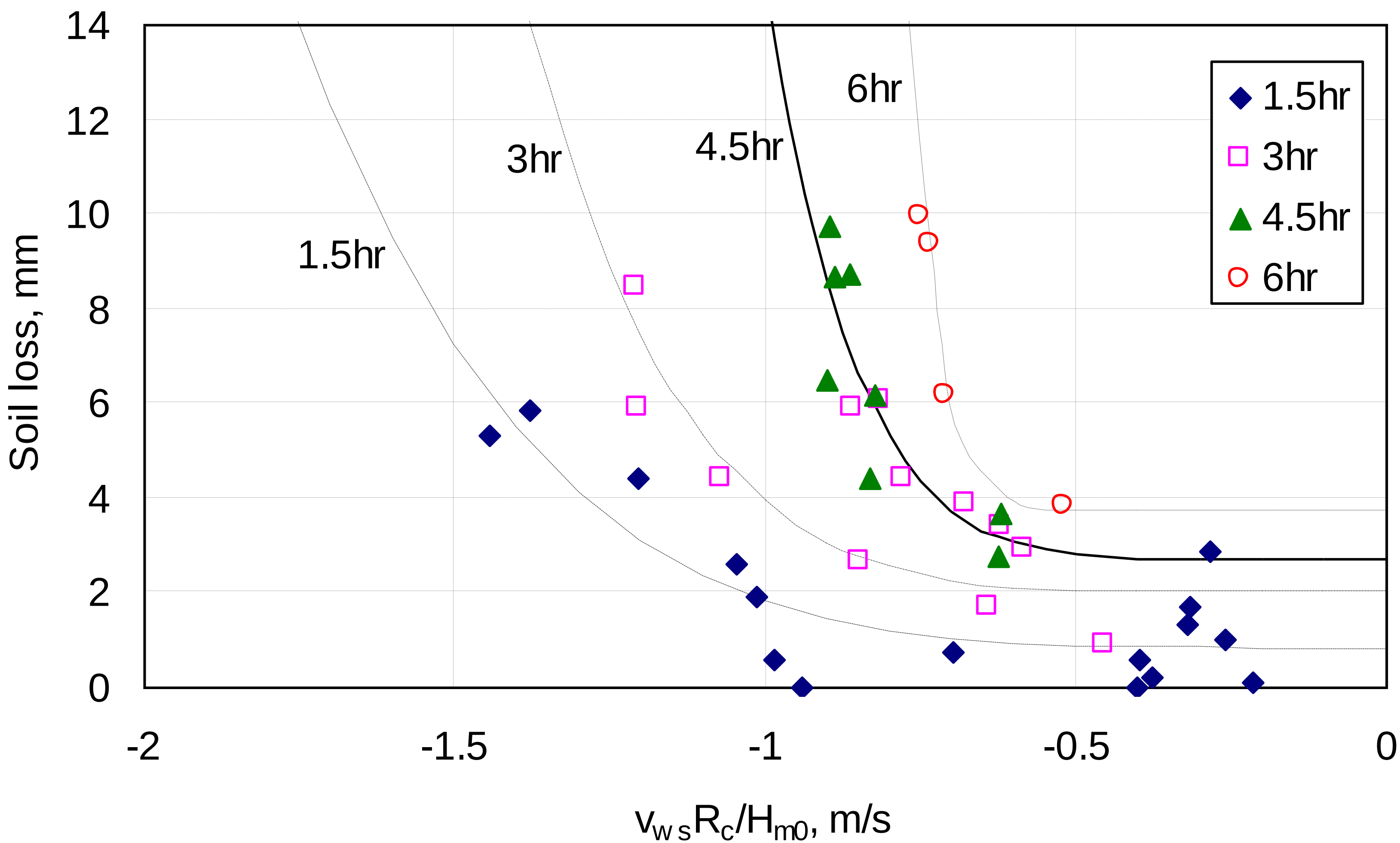








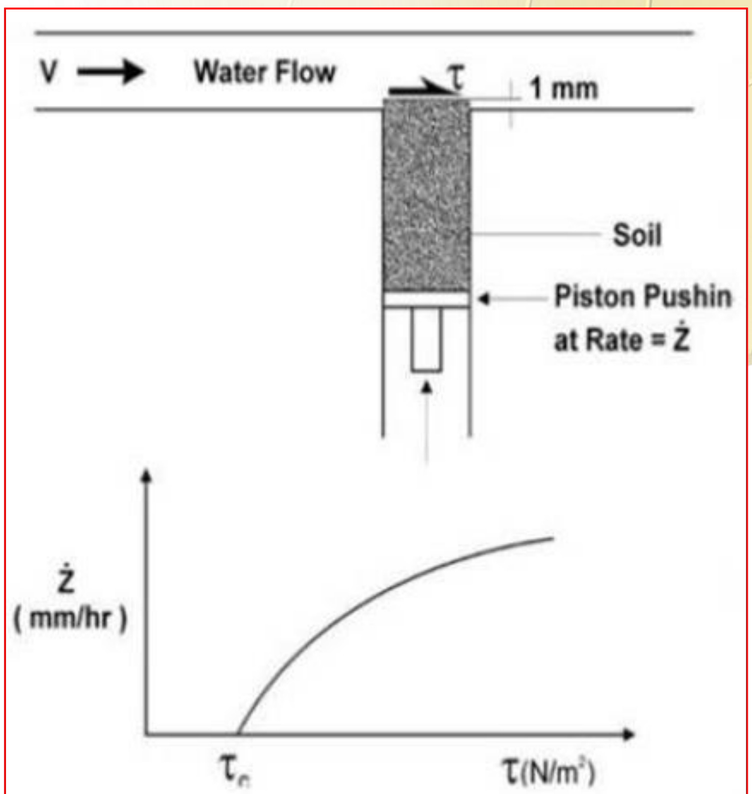
Estimation for Erosion of Different Time Duration



HPTRM section

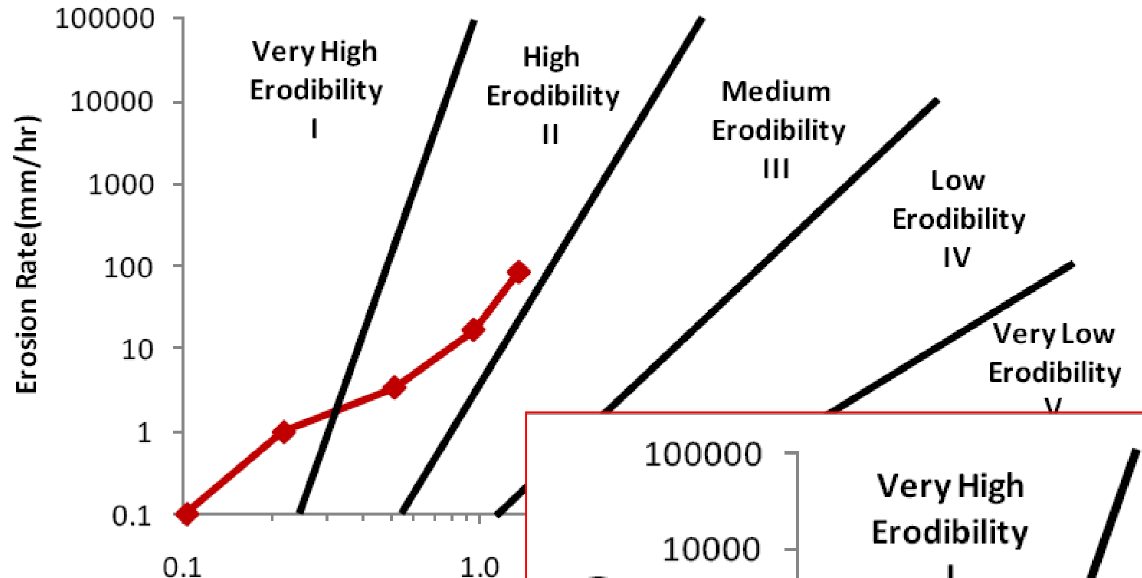
Improvement of Soil Erodibility

- Soil erodibility: relationship between the erosion rate and the shear stress at the soil-water interface.
- Measured with Erosion Function Apparatus (EFA) by Dr. Briaud Group at Texas A & M University.



