Prediction of Erosion Depth for New Orleans Levee Soils

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Background (IPET, 2007)

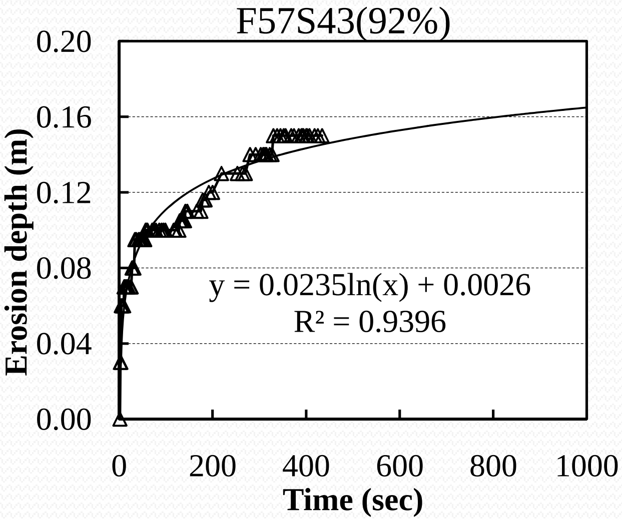
Hurricane Katrina,
Overtopping,
Erosion,
Failure.

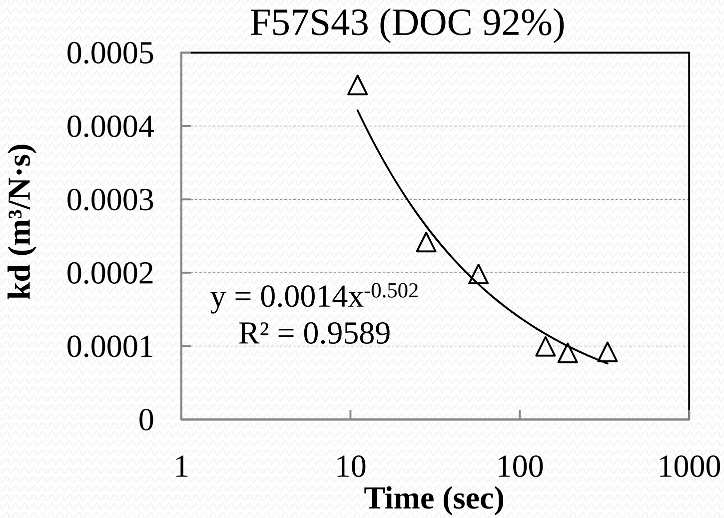
How to predict the erosion depth?

Estimation of non-constant k_d

$$\frac{\partial D}{\partial t} = k_d\left(\tau_e \frac{D_p}{D} - \tau_c\right) \longrightarrow T^* - T_p^* - \left[D_p^* - D^*\right] - \left[\ln(1 - D_p^*) - \ln(1 - D^*)\right] = 0$$

by Stein et al. (1993)





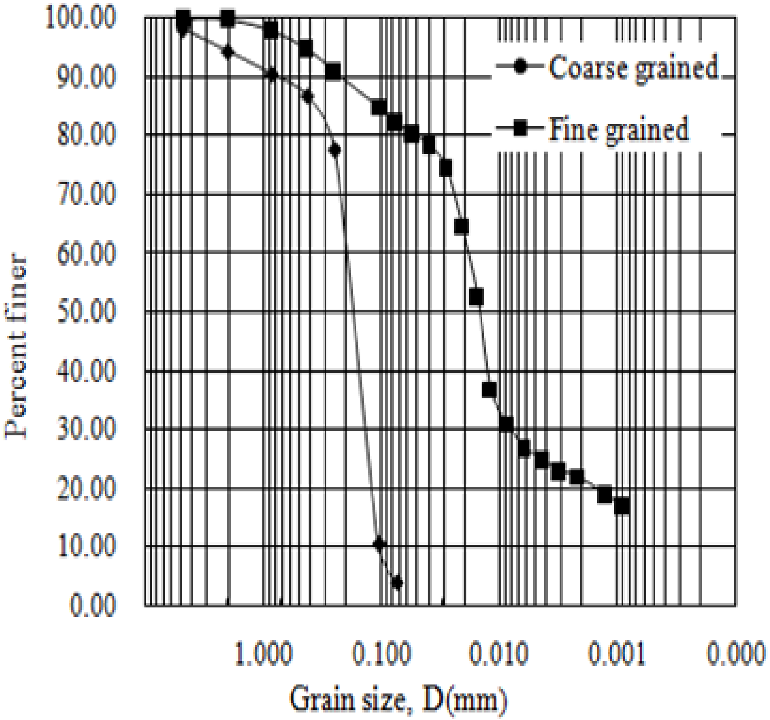
$$\tau_c = \frac{D_p}{D_e}\tau_e \qquad D_e = \frac{C_d^2 C_f \rho U_0^2 y_0}{\tau_c}\sin x$$

