BUREAU OF RECLAMATION

Submerged Jet Erodibility Test Methods Research

(and other overtopping-related things)

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Cohesive Soils - Erodibility

- Erosion of cohesive soils is a fundamental process important for many things
    - Embankment erosion and breach (WinDAM, HR BREACH)
    - Earthen spillway erosion (SITES)
    - Stream bank migration (BSTEM)
    - River channel degradation
    - Rill erosion
    - Bridge pier scour

Linear Excess Stress Equation

$$\varepsilon_r = k_d(\tau - \tau_c)$$

- Laboratory tests used to determine the erodibility parameters k_d and τ_c include:

- Submerged Jet Erosion Test (JET) – simulates scour caused by an impinging jet (developed at USDA-ARS, see Hanson and Cook 2004)
- Hole Erosion Test (HET) – simulates internal erosion of a soil "pipe" (Wan and Fell 2004)
- HET vs. JET – there are issues (some improved HETs may help…)

JET advantages

- The JET method has been favored by many in the field of dam breach modeling because it is:
  - Practical to perform
  - Robust
    - Has been successfully applied to materials ranging from very erodible to very resistant, spanning approximately 5.5 orders of magnitude of erosion rate (300 000 : 1)
  - Can be used in the field on exposed surfaces (horizontal or inclined) or in the lab to test remolded specimens or samples recovered from the field


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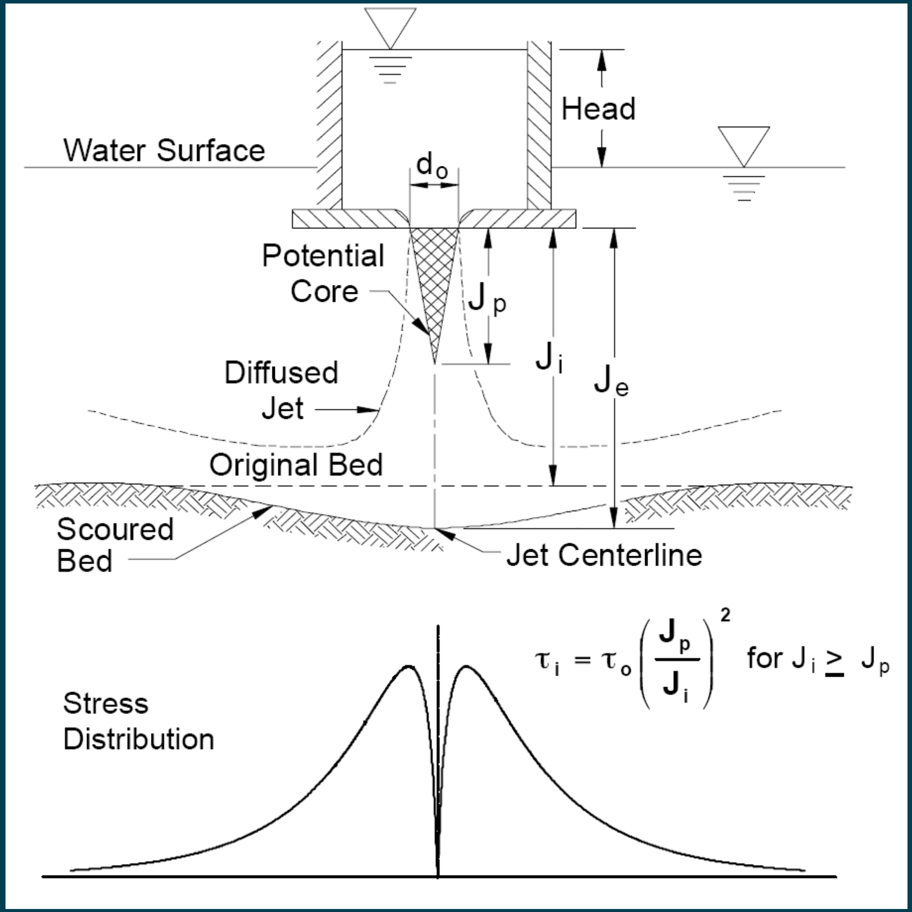
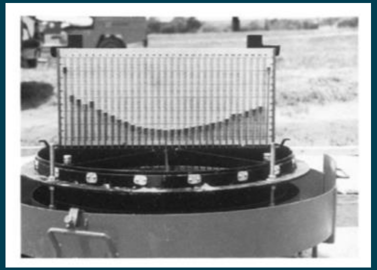
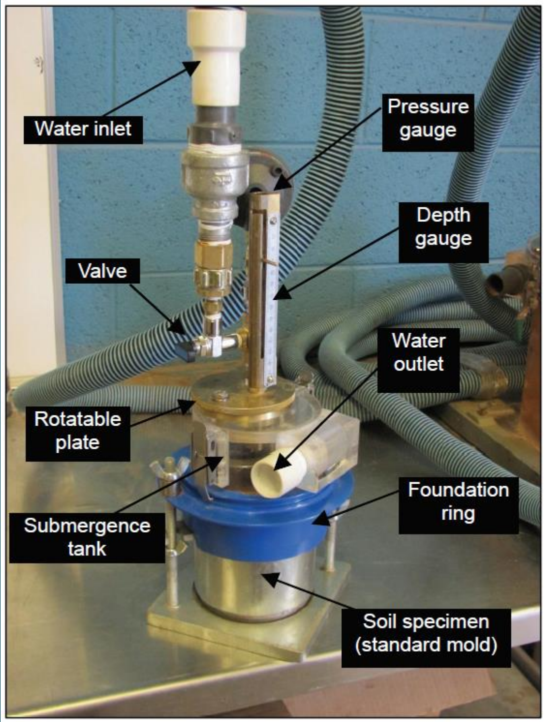

Head
Water Surface
d_o
Potential
Core
J_p
J_i
J_e
Diffused
Jet
Original Bed
Scoured
Bed
Jet Centerline
Stress
Distribution
$\tau_i = \tau_o \left(\frac{J_p}{J_i}\right)^2$ for $J_i \geq J_p$

Issues



- ASTM standard –has been long out-of-date with respect to the device in common use, (and the data analysis methods). Expired 2016.
- Smaller scale devices becoming more common. The Mini-JET.
- New data processing methods have been proliferating
  - Blaisdell method (Hanson-Cook 2004) most common
  - Scour depth method (Daly et al. 2013)
  - Iterative method (Simon 2010)
- New *non-linear* erosion models have been suggested
  - Wilson model (Wilson 1993a,b)



Method	Erosion Model	Details
Blaisdell method (Hanson and Cook 2004)	Linear excess stress	1. Predicts τ_c based on estimate of equilibrium scour at t=∞. (Asymptote of hyperbolic scour-time curve) 2. Adjusts k_d with Excel Solver to minimize sum of squared errors in **predicted times** to reach measured scour depths. Data-fitting uses dimensional times, although data are plotted nondimensionally
Iterative method (Simon 2010)		Uses Blaisdell solution as starting point. Constrains τ_c to not exceed stress applied at end of test. Adjusts k_d and τ_c simultaneously with same objective as Blaisdell method.
Scour depth method (Daly et al. 2013)		Adjusts k_d and τ_c simultaneously with objective of minimizing sum of squared errors in **predicted scour depths** (dimensional) at specific times. (τ_c>0)
Al-Madhhachi et al. 2013	Wilson model	Adjusts b_0 and b_1 simultaneously to minimize sum of squared errors in **predicted erosion rates**. Optimizing to minimize errors in predicted **scour depths** was also tested and has been adopted for more recent work (personal communication with Al-Madhhachi).
Wilson model in JET Spreadsheet V1.2 by Daly		Adjusts b_0 and b_1 simultaneously to minimize sum of squared errors in **predicted scour depths**

Objectives

- Evaluate use of different erosion models and solution methods
- Compare “original” ¼-inch (6-mm) JET and mini-JET (3 mm nozzle)
- Facilitate re-standardization

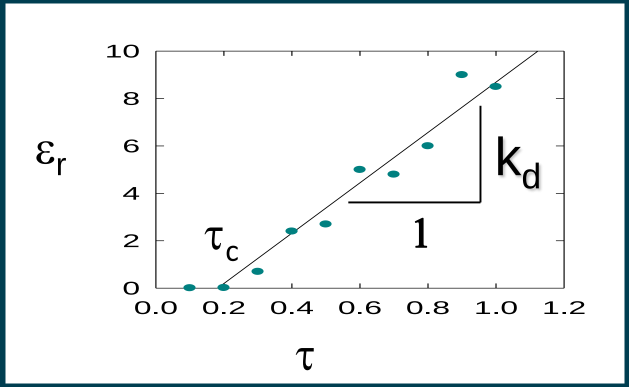
Approach

- Test four soil types at a range of moisture conditions
- Run original JETs
- Process data by many methods
    - Evaluate…