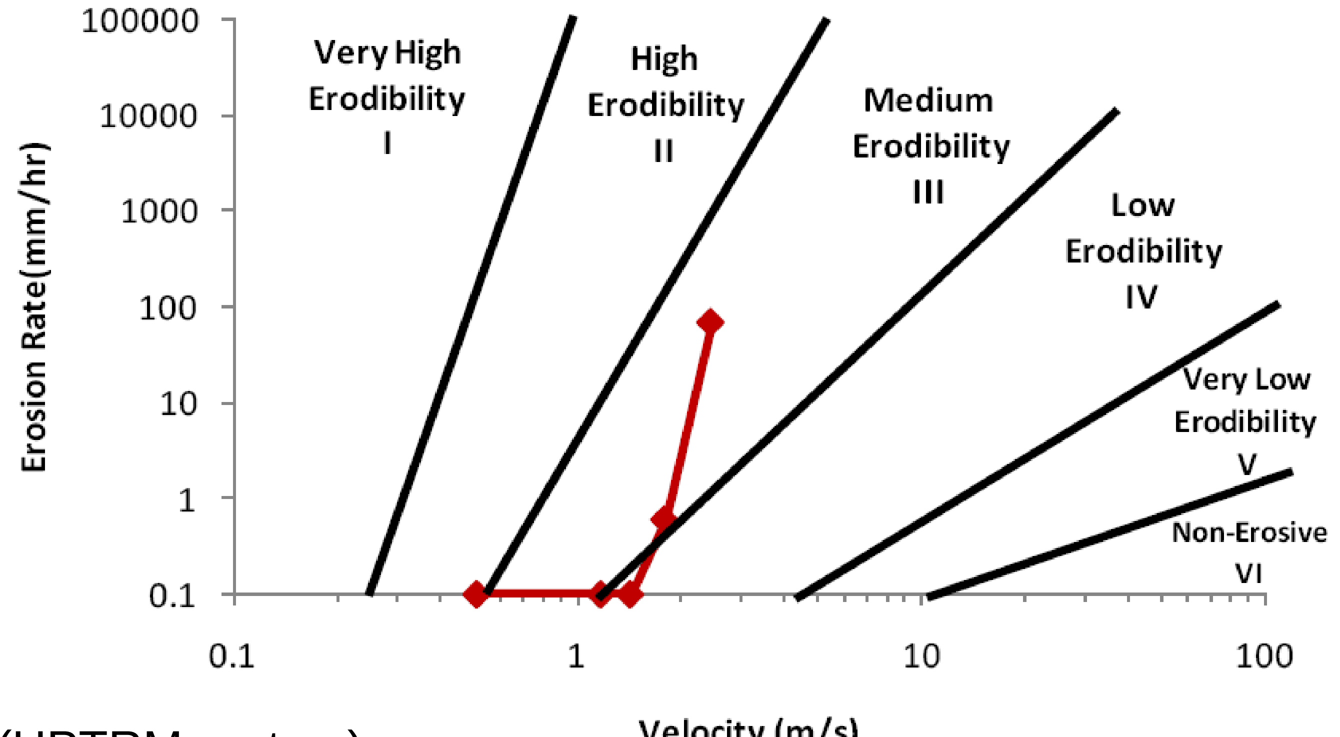
Measurement of Soil Erodibility

Soil Erodibility Improvement



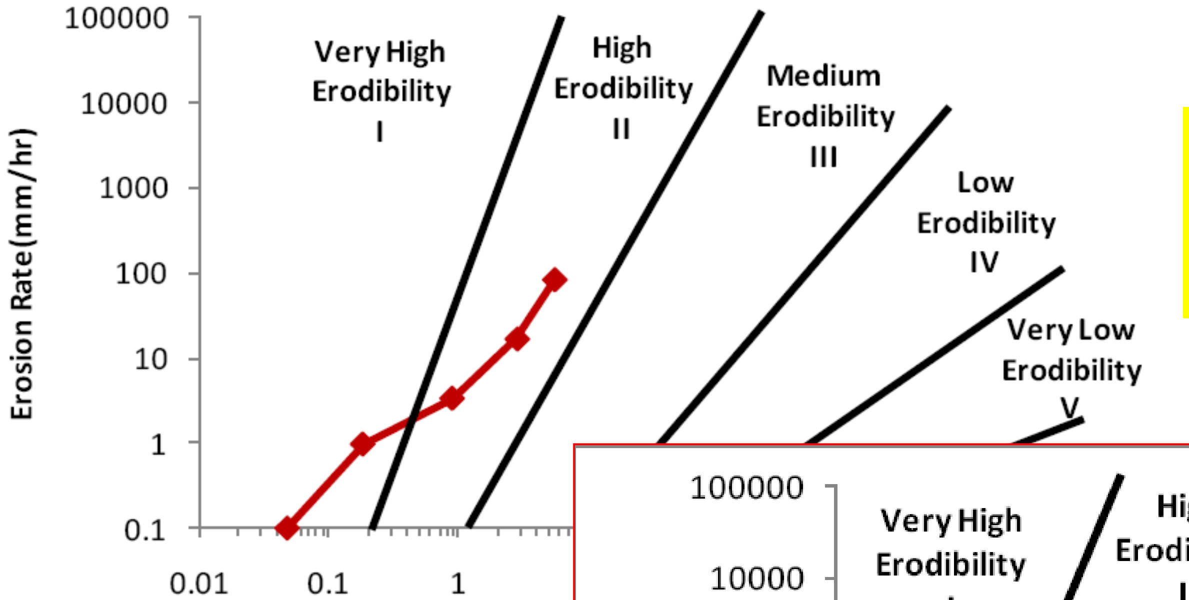