- Consider three particular erosion features in N.O.
  - plunging water
  - saturated levee soil
  - dispersive soil behavior
- UMETB (University of Mississippi Erosion Test Bed)
  - to **minimize scale effect**, 6m/sec of water velocity was used.

  (IHNC: average h_f from h_l is 6ft→ 6m/sec)
- Two soils used in constructing levees were taken from one of the quarry sites in N.O.
  - fine-grained soil.

    (CL, #200 = 80%, d_{50}=0.015 mm)
  - coarse grained soil

    (SM, #200 = 4.5%, d_{50} =0.15 mm)



Sample Preparation

Estimation of Field Erosion Depth

$$\frac{\partial D}{\partial t} = k_d(\tau_e \frac{D_p}{D} - \tau_c) \longrightarrow T^* - T_p^* - \left[D_p^* - D^* \right] - \left[\ln(1 - D_p^*) - \ln(1 - D^*) \right] = 0$$

by Stein et al. (1993)

$$at\ Equilibrium Depth, \tau_e = \frac{D_e}{D_p} \tau_c$$

$$D_e = \frac{C_d^2 C_f \rho U_0^2 y_0}{\tau_c} \sin x$$

Dimensional Analysis

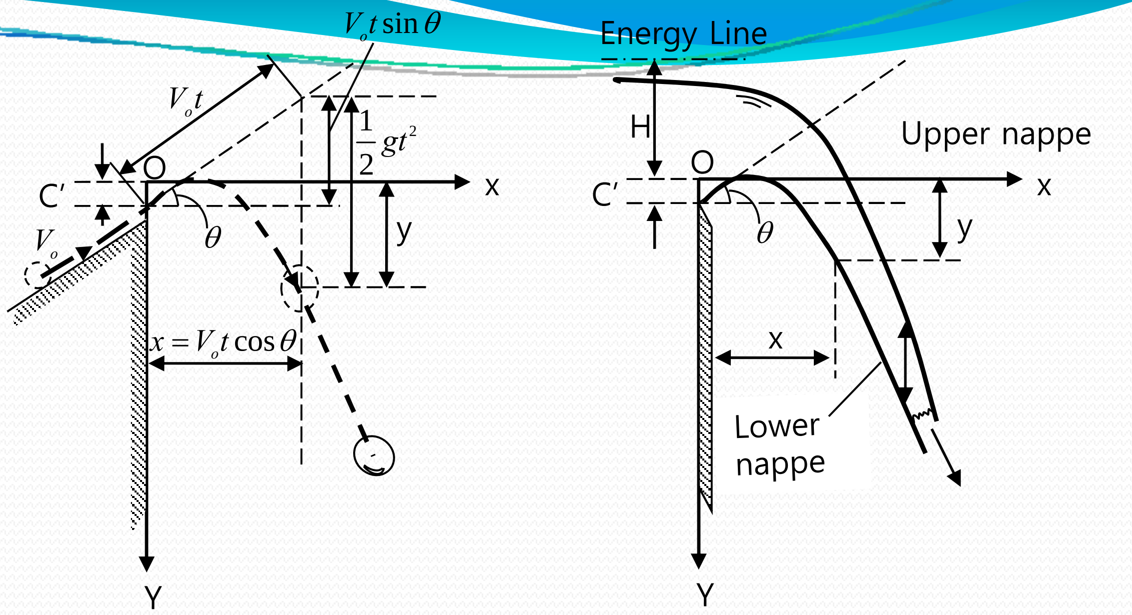
$$D \propto y_o$$

Therefore, we need correct y_o, and U_o, to predict the field erosion depth.

But y_o increased with time, so incremental approach was used.

By principle of projectile

- Nappe profiles of water overflowing weir can be expressed as below two equations.
- Using this equations, plunging water width at impact moment were estimated.