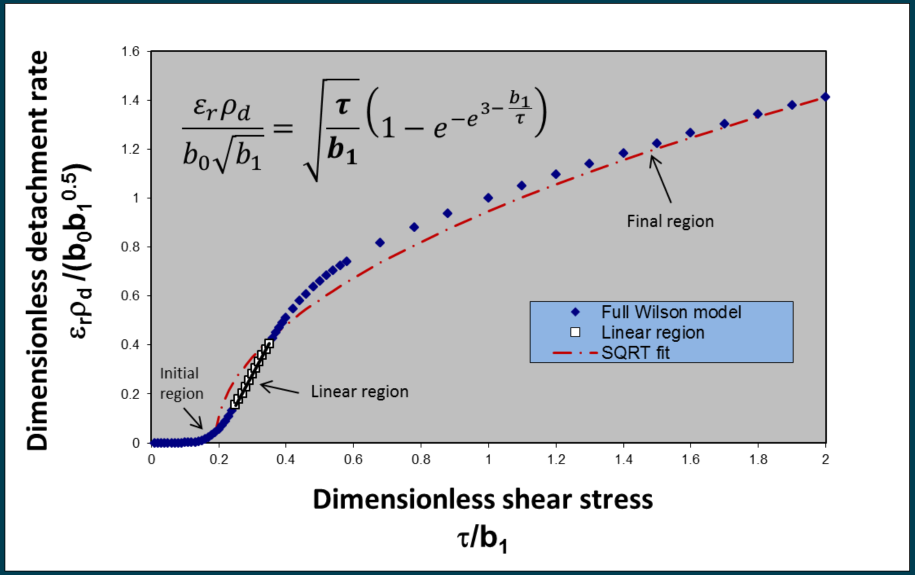
- Run comparable mini-JETs
    - Compare…

Erosion Models

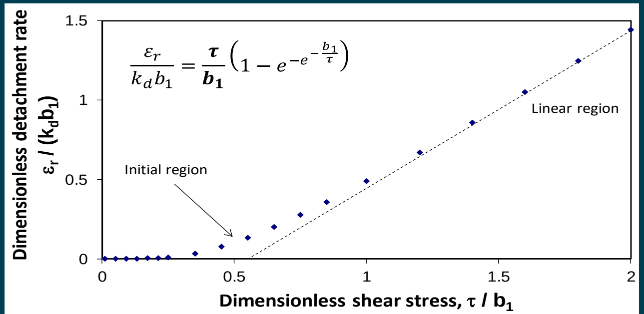
- Linear excess stress $\varepsilon_r = k_d(\tau - \tau_c)$
  - Solve by…Blaisdell, scour time, scour depth



- Nonlinear excess stress $\varepsilon_r = k_d(\tau - \tau_c)^a$…scour time or depth
- Wilson model
  - Solve for scour depths
  - Solve for scour rates

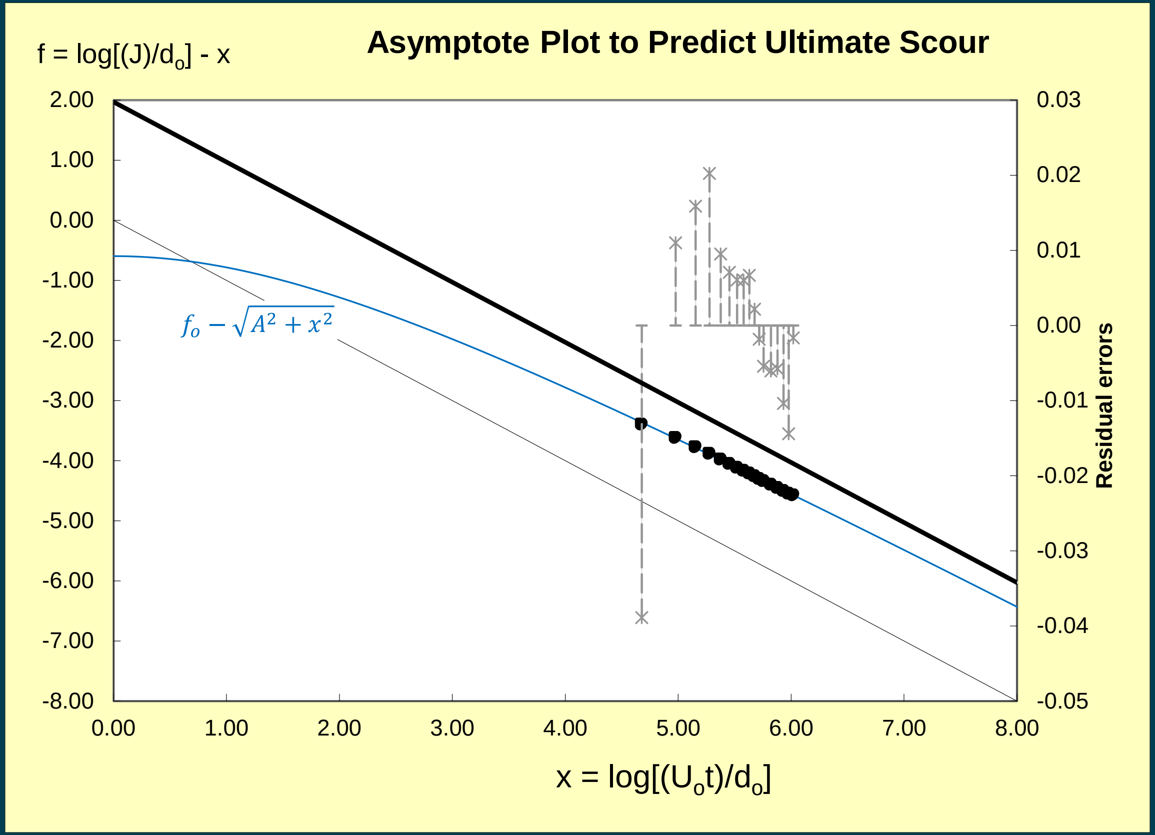


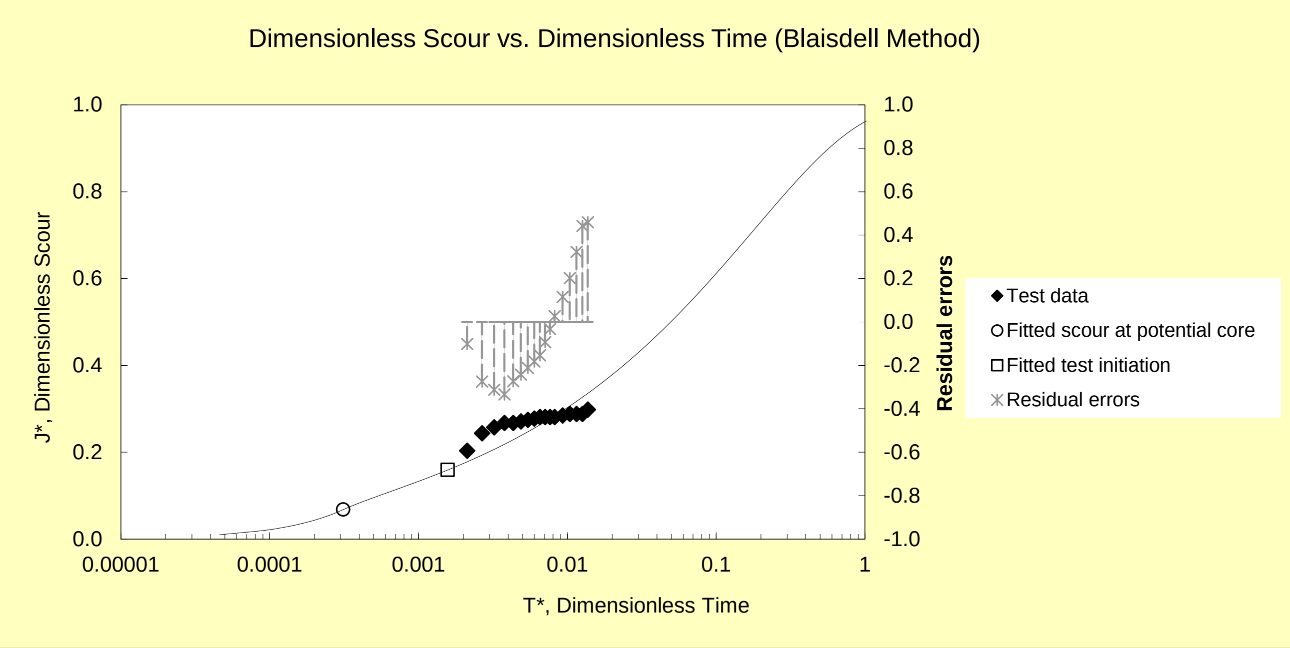
- Exponential-Linear model (depth, rate)