(clay + dormant grass)

From Very high/high erodibility decrease to Medium/low erodibility



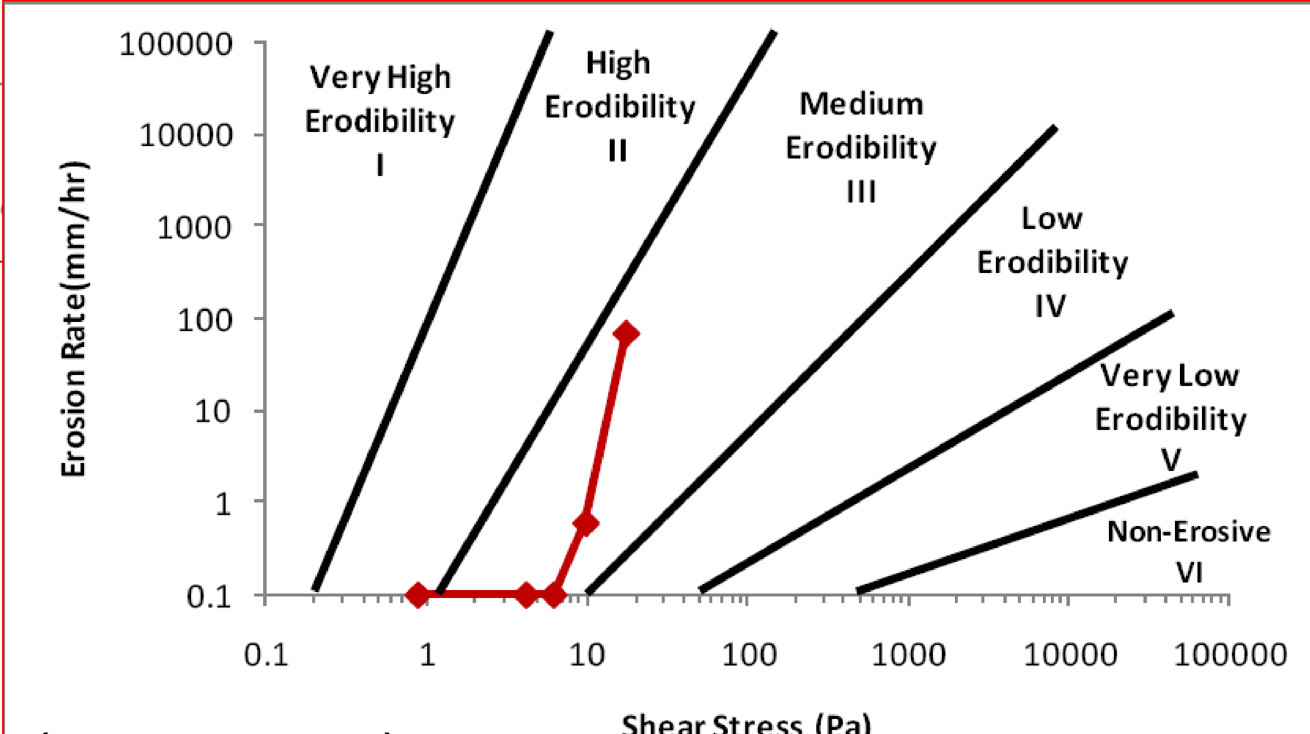
(HPTRM system)

