BET - BOREHOLE EROSION TEST

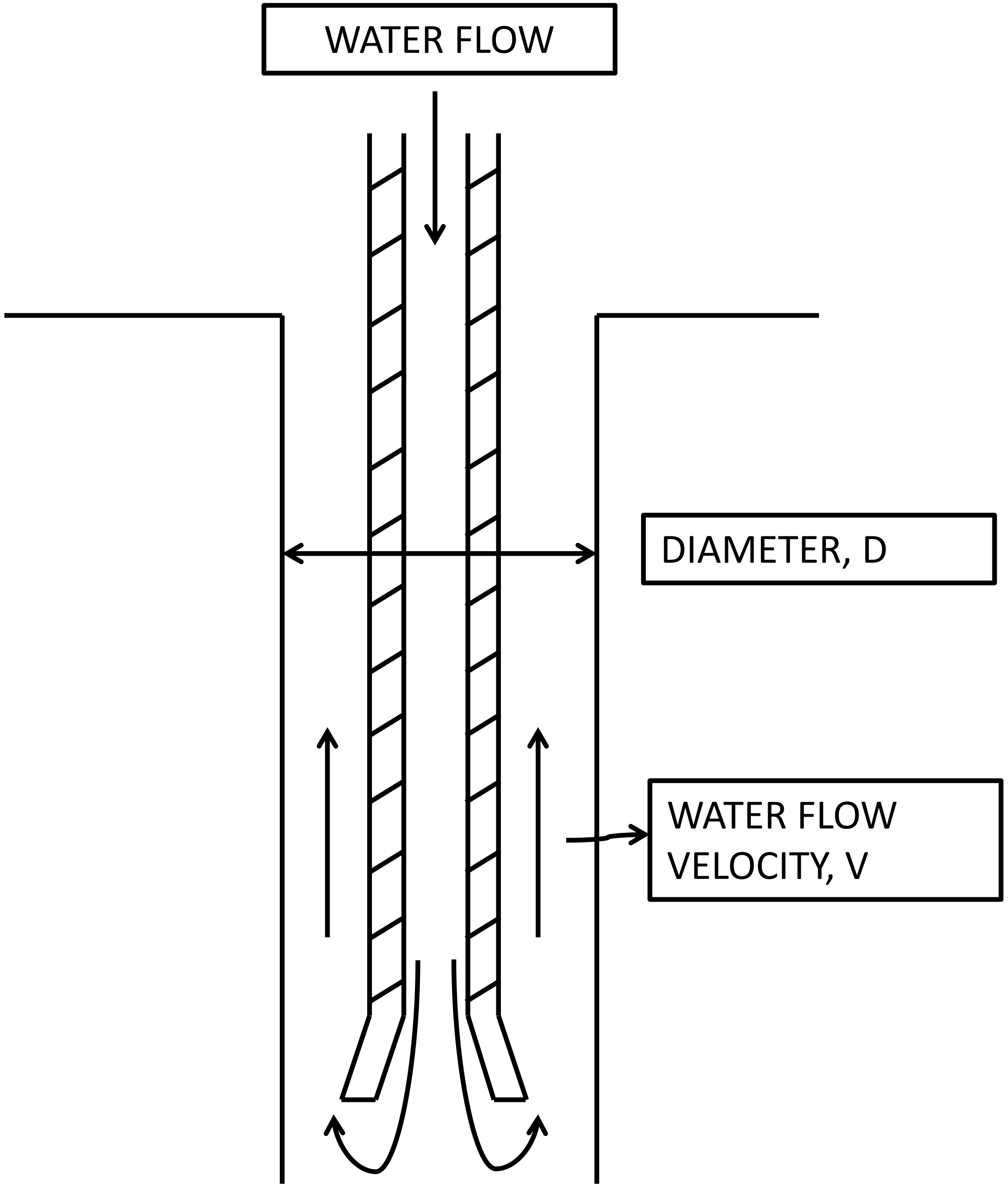
Procedure, Equipment, Data Reduction and Some Test Results

Jean-Louis BRIAUD

Distinguished Professor, Texas A&M Univ., USA
President of ISSMGE (2009-2013)
President of ASCE (2020-2021)

BOREHOLE EROSION TEST

- Invented in 2014
- Briaud J.-L., Chedid M., Chen H.C., Shidlovskaya A., 2017, “The Borehole Erosion Test”, Journal of Geotechnical and Geoenvironmental Engineering, Vol 143, Issue 8, ASCE.
- Shidlovskaya A., Bahmani, Briaud J.-L., Chen H.-C., 2023, “Improvements in Test Procedure And Data Reduction For The Borehole Erosion Test”, Geotechnical Testing Journal Vol. 46, No. 2 (March/April 2023): 295–315, ASTM.