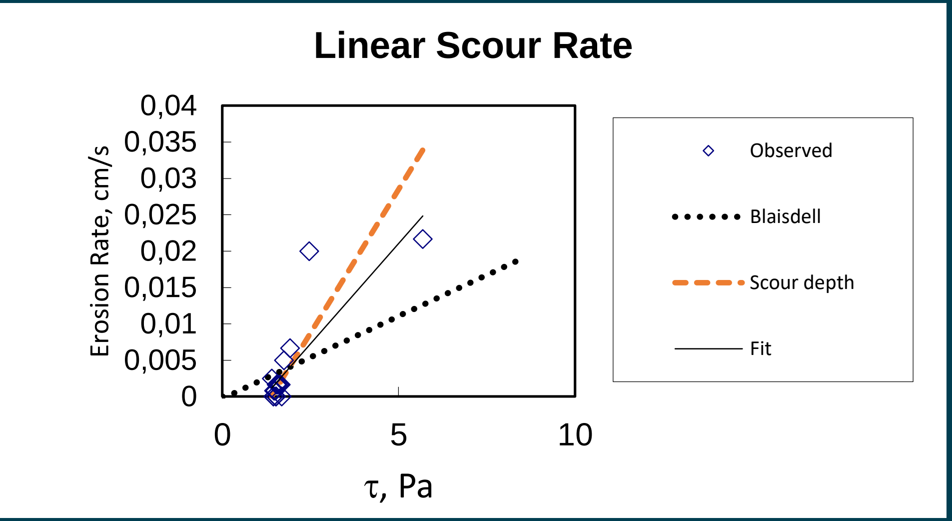


- Linear regression of scour rates

Blaisdell Method

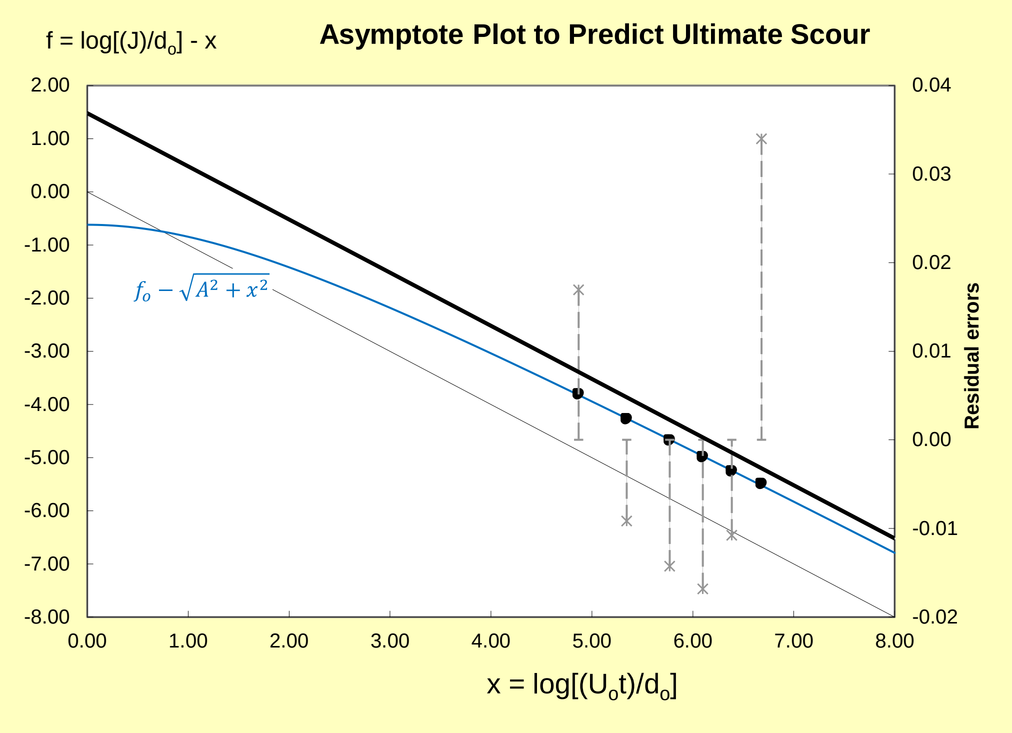




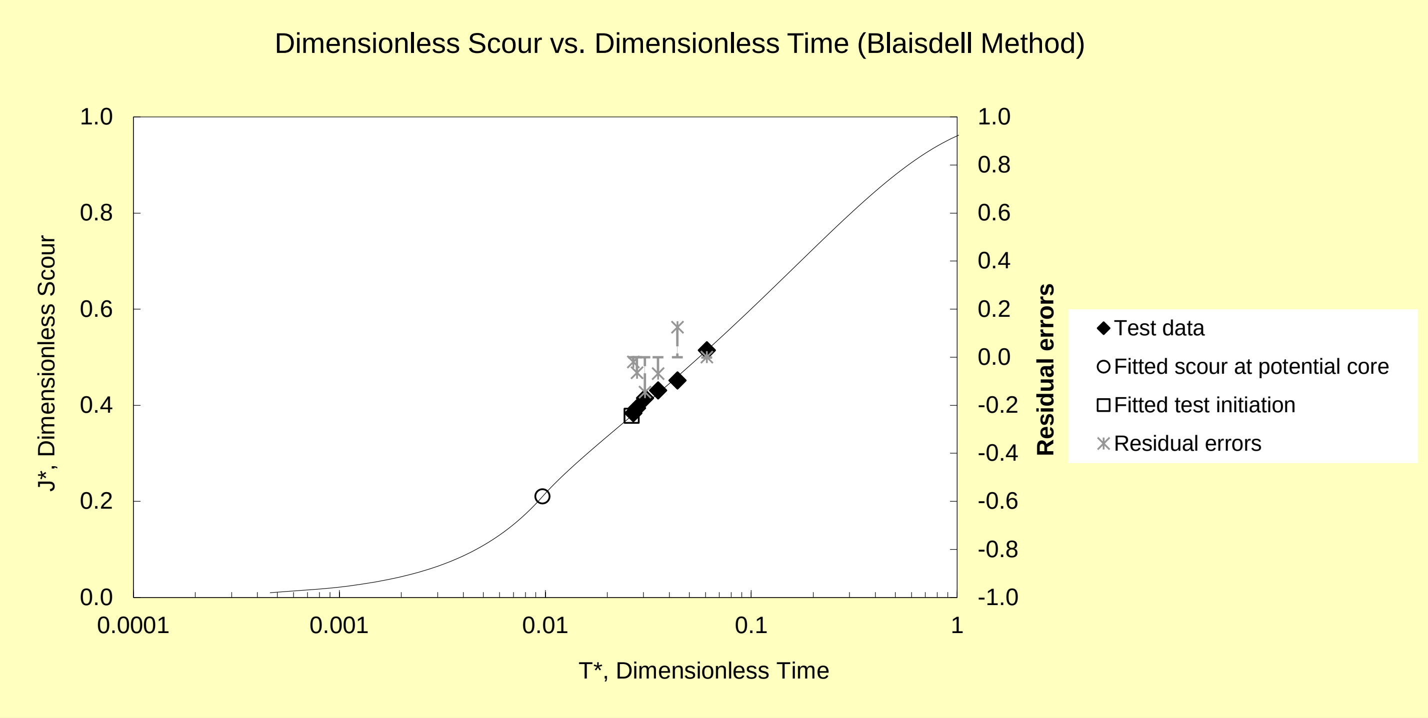


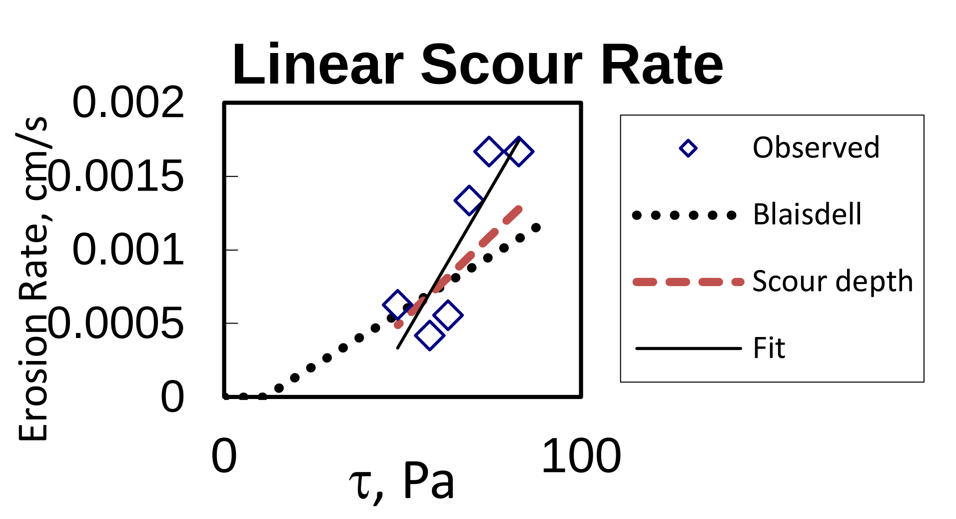
41 mm scour in 22 minutes…equilibrium projected to be 296 mm

Another Example



13 mm scour in 32.5 minutes…equilibrium projected to be 95 mm





JETs

- 4 soils

Table 1. Properties of tested soils and ASTM standards used to measure soil properties (ASTM, 2020).

USCS Soil Classification (ASTM D2487)	Particle Size Distribution (ASTM D7928) Clay (<2 µm) (%)	Silt (2 to 75 µm) (%)	Sand (>75 µm) (%)	Plasticity Index[a] (ASTM D4318)	Standard Compaction (ASTM D698A) $\gamma_{d,max}$ (g cm^{-3})	WC_{opt} (%)
Lean clay (CL)	40	53	7	25	1.67	20.3
Clayey sand (SC)	13	30	57	12	1.81	18.5
Silty clay (CL-ML)	8	83	9	7	1.69	17.0
Silty sand (SM)	12	27	61	Non-plastic	1.47	25.0

[a] Plasticity index is the difference between the liquid limit and plastic limit.