Soil Erodibility Improvement



(clay + dormant grass)

From Very high/high erodibility decrease to Medium erodibility



(HPTRM system)

Design Parameters for Three Levee Strengthening Systems

- Under combined wave and surge overtopping, strengthening levees in crest and landward-side slopes with:
  - HPTRM can withstand wave overtopping of 0.2 m^3/s-m, where Dutch guideline is 0.01 m^3/s-m for good quality grass cover (TAW 1989).
  - RCC can withstand wave overtopping of 0.34 m^3/s-m, where Goda (1985) suggested 0.05 m^3/s-m for concrete protected side slopes.
  - ACB can withstand wave overtopping of 0.17 m^3/s-m

Empirical Equations for Three Levee Strengthening Systems Design under Surge-only Overflow Conditions

Design parameters	Empirical equations developed by this study
steady overflow discharge q_s	$q_s = C_f \sqrt{g} h_1^{3/2}$ where C_f is 0.5445 for RCC, 0.4438 for ACB, and 0.415for HPTRM strengthened levees.
average flow thickness d_s on landward-side slope	$\frac{\sqrt{g d_s^3}}{q_s} = k_d$, where k_d is 0.1732 for RCC, 0.2365 for ACB, and 0.3076 for HPTRM strengthened levees.
steady flow velocity v_s on landward-side slope	$v_s = k_v \sqrt{g h_1}$, where k_v is 2.628 for RCC, 1.995 for ACB and 1.637 for HPTRM strengthened levees.

Empirical Equations for Three Levee Strengthening Systems Design under Combined Wave and Surge Overtopping Conditions

Design parameters	Empirical equations developed by this study
dimensionless average wave overtopping discharge q_{ws}/ q_s	$q_{ws}/q_s = 36.12\exp(19.59\frac{R_c}{H_{m0}})+1$
distributions of instantaneous overtopping discharge	$P(q \le q_*) = 1-\exp[(-\frac{q_*}{c})^b]$, where c can be calculated by $c = \frac{q_{ws}}{\Gamma\left(1+\frac{1}{b}\right)}$, b can be calculated by $b = \beta\left(\frac{q_{ws}}{gH_{mo}T_p}\right)^{0.42}$ where β is 6.93 for RCC, 6.9 for ACB and 8.3 for HPTRM strengthened levees, and Γ is the gamma function.
average flow thickness d_m on landward-side slope	$d_m = 1.174 d_s$
average flow velocity v_{ws} on landward-side slope	$v_{ws}/v_s = 3.35\exp(13.59\frac{R_c}{H_{m0}})+1$
Distribution of wave heights on landward-side slope	$H_{1/3} = 1.416\cdot H_{rms}$, $H_{1/10} = 1.80\cdot H_{rms}$, $H_{1/100} = 2.36\cdot H_{rms}$