WATER FLOW
DIAMETER, D
WATER FLOW
VELOCITY, V

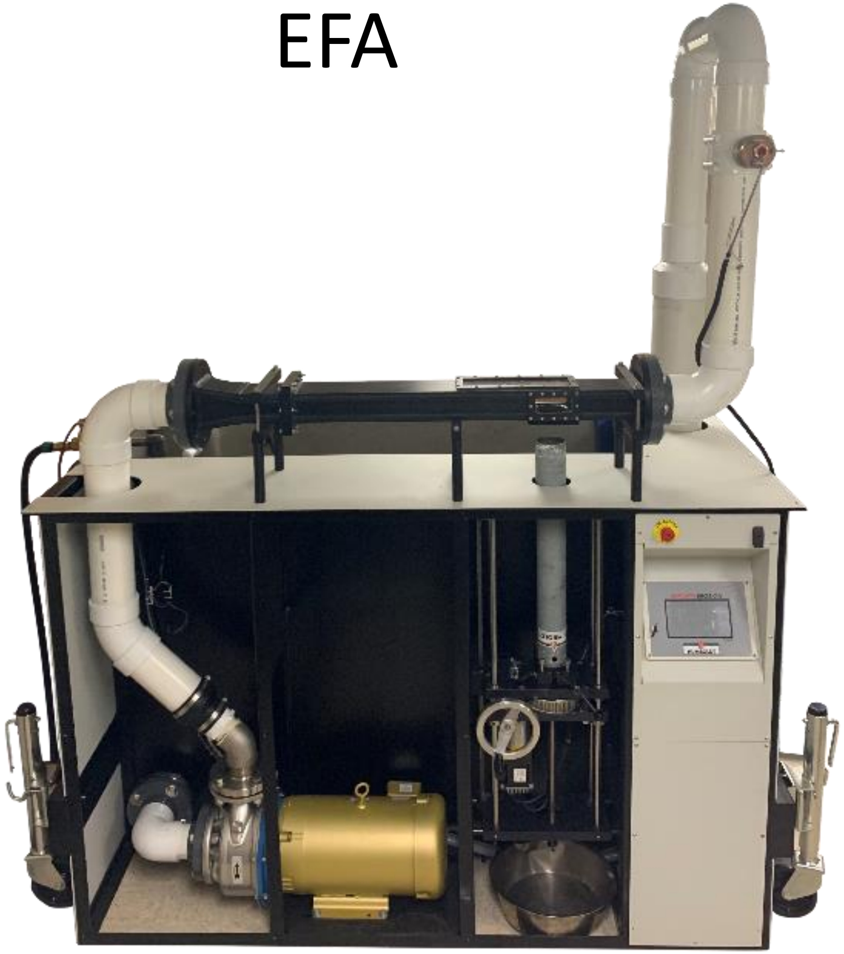

SENSUS
GALLONS


USGS
RESEARCH DRILLING

BET

PET

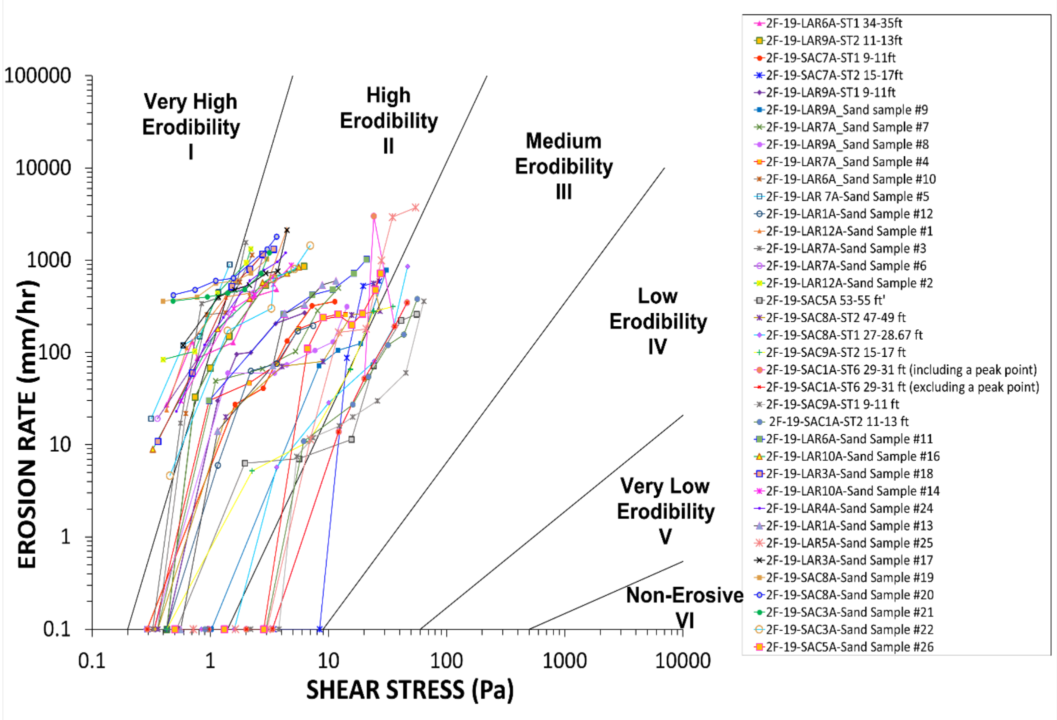
EFA



TESTING PROCEDURE

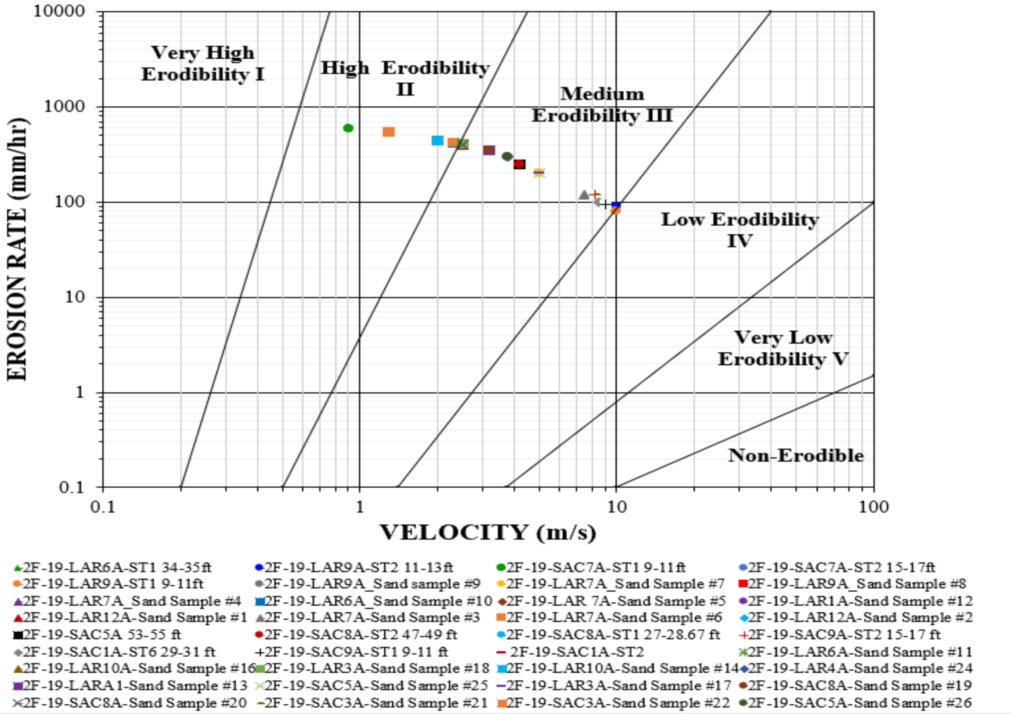
1. Drill a borehole ($OD_{rod} < 0.75 \times OD_{drill\ bit}$)
2. Remove the drilling equipment
3. Insert a mechanical caliper to the bottom of the hole.
4. Pull the caliper up the hole recording the borehole diameter (repeat this process) – BOREHOLE DIAMETER PROFILE BEFORE FLOW
5. Insert the drilling rods (no bit) and start the flow at a chosen velocity
6. Maintain the flow for 10 minutes at least and record the flow as a function of time.
7. Remove the drilling rods
8. Insert the caliper and repeat step 4. BOREHOLE DIAMETER PROFILE AFTER FLOW
9. Repeat steps 5 to 8 at different velocities as desired
10. Reduce the data

EFA



EROSION RATE (mm/hr)
100000
10000
1000
100
10
1
0.1
SHEAR STRESS (Pa)
0.1
1
10
100
1000
10000
Very High Erodibility I
High Erodibility II
Medium Erodibility III
Low Erodibility IV
Very Low Erodibility V
Non-Erosive VI
2F-19-LAR6A-ST1 34-35ft
2F-19-LAR9A-ST2 11-13ft
2F-19-SAC7A-ST1 9-11ft
2F-19-SAC7A-ST2 15-17ft
2F-19-LAR9A-ST1 9-11ft
2F-19-LAR9A_Sand sample #9
2F-19-LAR7A_Sand Sample #7
2F-19-LAR9A_Sand Sample #8
2F-19-LAR7A_Sand Sample #4
2F-19-LAR6A_Sand Sample #10
2F-19-LAR 7A-Sand Sample #5
2F-19-LAR1A-Sand Sample #12
2F-19-LAR12A-Sand Sample #1
2F-19-LAR7A-Sand Sample #3
2F-19-LAR7A-Sand Sample #6
2F-19-LAR12A-Sand Sample #2
2F-19-SAC5A 53-55 ft'
2F-19-SAC8A-ST2 47-49 ft
2F-19-SAC8A-ST1 27-28.67 ft
2F-19-SAC9A-ST2 15-17 ft
2F-19-SAC1A-ST6 29-31 ft (including a peak point)
2F-19-SAC1A-ST6 29-31 ft (excluding a peak point)
2F-19-SAC9A-ST1 9-11 ft
2F-19-SAC1A-ST2 11-13 ft
2F-19-LAR6A-Sand Sample #11
2F-19-LAR10A-Sand Sample #16
2F-19-LAR3A-Sand Sample #18
2F-19-LAR10A-Sand Sample #14
2F-19-LAR4A-Sand Sample #24
2F-19-LAR1A-Sand Sample #13
2F-19-LAR5A-Sand Sample #25
2F-19-LAR3A-Sand Sample #17
2F-19-SAC8A-Sand Sample #19
2F-19-SAC8A-Sand Sample #20
2F-19-SAC3A-Sand Sample #21
2F-19-SAC3A-Sand Sample #22
2F-19-SAC5A-Sand Sample #26

PET



EROSION RATE (mm/hr)
10000
1000
100
10
1
0.1
VELOCITY (m/s)
0.1
1
10
100
Very High Erodibility I
High Erodibility II
Medium Erodibility III
Low Erodibility IV
Very Low Erodibility V
Non-Erodible
2F-19-LAR6A-ST1 34-35ft
2F-19-LAR9A-ST2 11-13ft
2F-19-SAC7A-ST1 9-11ft
2F-19-SAC7A-ST2 15-17ft
2F-19-LAR9A-ST1 9-11ft
2F-19-LAR9A_Sand sample #9
2F-19-LAR7A_Sand Sample #7
2F-19-LAR9A_Sand Sample #8
2F-19-LAR7A_Sand Sample #4
2F-19-LAR6A_Sand Sample #10
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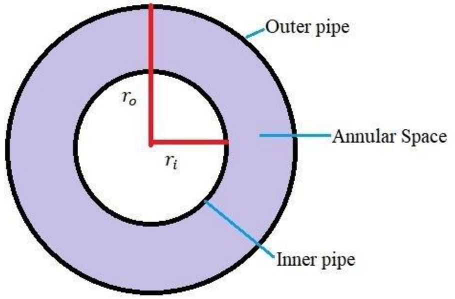
2F-19-LARA1-Sand Sample #13
2F-19-SAC5A-Sand Sample #25
2F-19-LAR3A-Sand Sample #17
2F-19-SAC8A-Sand Sample #19
2F-19-SAC8A-Sand Sample #20
2F-19-SAC3A-Sand Sample #21
2F-19-SAC3A-Sand Sample #22
2F-19-SAC5A-Sand Sample #26