(Chow, 1959)

Time (min) (7:30-8:30)	Canal water height from the top of the floodwall (m)	Water width at impact moment (m)	
		By continuity eq'	By principle of projectile
0	0 (12.7ft)	-	-
10	0.0766	0.0069	0.0069
20	0.15334		-
30	0.23001	0.0364	0.0352
40	0.30668		-
50	0.38335	0.0792	0.0746
60	0.45 (14.2ft)		-

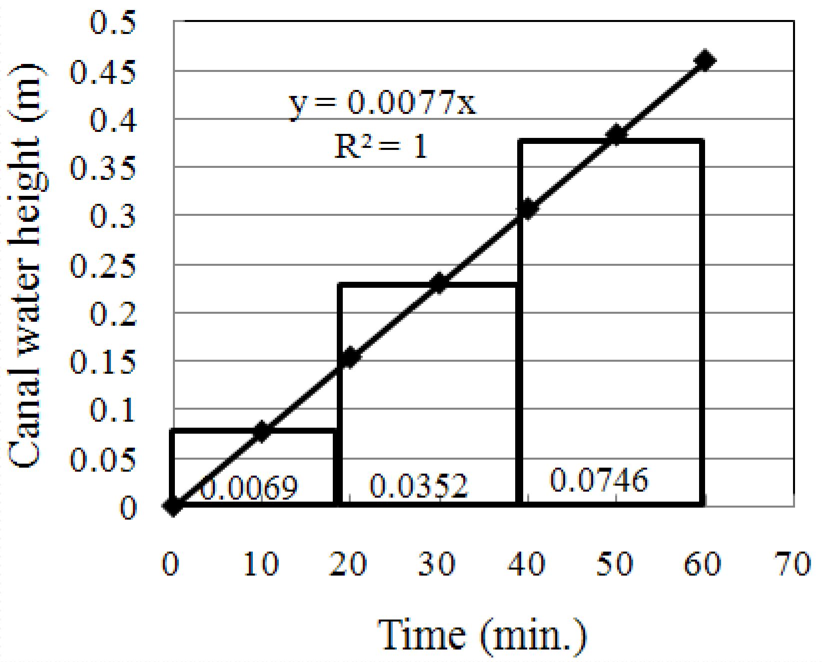
$$x = v_0 t \cos\theta$$

$$y = -v_0 t \sin\theta + \frac{1}{2} g t^2 + C'$$

In this study, use the plunging water width developed using the principle of projectile.

Sample	DOC (%)	Width (m)	Equation
F57S43	92%	0.0069	$t=\left[137\left\{\frac{15.4D^2}{8.66-11.55D}-\frac{D-0.038}{0.75}+\ln\left(\frac{0.712}{0.75-D}\right)\right\}\right]^2$
		0.0352	$t=\left[1034\left\{\frac{7.49D^2}{117-29.66D}-\frac{D-0.1936}{3.84}+\ln\left(\frac{3.646}{3.84-D}\right)\right\}\right]^2$
		0.0746	$t=\left[2692\left\{\frac{5.25D^2}{391-45.27D}-\frac{D-0.41}{8.14}+\ln\left(\frac{7.73}{8.14-D}\right)\right\}\right]^2$

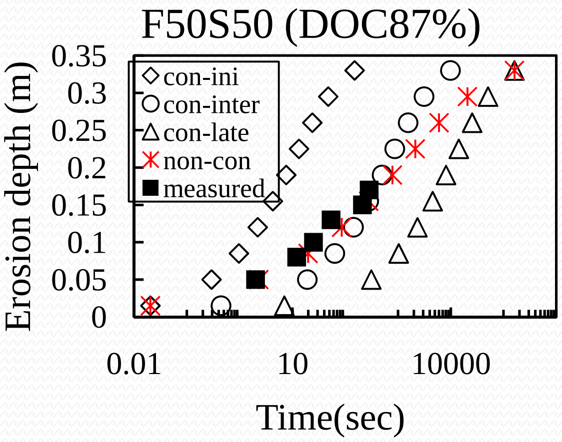
With above equation, field erosion depths were computed incrementally and finally summed.