- Standard Proctor compaction at -2%, optimum, +2% water content
- At least 3 repetitions of each condition
- Original JET device, using mostly similar test heads for each soil across different compaction moisture states
- Wide range of test heads for SC soil at +2%

- Total of 52 tests

Data analysis methods

1. Linear excess stress, Blaisdell solution
2. Linear excess stress, scour time solution
3. Linear excess stress, scour depth solution
4. Linear excess stress, linear regression of scour rates
5. Nonlinear excess stress, scour depth solution
6. Wilson model, scour depth solution
7. Wilson model, scour rate solution
8. Exponential-linear model, scour depth solution
9. Exponential-linear model, scour rate solution

Evaluation

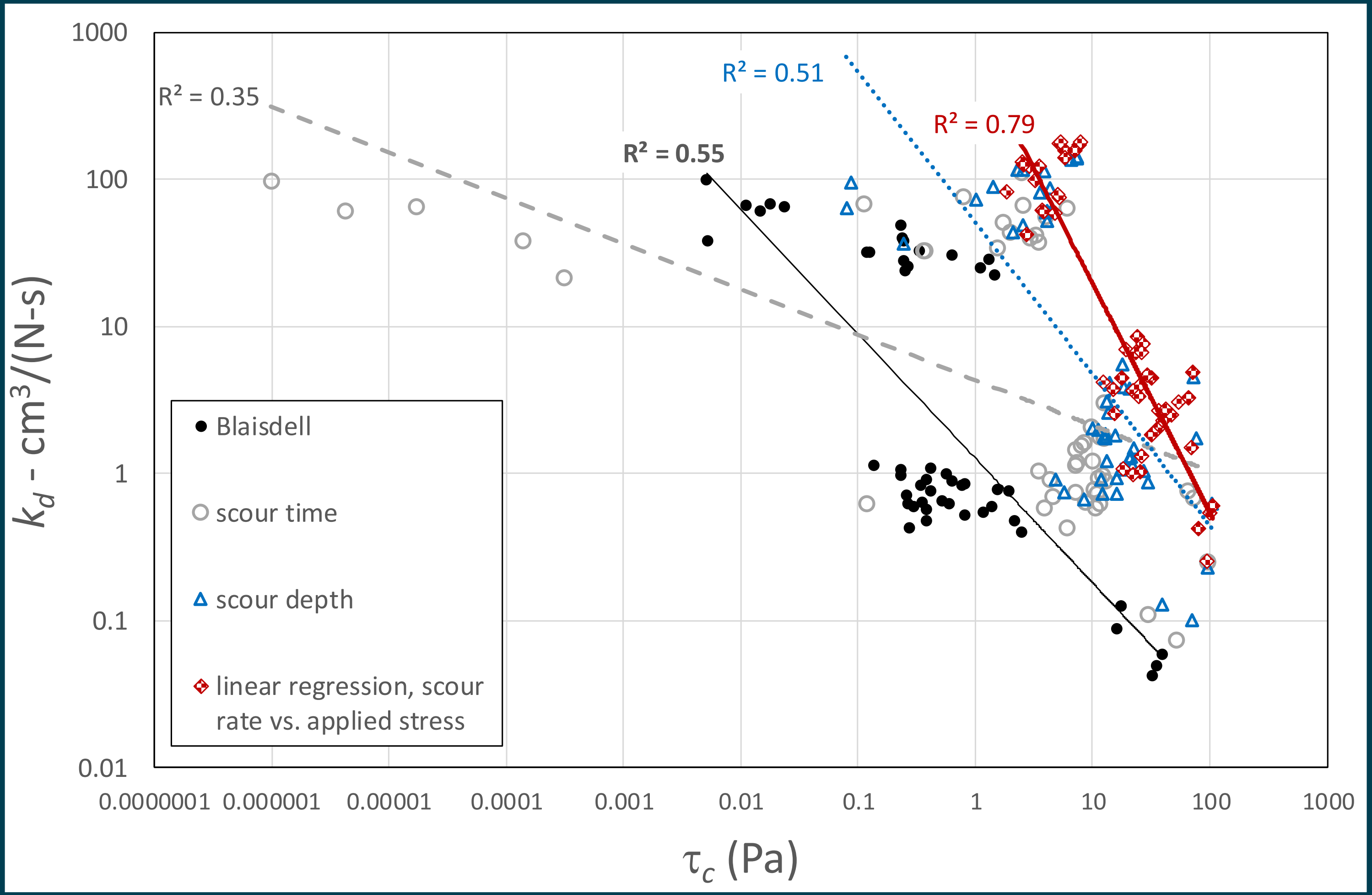
- Normalized objective function,
  standard deviation of errors, relative to mean
  Always positive. Values near zero indicate better fit.

$$\mathrm{NOF} = \frac{\sqrt{\sum_{i=1}^{N} \frac{(x_i - y_i)^2}{N}}}{X_a}$$

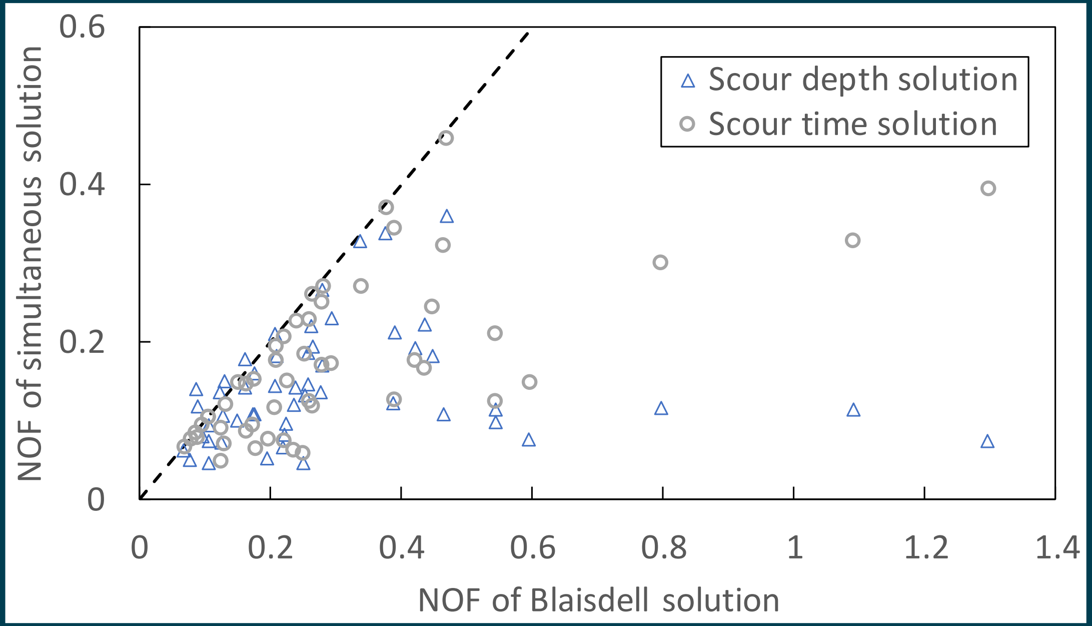
- Adjusted R^2 allows fair comparison of
  models with more/less parameters.
  Values near 1.0 indicate good fit.

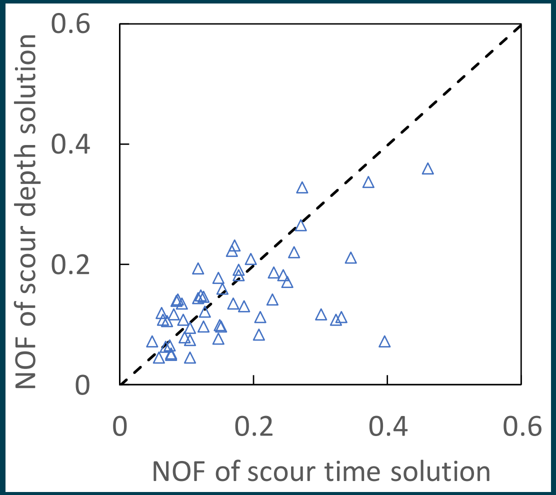
$$R_{adj}^2 = 1 - (1 - R^2)\frac{N - 1}{N - p - 1}$$

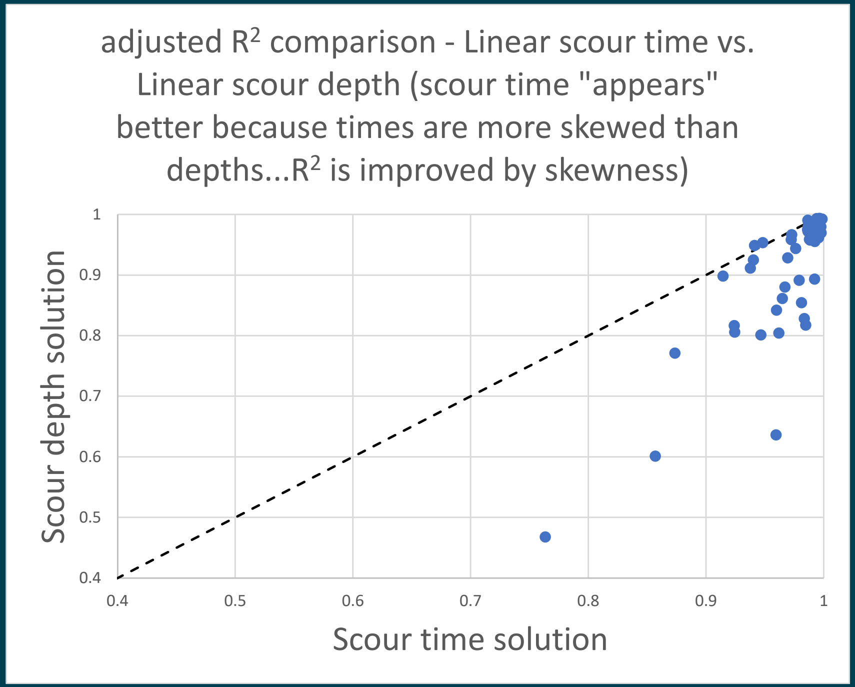
Methods based on Linear Excess Stress Eq’n