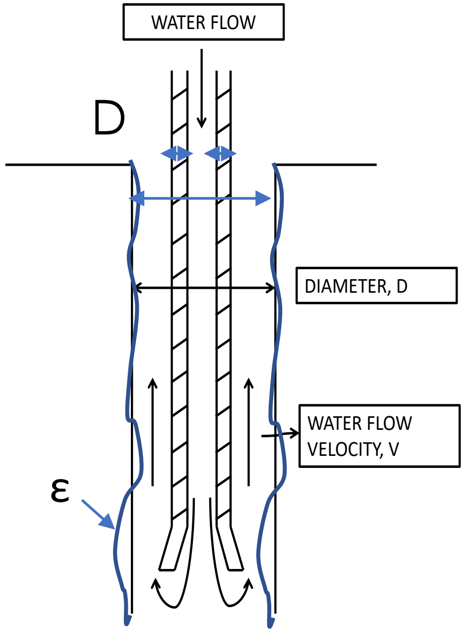
Getting the BET shear stress

The hydraulic shear stress at the water soil interface (Munson, 2005):

$$\tau = \frac{1}{8} f \rho V^2$$

f = friction factor, depends on ε/D_h and Reynolds number Re
ρ = density of water
V = mean flow velocity (m/s)





Step a. Obtain Reynolds number Re:

$$\mathrm{Re} = \frac{V D_h}{\nu}$$

ν = kinematic viscosity of a fluid, 10^{-6} m²/s at 20°C
D_h = hydraulic diameter of the annulus space between the rods and the borehole wall

Step b. Calculate hydraulic diameter D_h of the annulus space:

$$D_h = \frac{4\ \textit{cross sectional area of flow}}{\textit{wetted perimeter}} = Do - Di$$

D_o = outer diameter (borehole)
D_i = inner diameter (rods)

Step c. Obtain friction factor for the circular pipe (Moody chart):

$$\frac{1}{\sqrt{f}} = -1.8 \log\left[\left(\frac{\varepsilon/Dh}{3.7}\right)^{1.11} + \frac{6.9}{Re}\right]$$

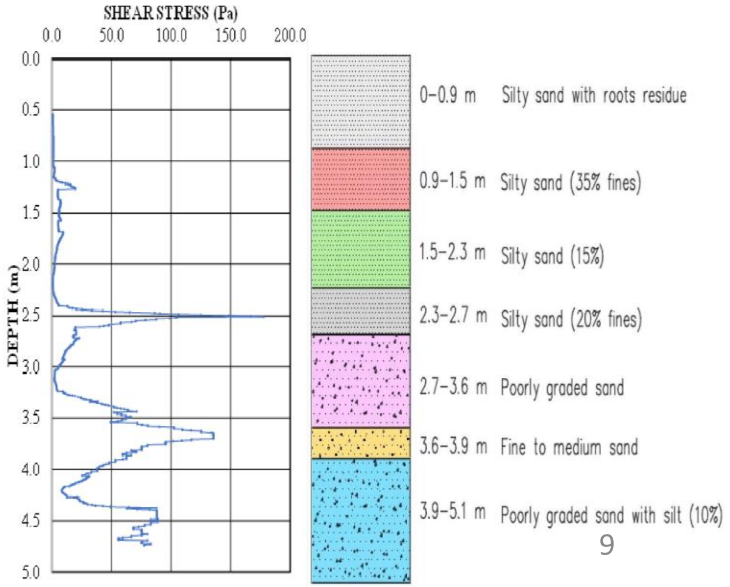
(Haaland, 1983)

ε = roughness depth
ε/Dh = relative roughness

Step d. Correct friction factor

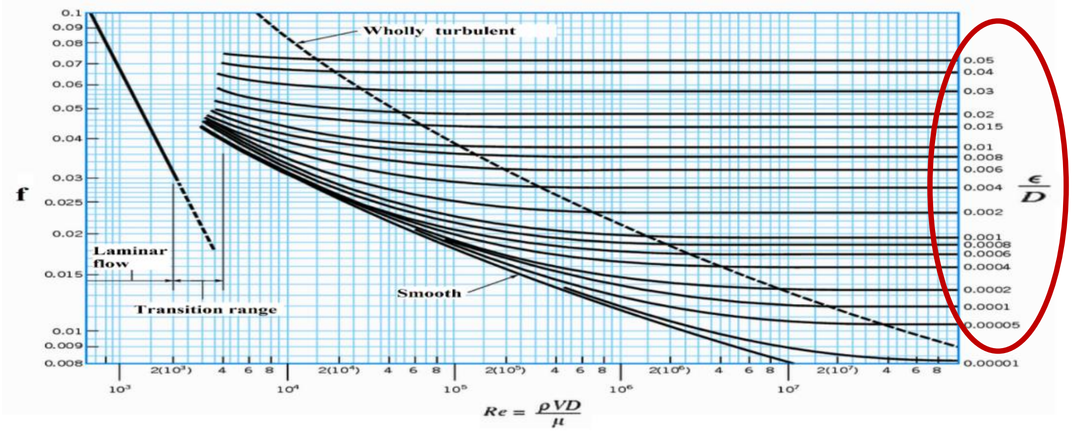
$$f_{annulus} = 1.5 f_{pipe}$$

(Munson, 2009)

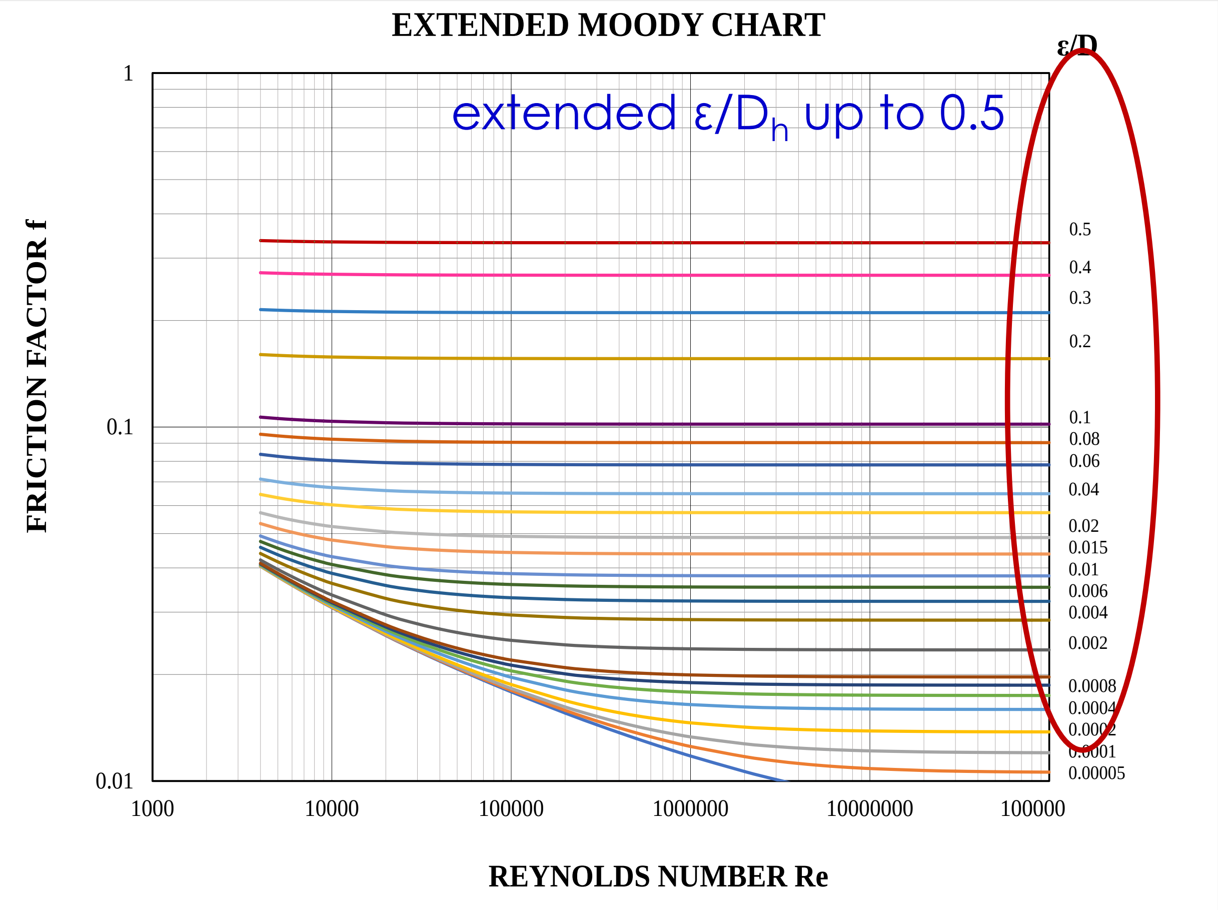


Extend Moody chart to very rough surfaces (for relative roughness ε/D > 0.05).

max ε/D_h=0.05



Moody chart (1944) for rough pipes



Extended Moody chart (Moody 1944; modified by Briaud and Shidlovskaya 2019) for very rough soil surfaces

Detailed data reduction procedure for the BET.