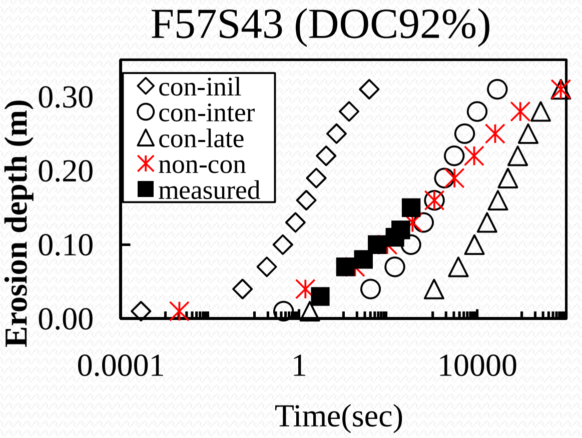


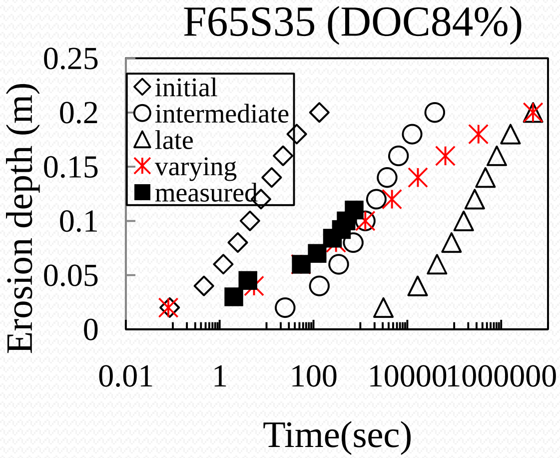
Comparison between measured and estimated

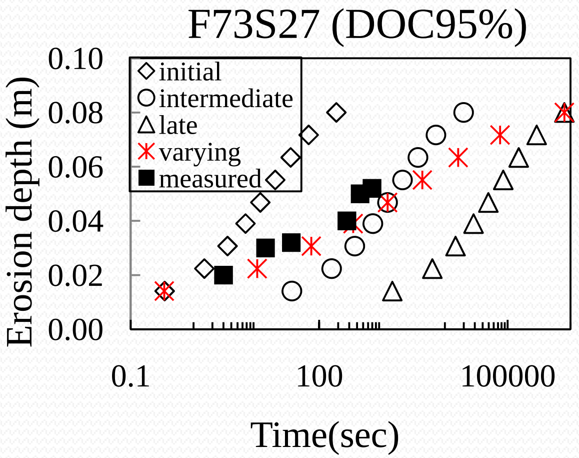
(constant vs. non-constant k_d)

- As shown in the plots, the relationship using non-constant erosion rate coefficient correspond better to measured data.
- Using intermediate constant k_d may cause underestimation of erosion in the initial stage and overestimation of erosion in the late stage of erosion.


F50S50 (DOC87%)


F57S43 (DOC92%)


F65S35 (DOC84%)

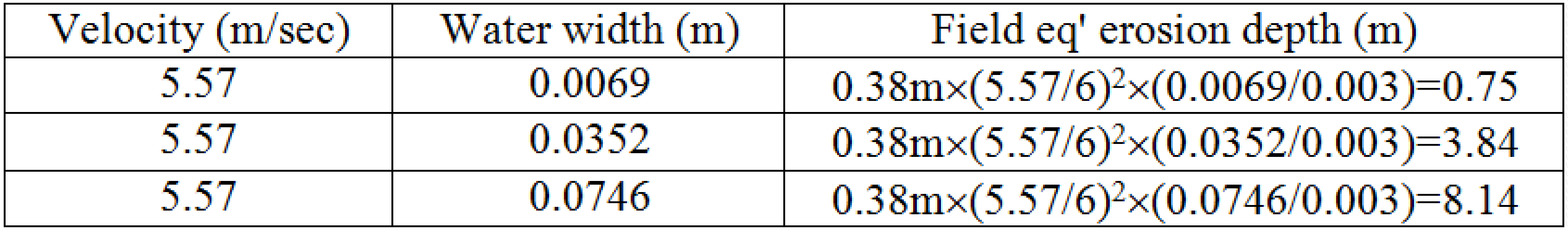

F73S27 (DOC95%)

Correction of field equilibrium erosion depths

Because three typical field plunging water widths (0.0069, 0.0352, 0.0746m) were determined, D_{ef} for each plunging water width should be computed