Linear excess stress - methods based on accumulated scour (as opposed to erosion rate)





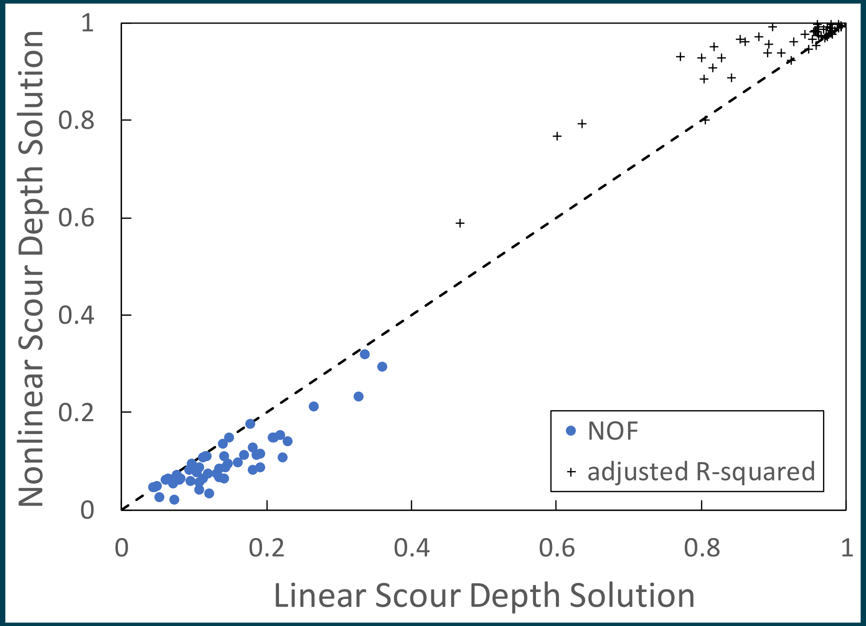


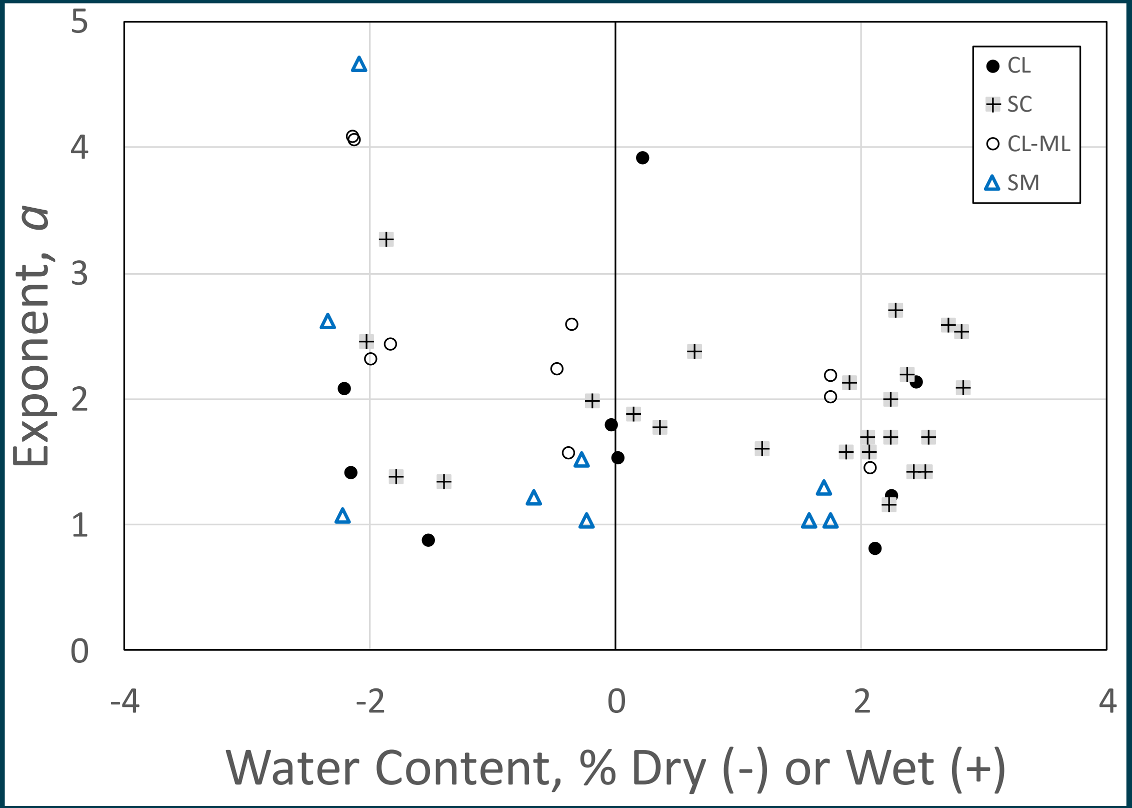
- Blaisdell solution inferior to methods that solve simultaneously for τ_c-k_d
- Scour depth appears to be better than scour time solution

Nonlinear Excess Stress

$$\varepsilon_r = k_d(\tau - \tau_c)^a$$

- Obviously better fits, but are they meaningful?