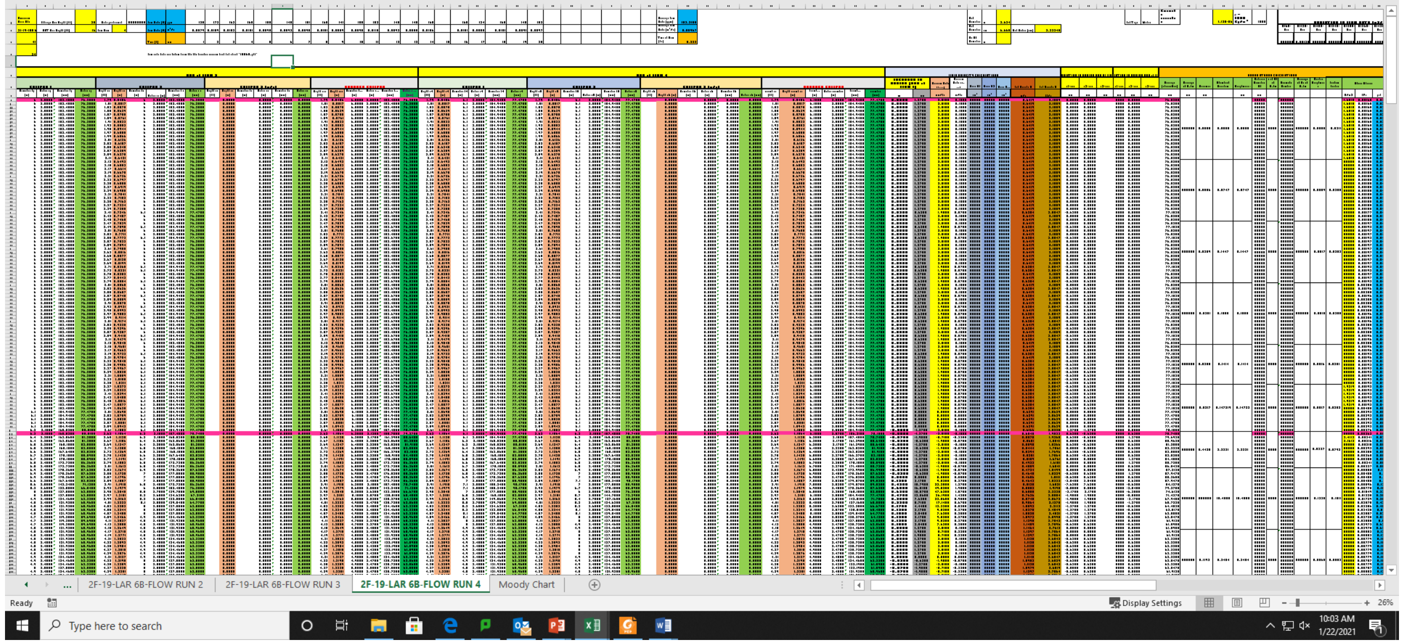
1. Input the field data which includes the site location, the site elevation, the borehole number, the depths at which the caliper reading are taken, the corresponding borehole diameter (caliper reading), the flow rate as a function of time, the time duration of the flow, and the outside radius of the rods.
2. Calculate the average radius versus depth profile for the borehole before any flow takes place. This requires making an average at any depth of the caliper diameter measurements recorded right after drilling the borehole. The radius is used because the erosion rate is the increase in radius divided by the elapsed time of flow. Indeed, several caliper diameter profiles are often recorded in the same borehole.
3. Calculate the average radius versus depth profile for the borehole after the first 10 minutes of flow. This requires making an average at any depth of the caliper diameter measurements recorded right after the 10 minutes of flow. Indeed, several caliper diameter profiles are often recorded in the same borehole.
4. Calculate the difference in radius between the profiles of step 1 and step 2 and record it as the radial erosion increment as a function of depth.
5. Calculate the erosion rate at any depth by dividing the radial erosion increment by the duration of the flow (~10 minutes). This gives the erosion rate profile for the first flow velocity.
6. Repeat steps 2 to 5 for the other chosen flow rates.
7. During the first flow rate application, the flow rate varies somewhat, and an average value must be calculated. Calculate the average flow rate for the duration of the flow (~10 minutes).
8. Repeat step 7 for all flow rates applied during the BET.
9. For each one of the flow rates, calculate the associated velocity by dividing the flow rate by the area available for the water to flow. This area varies with depth and is taken as the area of the annulus between the outside diameter of the rods and the diameter of the borehole at that depth. The diameter of the borehole at a given depth during the 10 minutes of flow is taken as the average of the annulus area before the flow start and after the flow stops. This step gives the velocity profile for the first average flow rate.

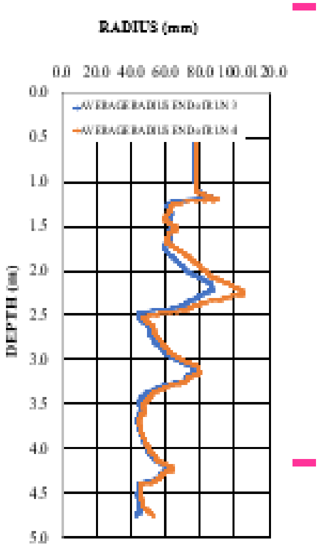
$$v = \frac{4Q}{\pi (R^2_{borehole} - R^2_{outsiderod})}$$

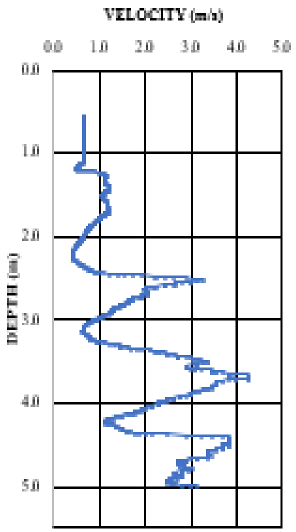
10. Repeat step 9 for all other flow rates.
11. Calculate the shear stress associated with the velocity as described in the following steps.
12. The equation to go from the velocity to the shear stress is $\tau = \frac{1}{8} f \rho v^2$ (Munson, 2009) where τ is the hydraulic shear stress at the water soil interface, f is the friction factor, ρ is the density of water (1000 kg/m^3), and v is the mean flow velocity (m/s). The friction factor f depends on the interface relative roughness ε/D_h and the Reynolds Number Re. The roughness ε is the mean depth of the asperities along the borehole wall. Note that the roughness of the outside wall of the pipe is much smoother and so would the associated shear stress but since the quantity of interest is the shear stress on the soil surface, the roughness of the soil surface is the one used here. The parameter D_h is the hydraulic diameter associated with the annulus between the outside diameter of the rods and the diameter of the borehole. The Reynolds Number Re is $\mathrm{Re} = \frac{VD_h}{\nu}$ where V is the velocity, D_h is the hydraulic diameter of the annulus space between the rods and the wall of the borehole and ν is the kinematic viscosity of water (10^{-6} m^2/s at 20°C). The parameter D_h for an annulus is given by $D_h = D_o - D_i$ where D_o is the outside diameter and D_i the inside diameter. At any depth, the outside diameter D_o is taken as the average of 2 times the borehole radius before the flow and 2 times the borehole radius after the flow. The inside diameter D_i is equal to 2 times the outside radius of the rods.
13. Moody (1944) developed a chart which gives the friction factor as a function of the relative roughness and the Reynolds Number (Fig. 4.1 and 4.2). This chart is for circular pipes and leads to the following equation proposed by Haaland (1983).