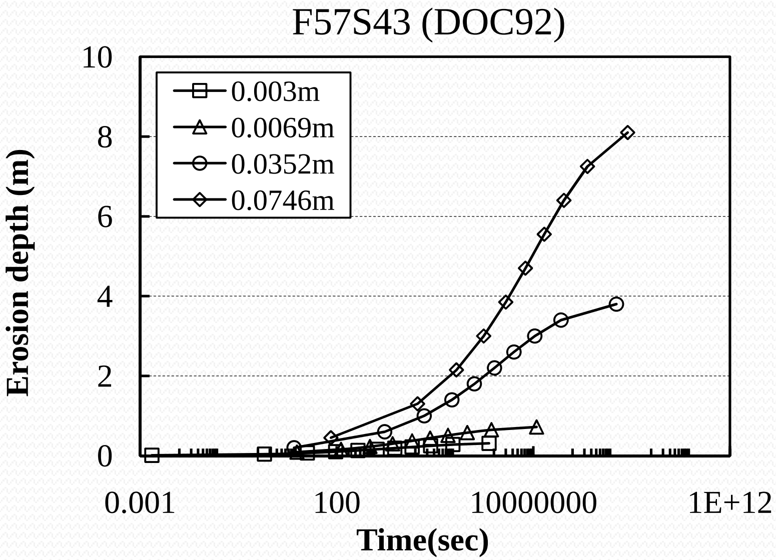
$D_{ef} = D_{el} \times$ (velocity factor)$^2 \times$(width factor)