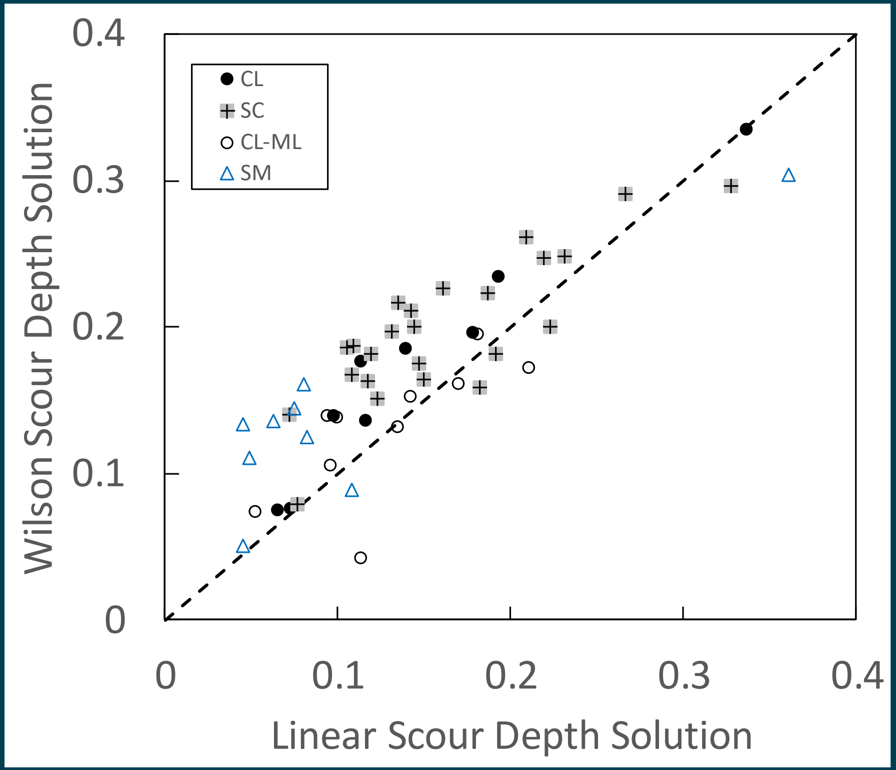


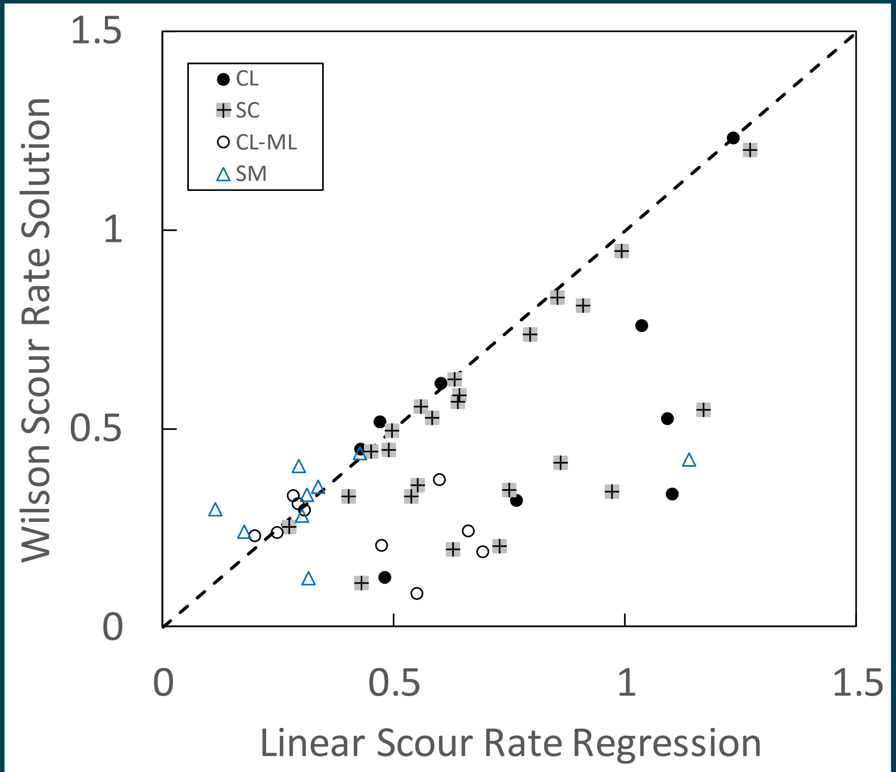


Note here that exponent is almost always > 1

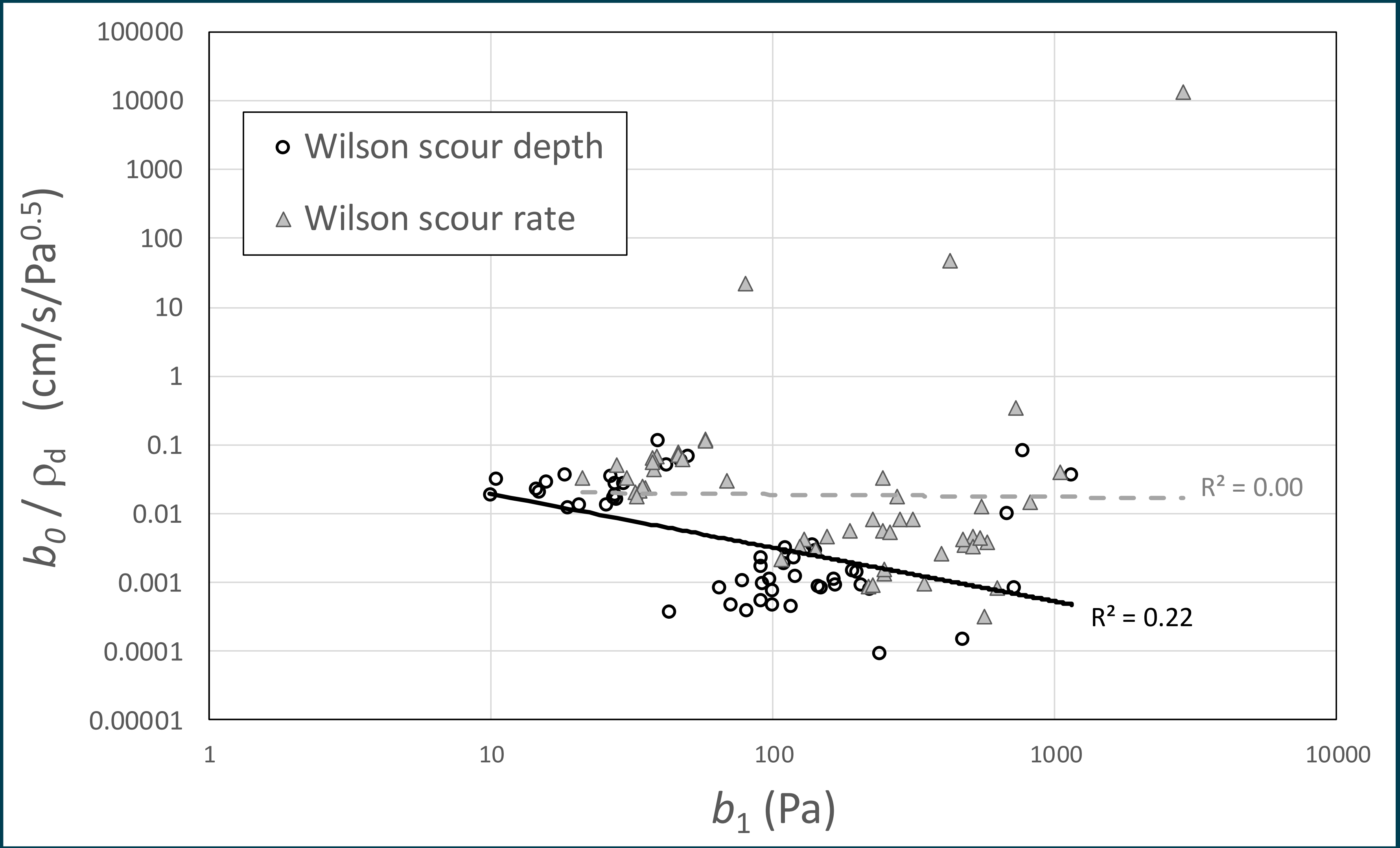
Wilson model

- Scour depth solution did do as well as linear excess stress model
- Scour rate solution appears better, but is it meaningful?