Empirical Equations for Three Levee Strengthening Systems Design under Combined Wave and Surge Overtopping Conditions

Design parameters	Empirical equations developed by this study
Wave front velocity v_w on landward-side slope	$v_w = 4.33(gq_{ws})^{1/3}$
Root-mean-square of shear stress $\tau_{t,rms}$ on landward-side slope	$\tau_{t,rms} = 0.0547\gamma_w h_m$ for HPTRM strengthened levee
Distribution of shear stress on landward-side slope	$\tau_{t,1/3} = 0.976 \cdot \tau_{t,rms}$, $\tau_{t,1/10} = 2.36 \cdot \tau_{t,rms}$, $\tau_{t,1/100} = 7.04 \cdot \tau_{t,rms}$ for HPTRM strengthened levee
Maximum soil loss depth E_{max}, in mm	$E_{max} = 11.23 v_{ws} - 16.24$ for HPTRM strengthened levee, where v_{ws} is the average overtopping flow velocity in m/ s
Erosion rate E in mm/ hr	$E = 5.3 v_{ws} - 9.3$ for HPTRM strengthened levee
Erosion rate E in mm/ hr	$E = 0.394 + 0.735(-v_{ws}\frac{R_c}{H_{m0}})^{4.44}$

Summary & Conclusions

- Effectiveness of HPTRM, RCC, and ACB were investigated with full-scale overtopping tests.
- HPTRM, RCC, and ACB can significantly decrease the flow velocity on landward-side slope.
- Average overtopping discharges are HPTRM < ACB < RCC for the same hydraulic conditions.
  - For $R_c/H_{m0} < -0.3$, q_{ws}/q_s is close to 1.
  - For $-0.3 < R_c/H_{m0} < 0$, q_{ws}/q_s increases sharply with $-R_c/H_{m0}$
- Average flow thicknesses on landward-side slope are RCC < ACB < HPTRM for the same overtopping discharge
  - $d_m/d_s = 1.174$

Summary & Conclusions

- Average flow velocities are HPTRM < ACB < RCC for the same overtopping discharge
  - For $R_c/H_{m0} < -0.3$, v_{ws}/v_s is close to 1.
  - For $-0.3 < R_c/H_{m0} < 0$, v_{ws}/v_s increases sharply with $-R_c/H_{m0}$
- Wave front velocities are HPTRM < ACB < RCC for the same relative freeboard.
- HPTRM system has the best effect in reducing overtopping discharge and wave front velocity on landward-side slope, while RCC has the least effect.
- Flow equivalency shows that the impact of wave on overtopping parameters weakens with an increase in the negative relative freeboard.
- The maximum erosion depth in HPTRM test section is mainly impacted by overtopping flow velocity.

Summary & Conclusions

- After the maximum soil loss is reached, the relationship between erosion rate and average overtopping flow velocity is approximately linear.
- Both the grass roots and HPTRM can increase the critical velocity by 1 m/s. The erodibility of the soil is lowered from high erodibility to median erodibility by both the grass roots and HPTRM.
- HPTRM can strengthen the clay levee by increasing the threshold value of both flow velocity and shear stress.
- Aside from the surface erosion, the RCC remained intact throughout all of the experimental tests, and there was no catastrophic failure in the RCC test section.
- According to this full-scale overtopping test, the crest and landward-side slope strengthened by HPTRM, RCC and ACB can withstand wave overtopping of 0.2, 0.34, and 0.17 $m^3/s/m$, respectively in the combined wave and surge overtopping conditions.

THE END