$$D_e \propto f\left(U_0^2 y_0\right)$$

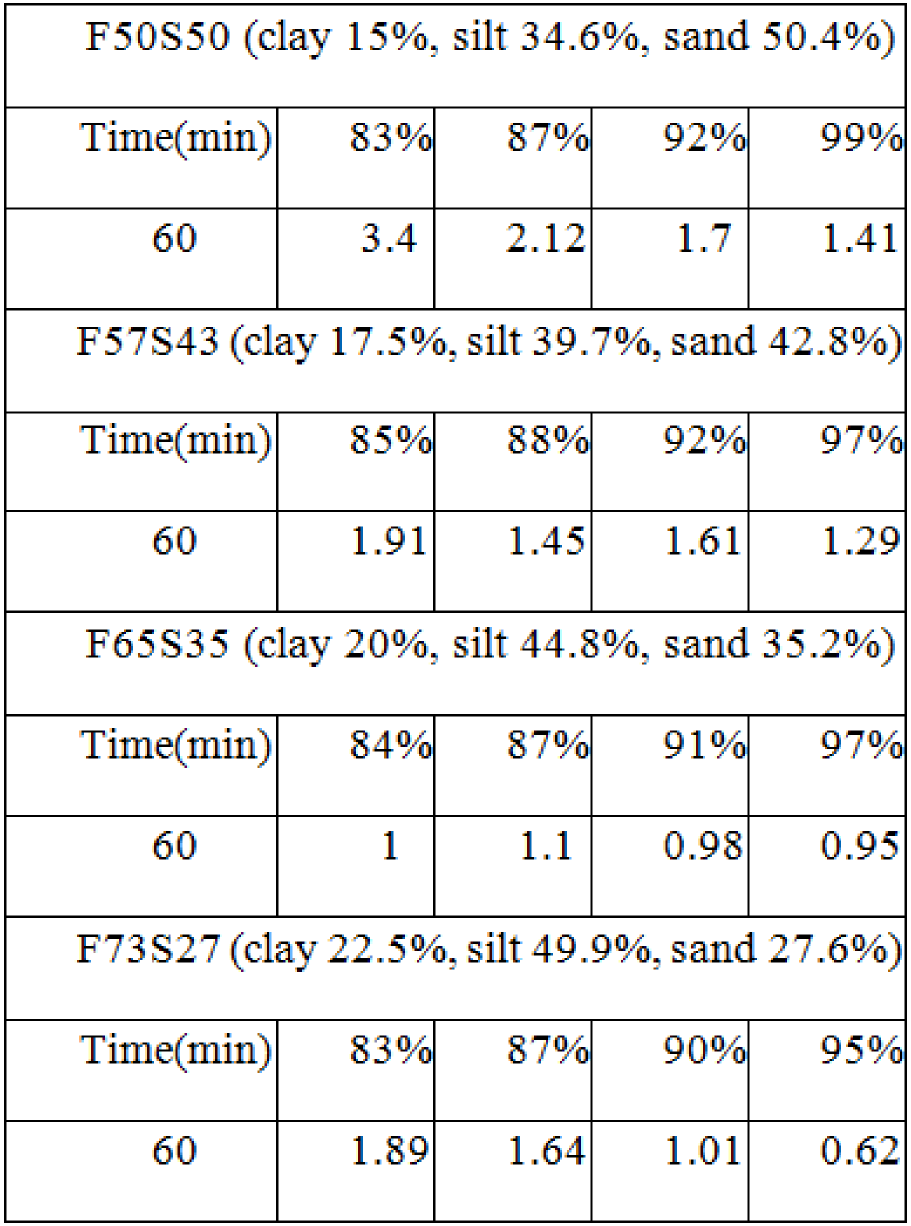


Velocity (m/sec)	Water width (m)	Field eq' erosion depth (m)
5.57	0.0069	$0.38\text{m}\times(5.57/6)^2\times(0.0069/0.003)=0.75$
5.57	0.0352	$0.38\text{m}\times(5.57/6)^2\times(0.0352/0.003)=3.84$
5.57	0.0746	$0.38\text{m}\times(5.57/6)^2\times(0.0746/0.003)=8.14$

$$(t,\ D,\ \boldsymbol{k_d},\ \boldsymbol{D_e}) \longrightarrow (t,\ D)$$



Estimated field erosion depth



F50S50 (clay 15%, silt 34.6%, sand 50.4%)				
Time(min)	83%	87%	92%	99%
60	3.4	2.12	1.7	1.41
F57S43 (clay 17.5%, silt 39.7%, sand 42.8%)				
Time(min)	85%	88%	92%	97%
60	1.91	1.45	1.61	1.29
F65S35 (clay 20%, silt 44.8%, sand 35.2%)				
Time(min)	84%	87%	91%	97%
60	1	1.1	0.98	0.95
F73S27 (clay 22.5%, silt 49.9%, sand 27.6%)				
Time(min)	83%	87%	90%	95%
60	1.89	1.64	1.01	0.62

Field erosion depths were estimated in six different ways

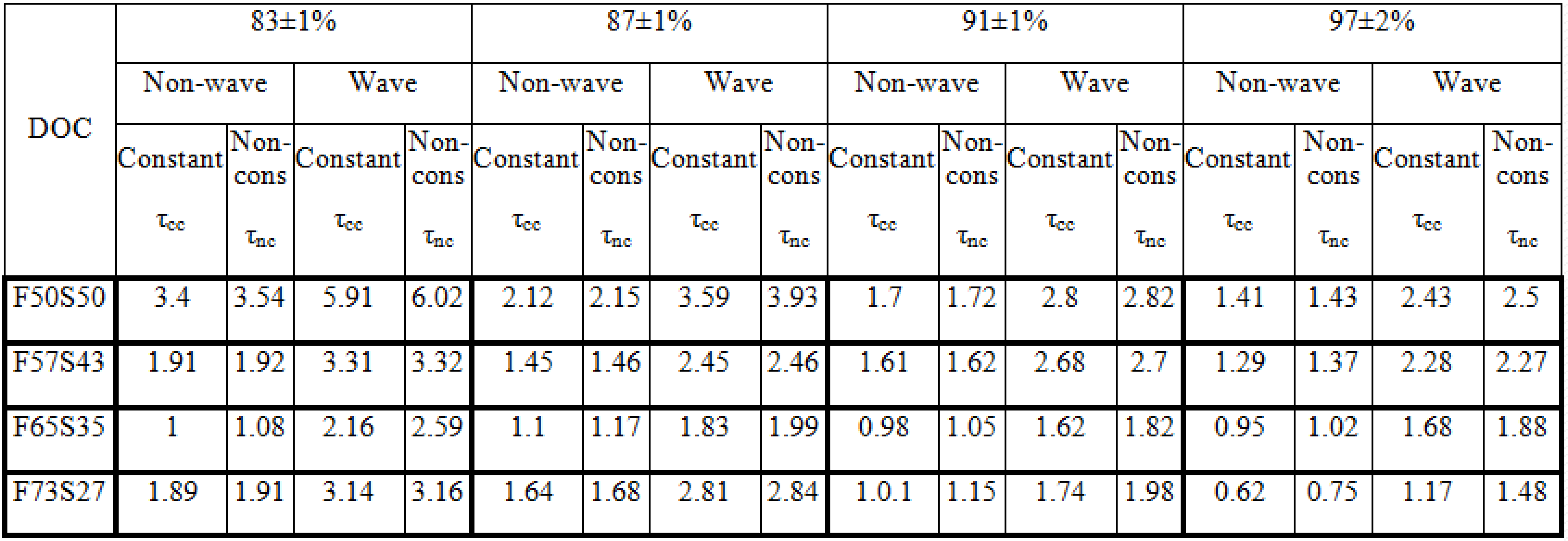
❑ ***When erosion depth is linearly proportional*** $\left(D_e \propto f\left(U_0^2 y_0\right)\right)$ ***to plunging water width***