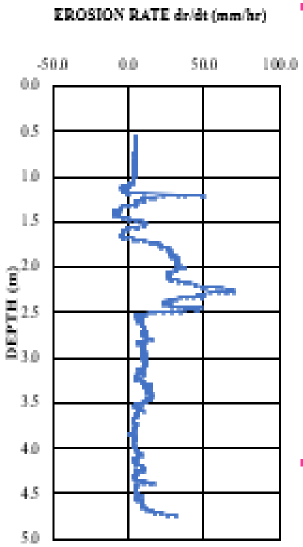
$$\frac{1}{\sqrt{f}} = -1.8 \log\left[\left(\frac{\varepsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}}\right]$$

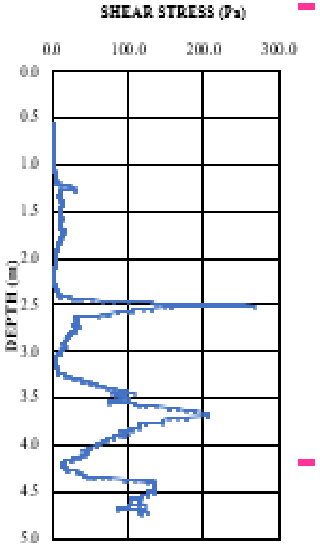
14. Applying this equation to pipes with an annulus cross section requires a modification of the value of f as follows (Munson, 2009): $f_{annulus} = 1.5 f_{pipe}$
15. The roughness ε is generated as a profile by considering a rolling depth equal to 0.1 m of the eroded radius profile and calculating for each one of those 0.1 m depth the mean depth of the asperities.
16. Now all the elements are set to calculate the shear stress from the velocity as follows. At any depth, obtain the velocity from step 9, then the fluid density, then the roughness, then the hydraulic diameter of the annulus, then Reynolds Number, then the friction factor, and then the hydraulic shear stress.
17. Prepare a profile of shear stress versus depth.
18. Use the profiles of erosion rate vs depth, velocity vs depth, and shear stress vs depth to generate for each stratigraphic layer the erosion functions of erosion rate vs velocity and erosion rate vs. shear stress.