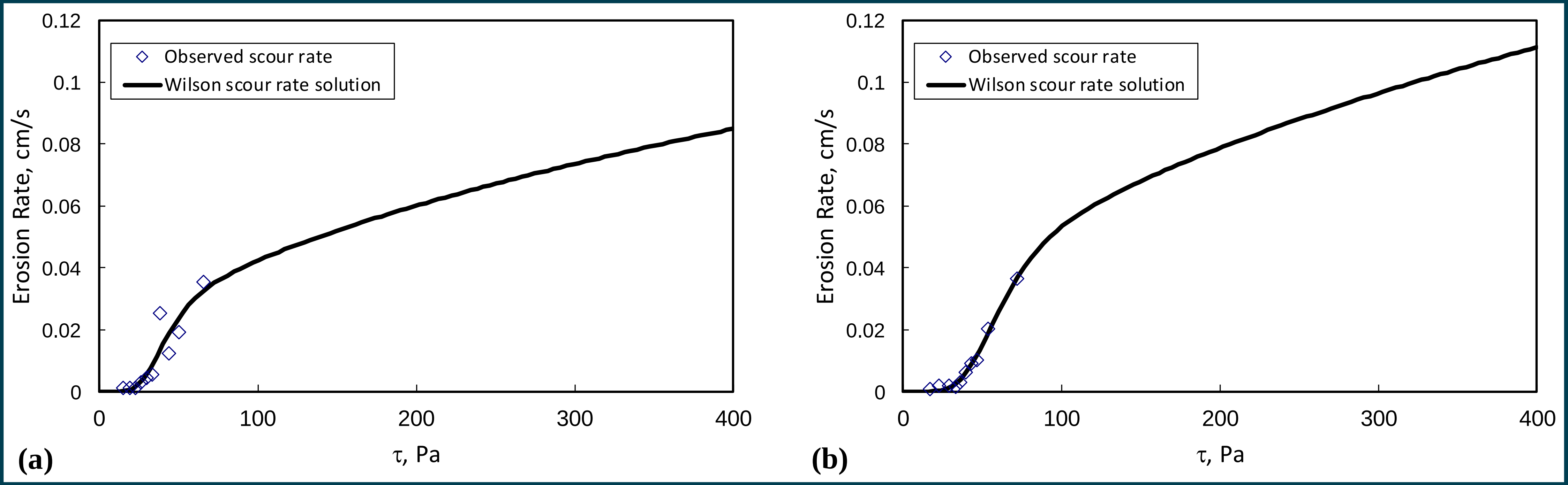


Little relation between rate parameter and erosion threshold parameter



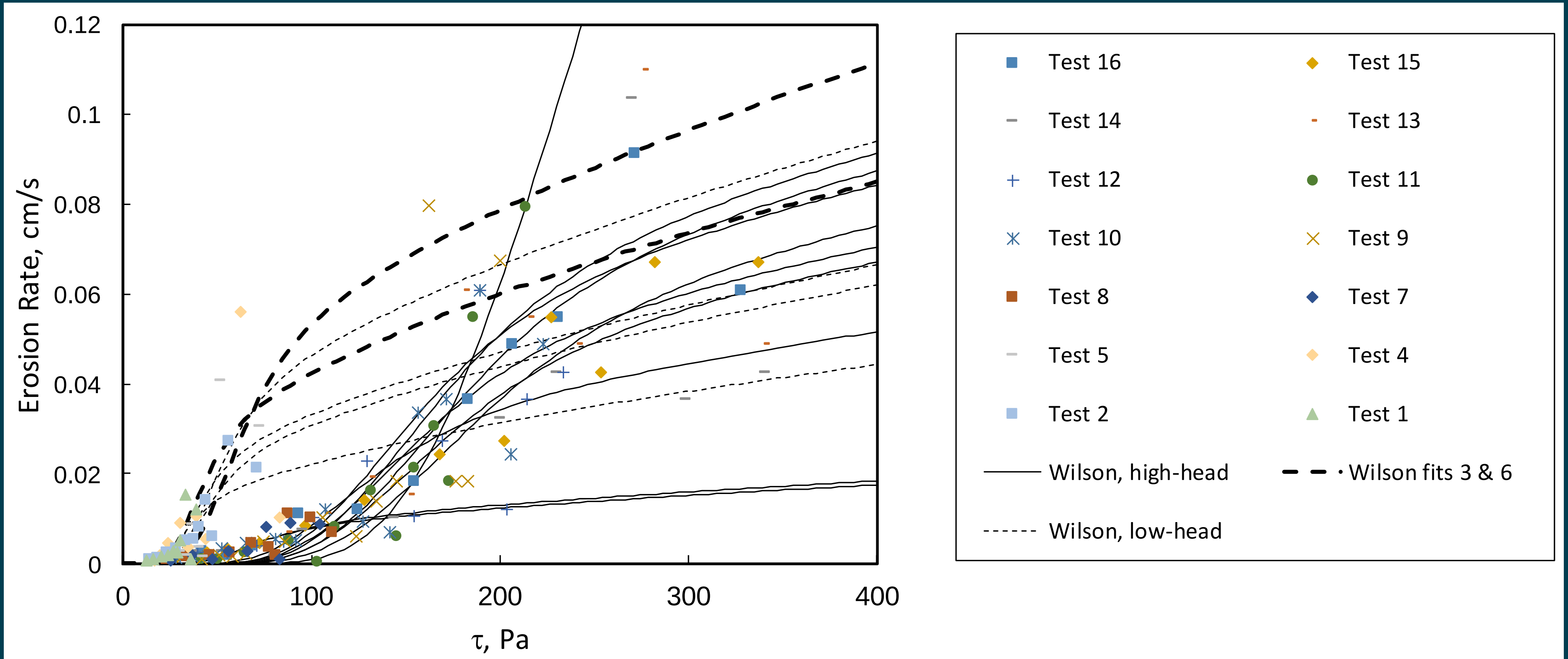
Wilson model

- Great fits to Wilson model don't include any data defining the final region (high stress area where we should see $\varepsilon_r \propto \sqrt{\tau}$)



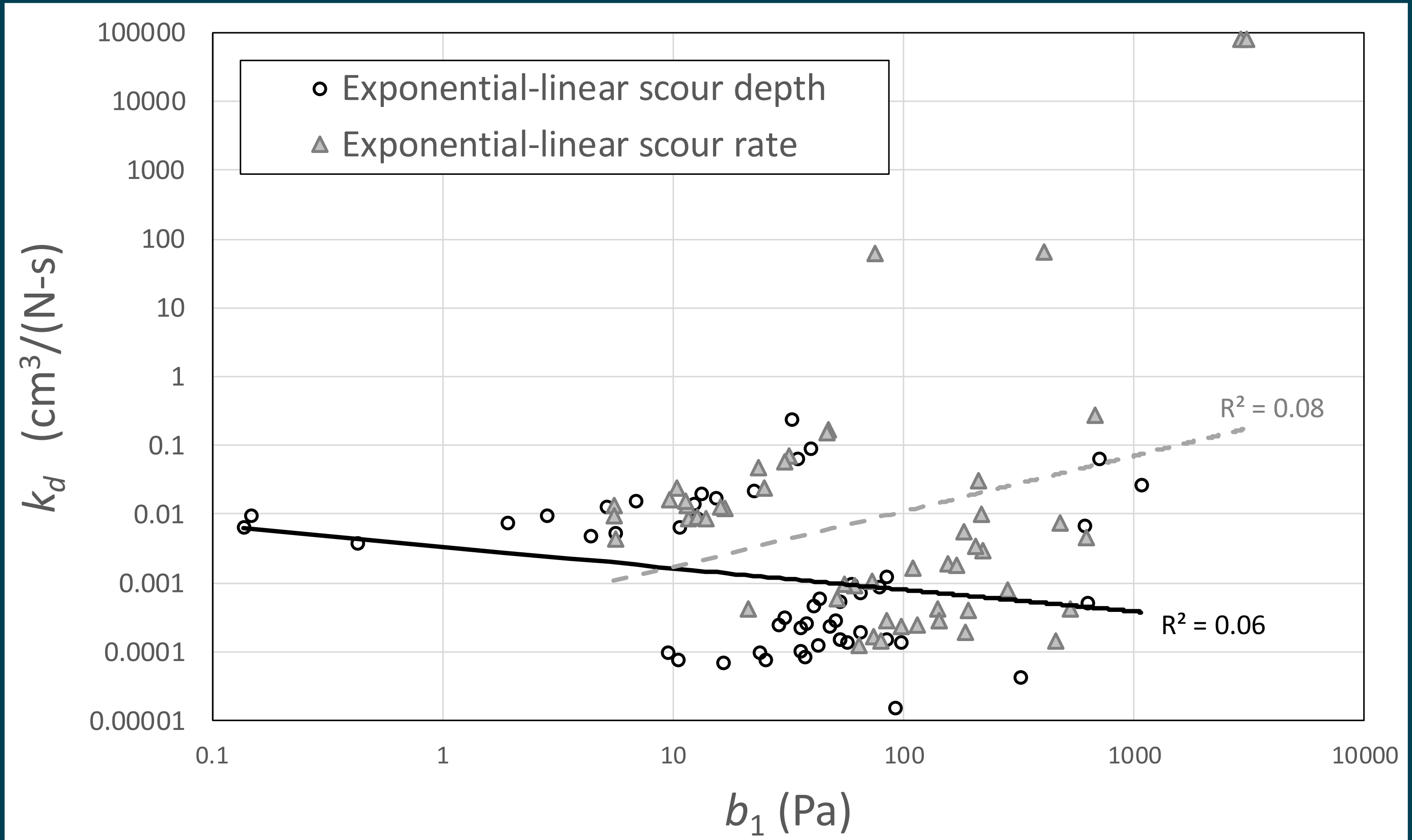
Running higher heads does not define final region either, but erosion behavior does change

Running tests at appropriate head is important!



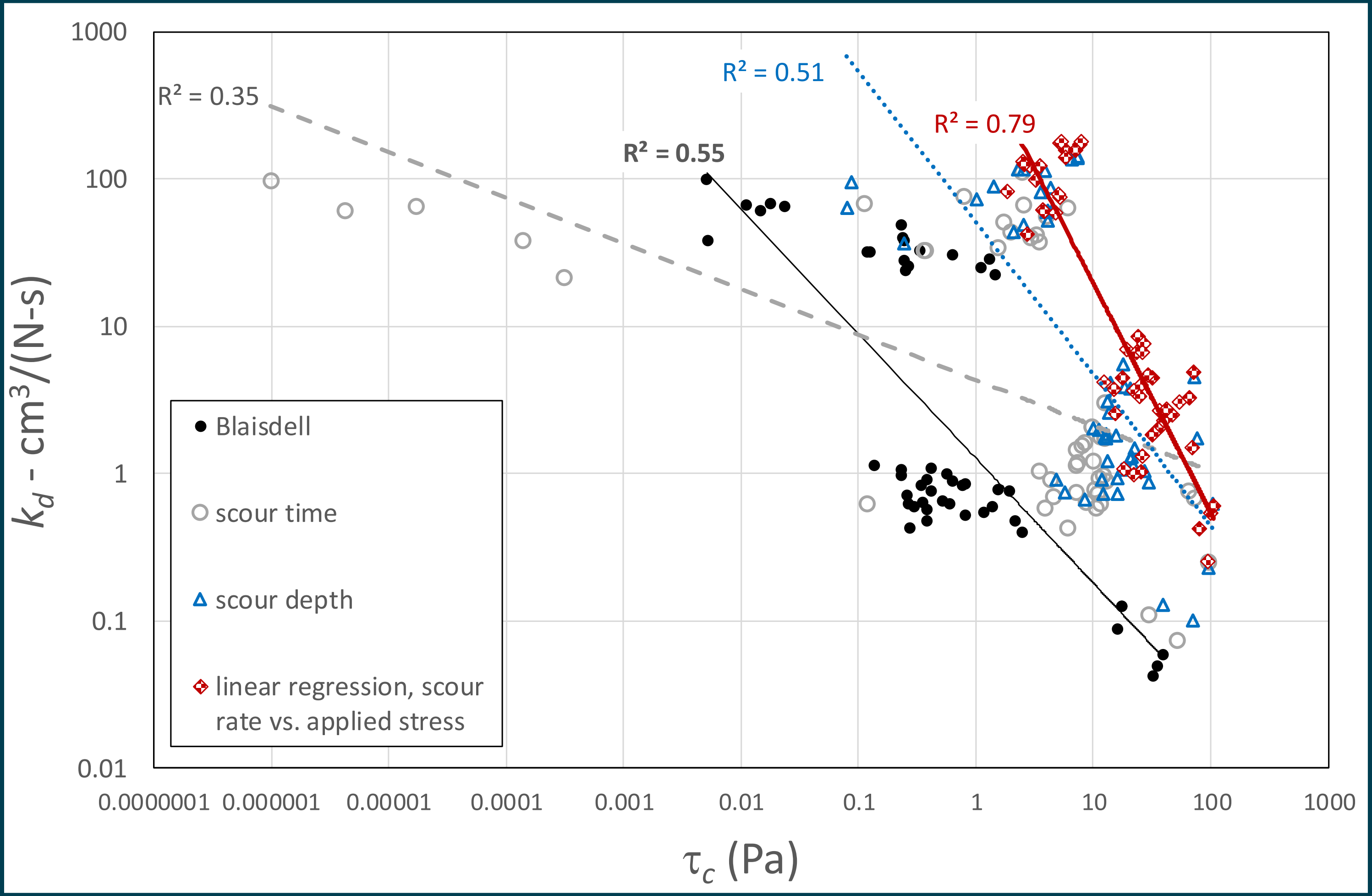
Exponential-Linear Model

No correlation of rate parameter and erosion threshold parameter



Fundamental tenet of erosion behavior is that rate of erosion and threshold stress should be correlated.