- Case I: τ_{cc} ($=\frac{D_p}{D_e}C_f\rho U_0^2$), non-wave (60 min., 0.0069m, 0.0352m, 0.0746m)
- Case II: τ_{nc} ($=\left(\frac{D_p}{D_e}C_f\rho U_0^2\right)\left(\frac{D}{D_e}\right)^{0.5}$), non-wave (60 min., 0.0069m, 0.0352m, 0.0746m)
- Case III: τ_{cc} ($=\frac{D_p}{D_e}C_f\rho U_0^2$), wave (120 min., 0.0148m, 0.0735m, 0.154m)
- Case IV: τ_{nc} ($=\left(\frac{D_p}{D_e}C_f\rho U_0^2\right)\left(\frac{D}{D_e}\right)^{0.5}$), wave (120 min., 0.0148m, 0.0735m, 0.154m)

❑ ***When erosion depth is non-linearly proportional (enlarged tests) to plunging water width***

- Case V: τ_{nc} ($=\left(\frac{D_p}{D_e}C_f\rho U_0^2\right)\left(\frac{D}{D_e}\right)^{0.5}$), non-wave (60 min., 0.0069m, 0.0352m, 0.0746m)
- Case VI: τ_{nc} ($=\left(\frac{D_p}{D_e}C_f\rho U_0^2\right)\left(\frac{D}{D_e}\right)^{0.5}$), wave (120 min., 0.0148m, 0.0735m, 0.154m)

Comparison of erosion depth for linear condition



DOC	83±1%				87±1%				91±1%				97±2%			
	Non-wave		Wave		Non-wave		Wave		Non-wave		Wave		Non-wave		Wave	
	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}	Constant τ_{cc}	Non-cons τ_{nc}
F50S50	3.4	3.54	5.91	6.02	2.12	2.15	3.59	3.93	1.7	1.72	2.8	2.82	1.41	1.43	2.43	2.5
F57S43	1.91	1.92	3.31	3.32	1.45	1.46	2.45	2.46	1.61	1.62	2.68	2.7	1.29	1.37	2.28	2.27
F65S35	1	1.08	2.16	2.59	1.1	1.17	1.83	1.99	0.98	1.05	1.62	1.82	0.95	1.02	1.68	1.88
F73S27	1.89	1.91	3.14	3.16	1.64	1.68	2.81	2.84	1.0.1	1.15	1.74	1.98	0.62	0.75	1.17	1.48

Case IV showed the highest erosion depth while Case I showed the lowest erosion.

Case I < Case II < Case III < Case IV

It seems logical considering higher static loading under wave condition and smaller critical shear stress for τ_{nc} .

However, enlarged nozzle test results showed that erosion depth vs. plunging water width is non-linear!

Summary of estimation for field erosion depth

Observed erosion depth in IHNC during Hurricane Katrina

- Citrus Back Levee: 1.98m (6.5ft)
- NOE back Levee (East of PP.15): average 2.44m (8ft), maximum 4.57m (15ft)
- South breach at Lower Ninth Ward in IHNC: 1.37m (4.5ft)
- According to Seed et al. (2008),

- erosion depth of the South Breach was deepened toward the edge of the South breach
- At least 1.98-2.44 m of erosion depth was required for the I-wall to be toppled by the lateral water pressure, and South breach contained high content of silt or sand.

- Consequently, before H.K., South Breach seems to have similar soil conditions or erosion properties to F57S43 (DOC 88%, silt or sand 82.5%), of which estimated erosion depths are ranged from 2.36 m (Case VI) to 1.44 m (Case V).
- Also, F50S50 (87%, 92%) and F57S43 (85%) also have the possibility to show similar erosion depths with what Seed et al. report (1.98-2.44m).

Acknowledgement

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Thanks for attention!