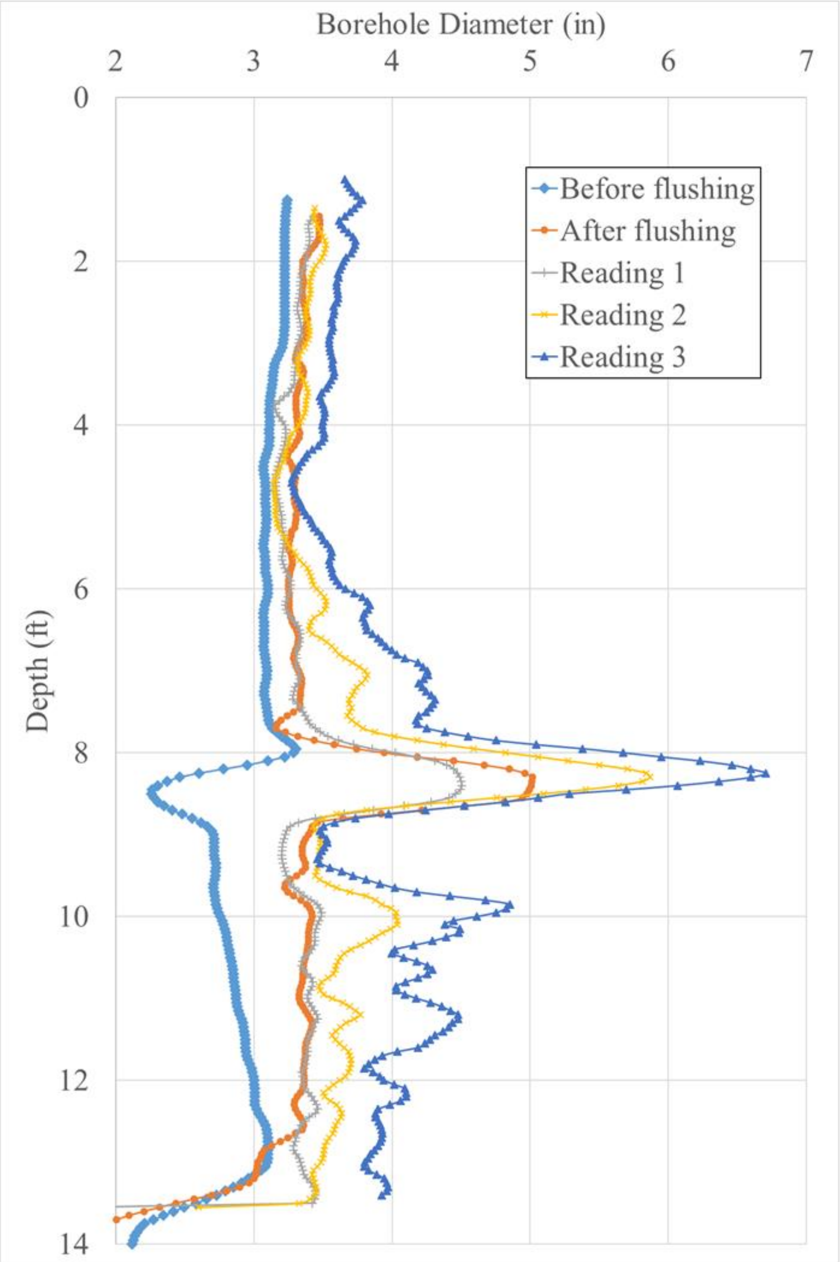


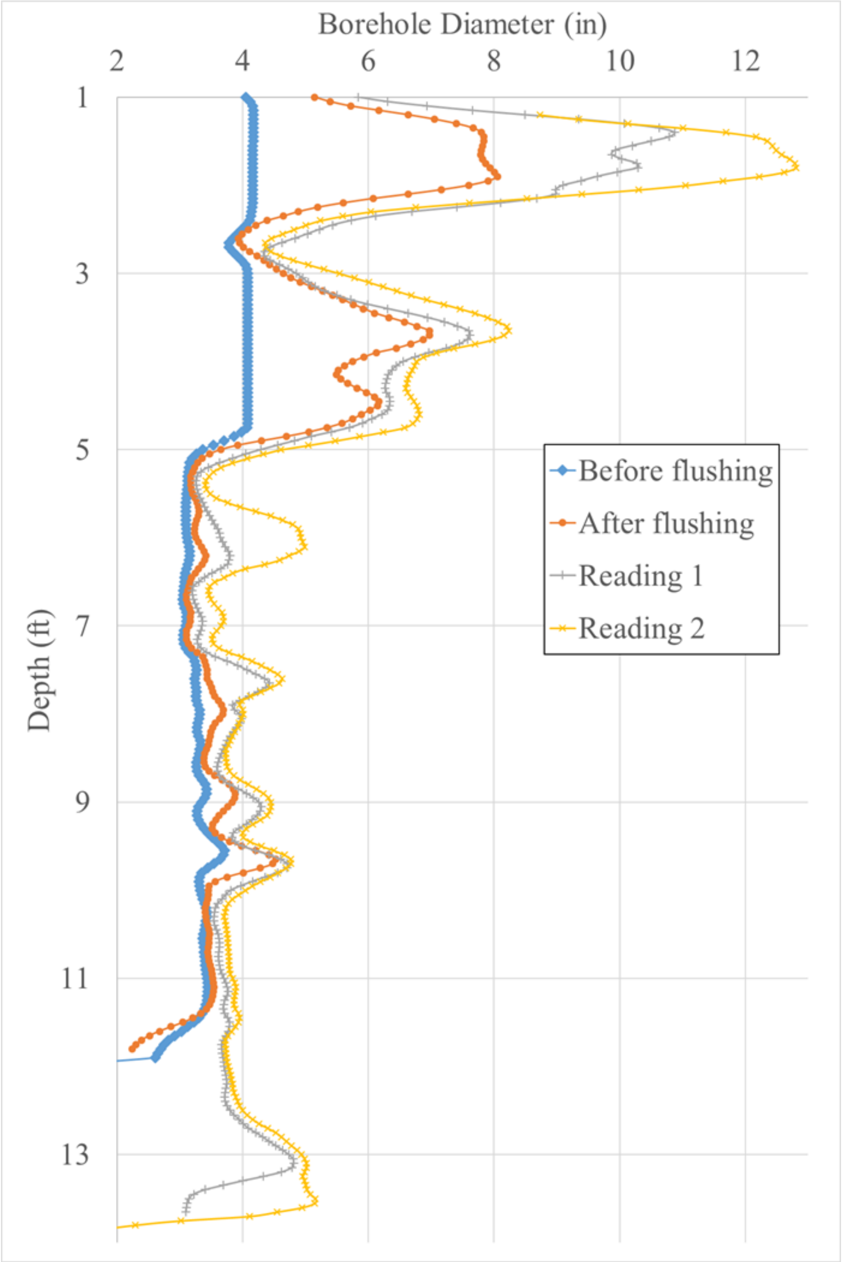






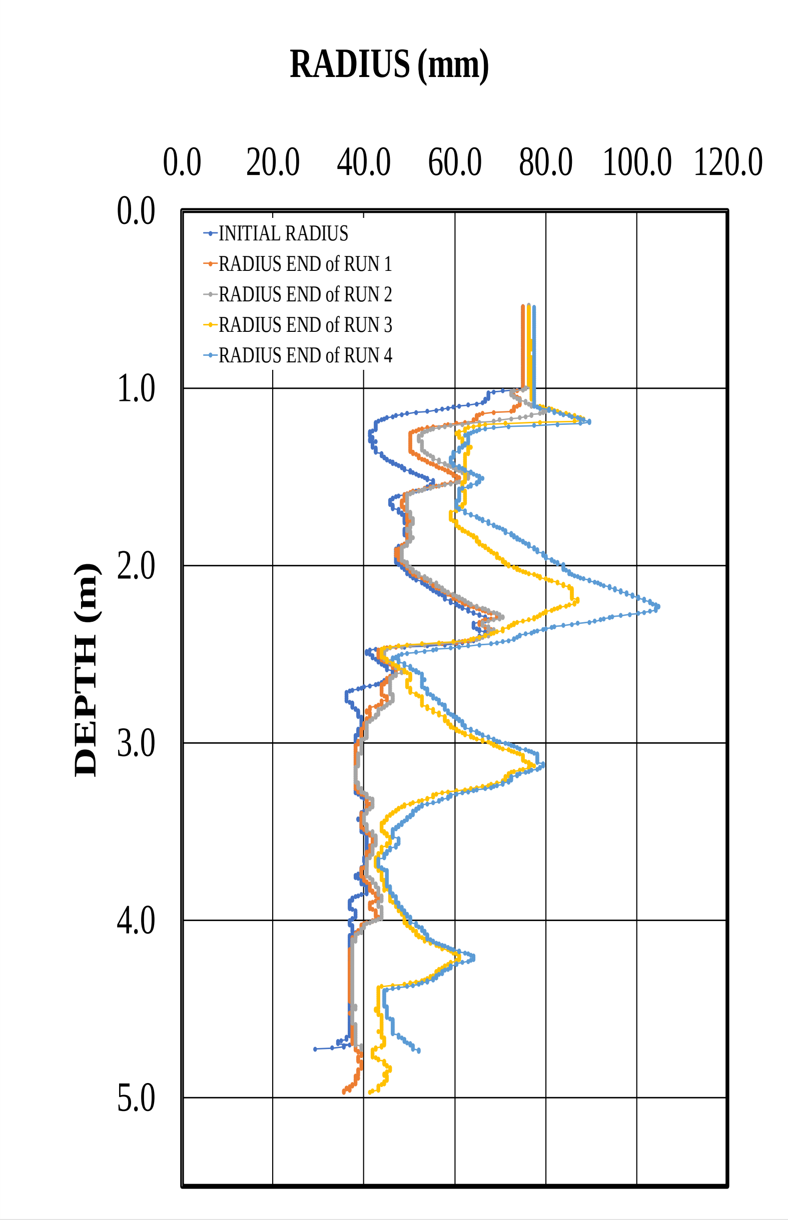
BOREHOLE EROSION TEST - BET

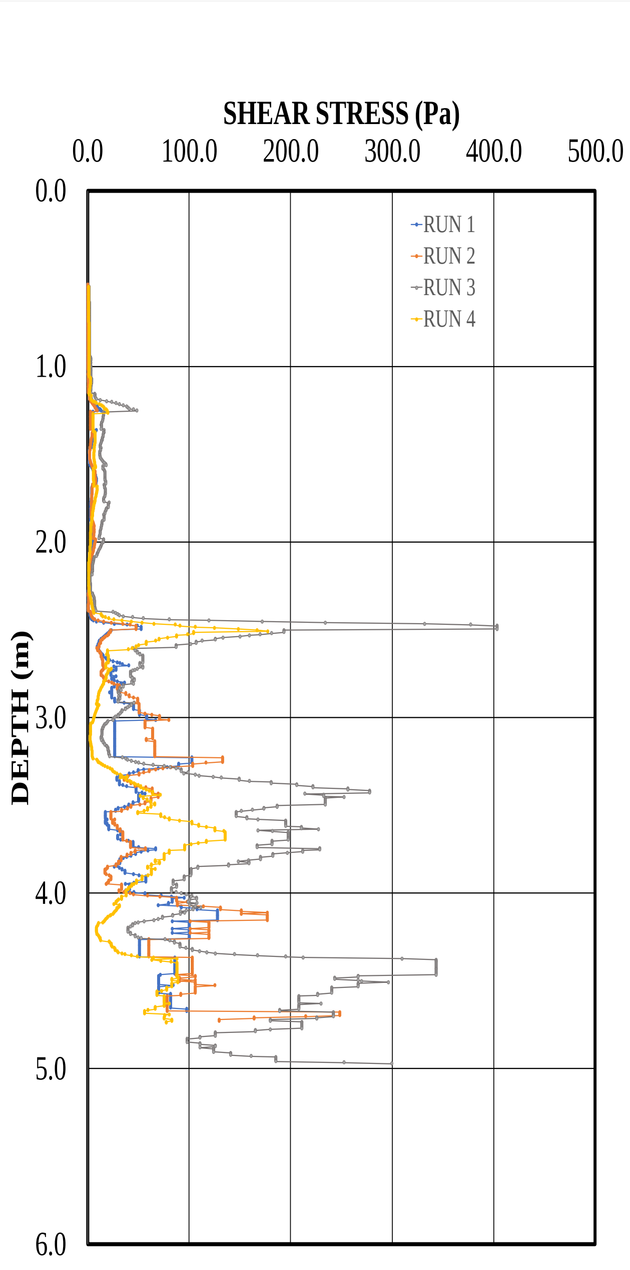


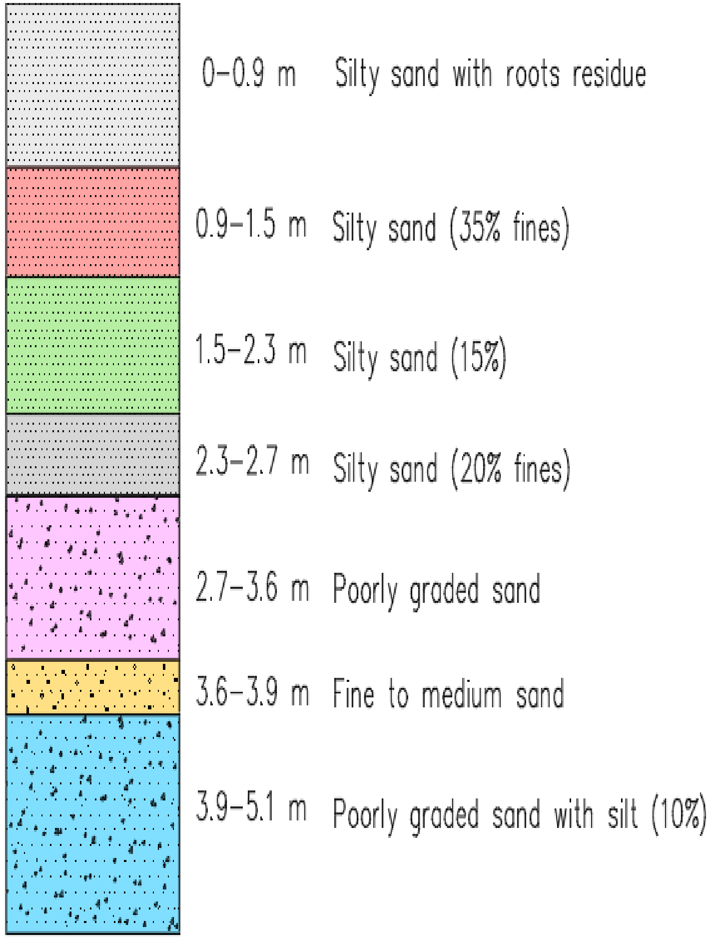


EXAMPLE OF BET RESULTS

Run 1 v = 1.71 m/s Run 2 v = 1.81 m/s, Run 3 v = 2.82 m/s, Run 4 v = 1.65m/s







Evaluating the BET precision

The BET precision: procedure

Variation in radius r:

- Consider two caliper reading profiles (radius r_1 and r_2 as a function of depth) recorded in the field within the same borehole at the end of a flow run.
- Calculate the average caliper reading profile as $r_{av} = 0.5(r_1 + r_2)$ as a function of depth.
- Calculate the differences Δr_1 and Δr_2 at any given depth between the radius given by each caliper reading (r_1 and r_2) and the average radius r_{av} calculated in step 2.
- Calculate the sum of the absolute values of the differences Δr_1 and Δr_2 over the borehole depth.
- The variation V_r is estimated as: $$V_r = \frac{\sum|\Delta r_1| + \sum|\Delta r_2|}{\sum(r_1 + r_2)}$$

Variation in flow rate Q(t):

- The difference between a flow value Q(t) and the average flow value Q_{av} is calculated for many time values, say every minute.
  - $\Delta Q(t) = Q(t) - Q_{av}$
- The variation is quantified by the ratio of the sum of the absolute values of ΔQ(t) over the sum of the flow values for all time values. $$V_Q = \frac{\sum|\Delta Q(t)|}{\sum Q(t)}$$

The BET precision Results:

- The out of roundness of the borehole - 0% to 11.91% with average 1.89%. $(\Delta r/r)_{av} = 1.89\%$.
- The flow variation during the "constant flow" - 2.12% to 34.78% with average 10.31%. $(\Delta Q/Q)_{av} = 10.31\%$

BET advantages and limitations.

Advantages

- ❑ Continuous profile of erodibility
- ❑ Commonly available equipment
- ❑ Calibration of laboratory data
- ❑ Calibration of numerical simulation
- ❑ Economically advantageous: $5,000-$6,000 per 10m borehole

Recommendations:

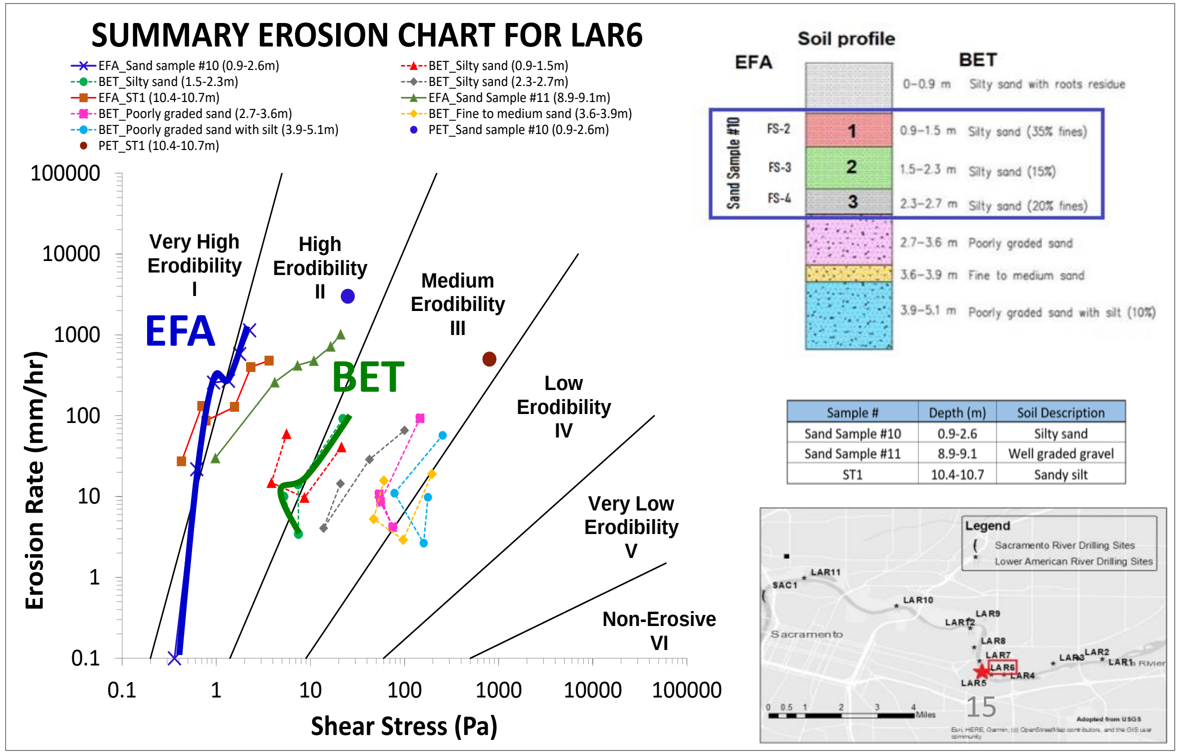
- ❑ Use BET in parallel with a few EFA tests
- ❑ Use BET to identify erodible layers
- ❑ Collect samples after inspection of profile

Limitations

- ❑ Precision less than laboratory
- ❑ Less erosion than EFA

$$\tau_c(BET) = 5.6\ \tau_c(EFA)$$

- ❑ Instability of the walls
- ❑ Water permeating walls



TAMU-Erosion Spreadsheet
1200 erosion tests & 1200 associated sets of soil properties

Part 1: Record Info.

Part 2: Erosion Info.

Part 3: Soil Properties Info.

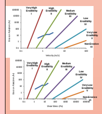
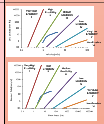
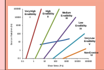
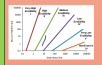
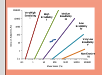
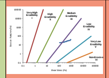
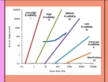
Section I

Section II

Part 1: Record Info.

Record Numer	Contact / Credit	Date conducted	Project title / Sponser	Sample Name	Sample Depth	Soil Type	USCS Classification	Natural / Manmade	Quality of the data (1-3)	Erosion Test Type
1	Dr. Brian Anderson/Auburn University, USA	4/15/2012	ALDOT	Buccatunna	-	CLAY	MH (Sandy Elastic Silt)	Natural	1	EFA
75	Dr. JL Briaud / TAMU, USA	7/12/2000	Yiwen Cao	Porcelain salinity\new-7-500-0-B	-	Clay		Natural	1	EFA
164	Kiseok / KICT, Korea	-	Kwangyang Area	Sample 1	-	Silt/CLAY	CL	Natural	1	EFA
167	Kornel Kerenyi / FHWA Hydraulic Lab, US	5/2/2013	??	1W156	-	Sandy silty clay	CL-ML	Manmade	1	ESTD
251	Stephane Bonelli / IRSTEA, France	21/12/00	UNCIV R-412	BDHET005	-	Clay	CH	Manmade	1	HET
308	Stephane Bonelli / IRSTEA, France	10/7/2001	UNCIV R-412	LDHET011	-	Clayey silty sand	SM	Manmade	1	HET
402	Stephane Bonelli / IRSTEA, France	12/9/2000	UNCIV R-412	FTDSET006	-	Sandy Clay	CL-CH	Manmade	1	SET