Linear regression of scour rates achieves that best.



Conclusions

- Nonlinear models produce occasional great fits to individual tests, but looking at the big picture, they are often achieving this by overfitting their nonlinear shape to noise in the data
- Linear models are more consistent and useful
- Several methods are superior to Blaisdell method for…
  - Fitting to individual tests
  - Correlation of k_d & τ_c across multiple tests
- Linear regression of scour rates is most consistent, but…
  - Existing classification schemes and application models were developed in era when Blaisdell method was the de facto standard
  - Models may be unintentionally calibrated to Blaisdell method

ASTM Standard

- I am working with a USBR retiree from our soils lab (Jeff Farrar) to get a new standard in place
  - Original JET
  - Mini JET
  - Data analysis methods in an appendix

Stability of RCC Crest Caps

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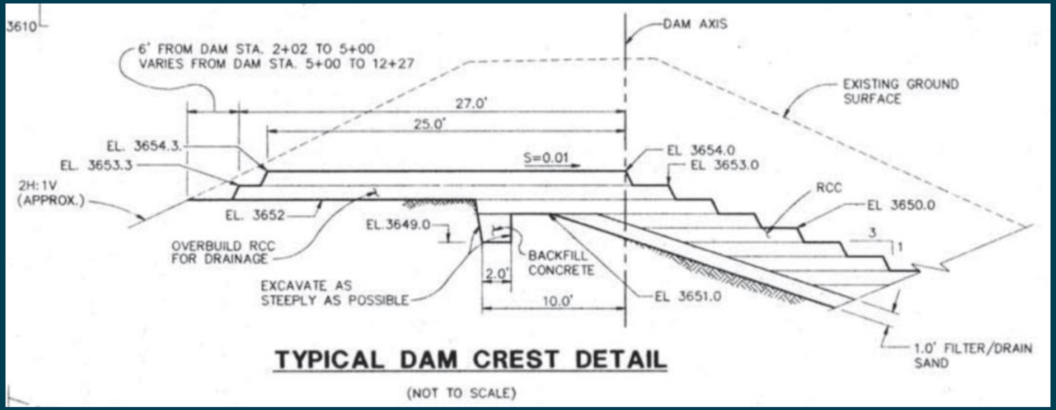
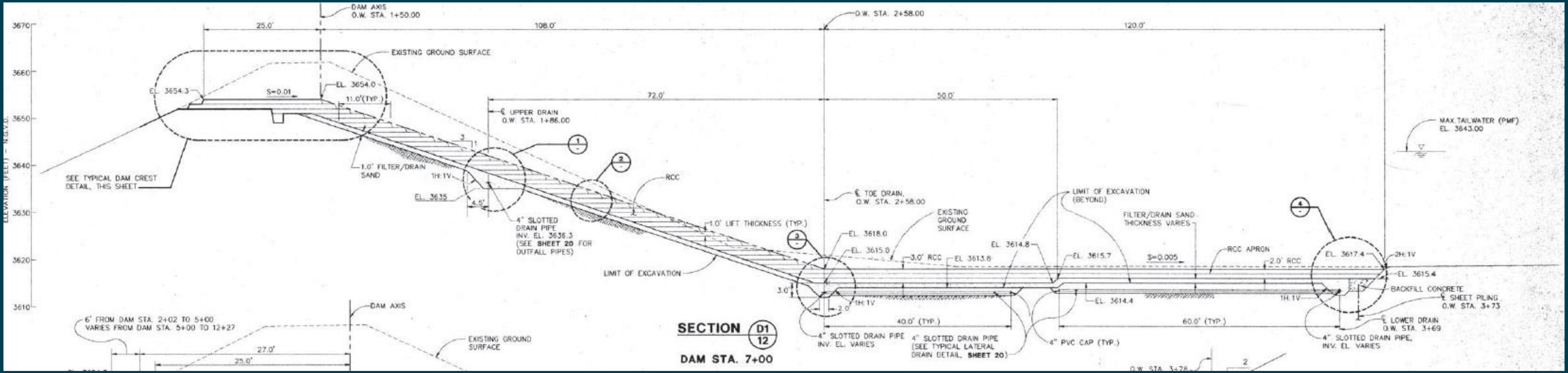
RCC Overlay of embankment dam ~ 1993





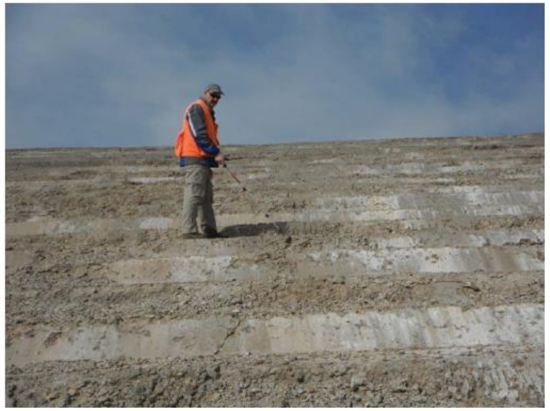
Issues

- Overlay deteriorating (cracks, freeze/thaw)
- Lifts at crest may be poorly bonded to those below
- Concern for sliding of top lifts in overtopping event
- Analytical evaluations and CFD studies have produced wide-ranging estimates of failure probability

13. Transverse crack (foreground) in dam crest at STA 6+50 in foreground, looking left. Longitudinal crack extends from transverse crack about 20 feet to left. Top lift is unbonded left of transverse crack and downstream of longitudinal crack.

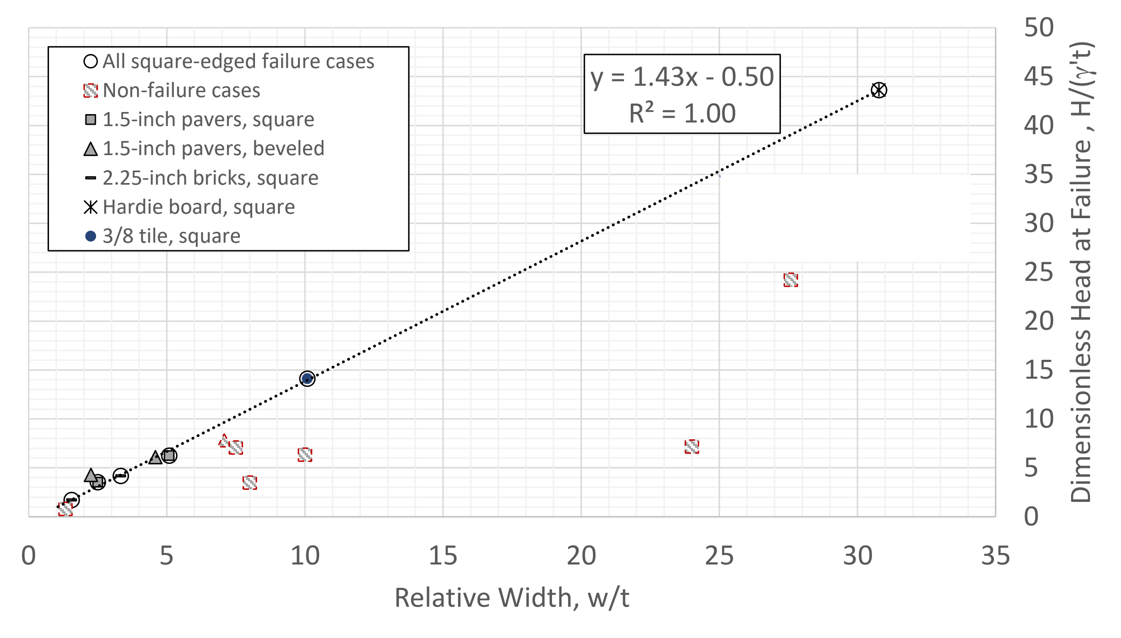
14. Longitudinal crack in dam crest near STA 8+50 and B-103, looking right from STA 8+60. This crack is about 0.25 to 0.5 inches wide and 25 feet long.

15. Downstream slope, looking left from near STA 7+50.



16. Downstream slope near STA 6+50, looking upstream. Note typical transverse crack.


t
w
H


All square-edged failure cases
Non-failure cases
1.5-inch pavers, square
1.5-inch pavers, beveled
2.25-inch bricks, square
Hardie board, square
3/8 tile, square
y = 1.43x - 0.50
R^2 = 1.00
0 5 10 15 20 25 30 35
Relative Width, w/t
0 5 10 15 20 25 30 35 40 45 50
Dimensionless Head at Failure , H/(γ't)

Plan

- M.S. student who will intern with us this summer is going to run careful tests at larger scale