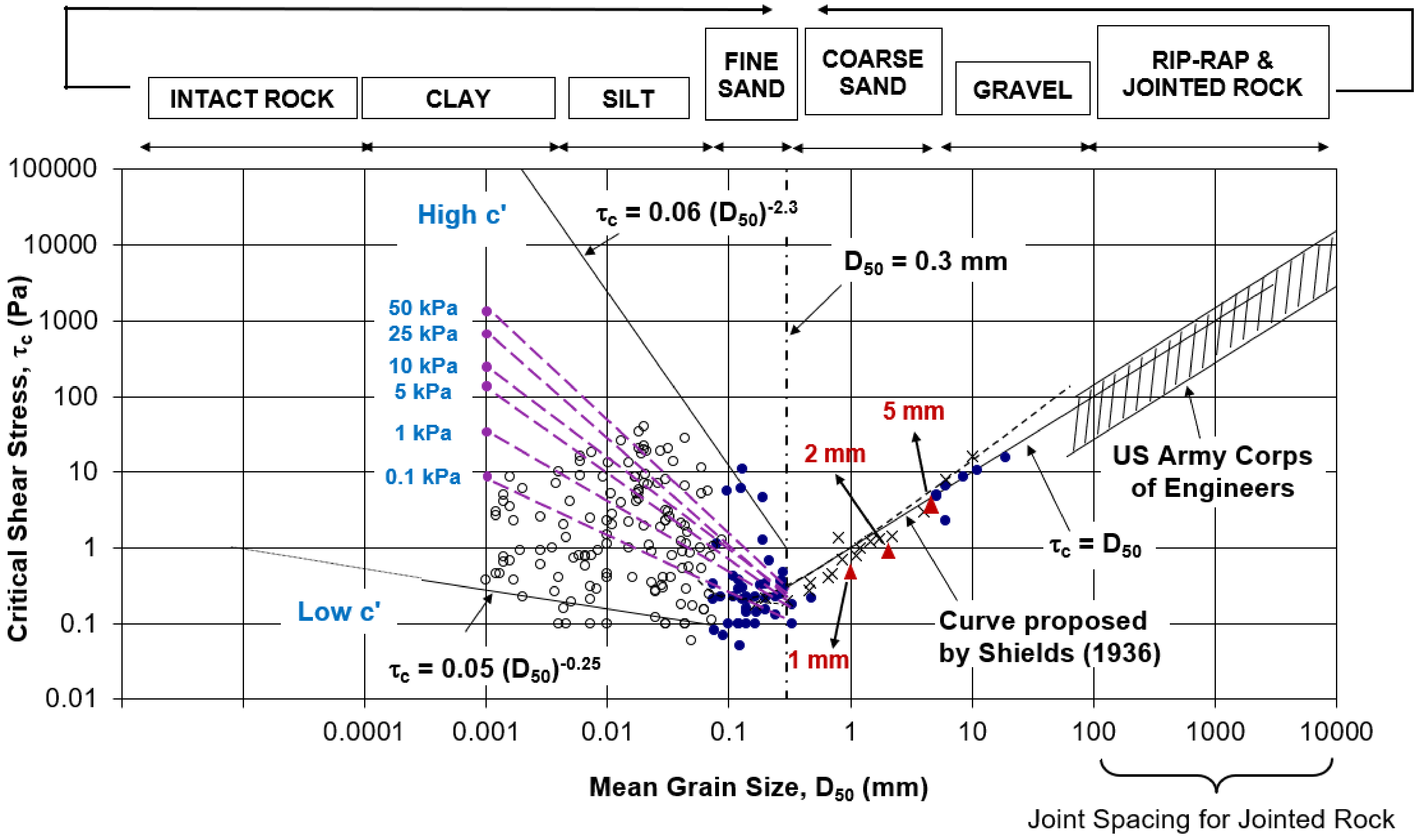
EROSION PARAMETERS

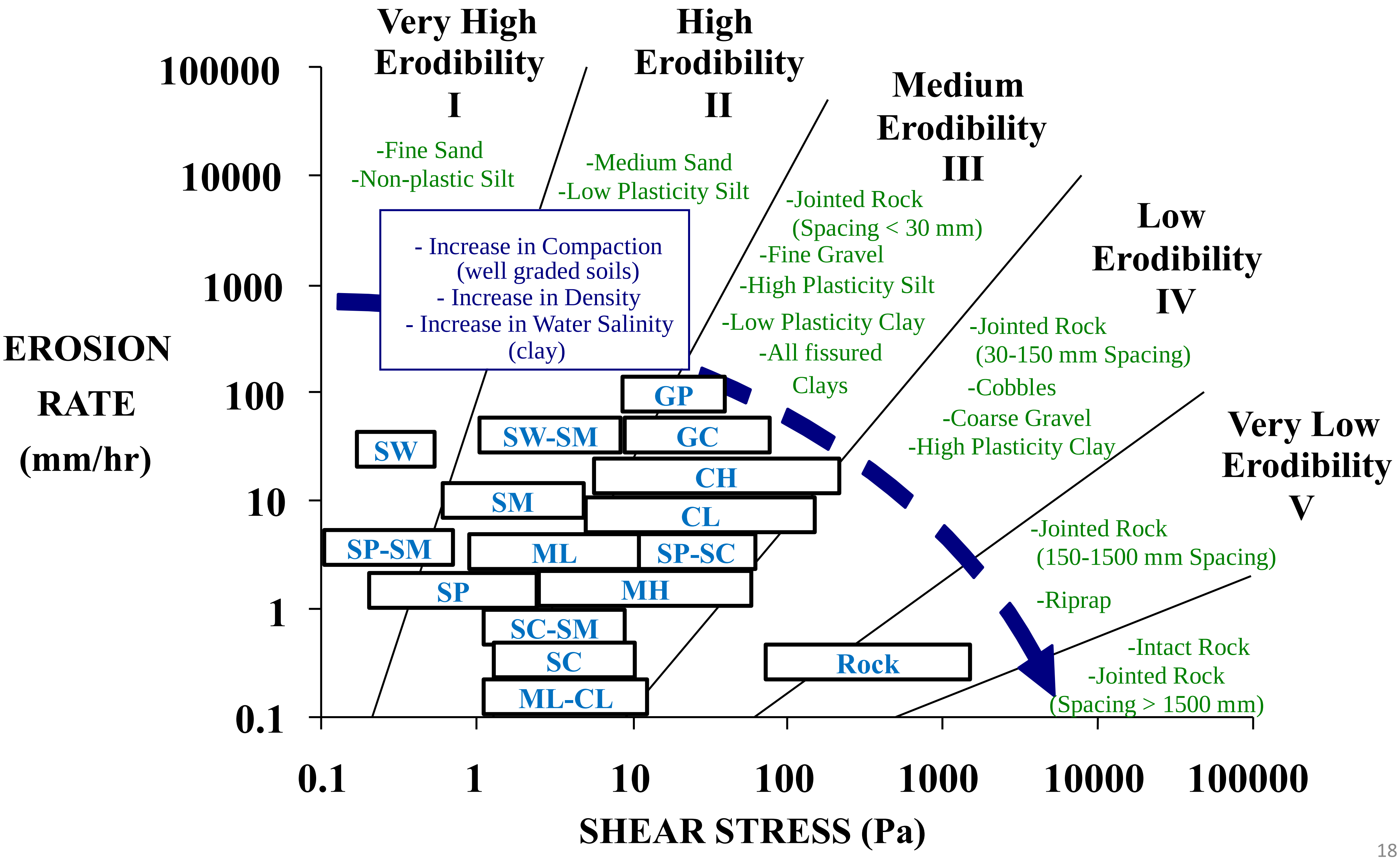
Record Numer	Erosion Function	Erosion Category	K_D	Vc (m/s)	τ_c (Pa)	Comment
1		2.5	TBD	0.39	0.53	Date shown are sampling dates
75		3	TBD	0.63	1.97	-
164		3.5	TBD		2.74	1- Unit weights are calculated from Gs in room temperature 2- Blue line means the shear stresses corresponding the design velocities 3- Mean grain size is manually read from the grain distribution curve
167		2.9	TBD		4.9	D10, D30, D60 are read from the grain distribution plot manually
251		3.2	TBD		2.53	1- Test head is 50 mm. 2- Duraion of erosion is 1620 sec 3- coefficient of determination r2 is 0.842 4- Percent compaction is 95.5% 5- Plot is coming from 300 sec to 1020 sec 6- D50, D10, D30, D60 are manually read from the distribution curve 7- Dispersion ratio is coming from SCS lab dispersion test
308		3.8	TBD		14.21	1- Test head is 50 mm. 2- Duraion of erosion is 330 sec 3- Coefficient of determination r2 is 0.976 4- D50, D10, D30, D60 are manually read from the distribution curve 5- Dispersion ratio is coming from SCS lab dispersion test
402		3	TBD		-13	1- Duraion of erosion is 263 sec 2- Coefficient of determination r2 is 0.967 3- D50, D10, D30, D60 are manually read from the distribution curve 4- Dispersion ratio is coming from SCS lab dispersion test

GEOTECHNICAL PROPERTIES

Record Numer	LL	PL	PI	γ (kN/m^3)	W. C. (%)	PPT Su (tsf)	UCS (KPa)	VST Su (KPa)	Percent Fines (%)	SPT N-value	D_{50} (mm)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_u	C_c
1	68.0	39.0	29.0		47.9				65	9	0.033				-	-
75	36.8	12.8	24.0	24.78	28.90			20	99.5		-				-	-
164	46.7	23.7	23.0	26.8	157.7			43.3	87.4		0.012				-	-
167	21.0	16.7	4.3	21.1	15.6		113.764		60.6		0.031	0.003	0.0115	0.07	23.3333	0.62976
251	62	31	31.0	16.6	34.6				75		0.0025	-	-	0.005	-	
308	NP	NP	#VALUE!	20.1	9.7				29		0.29	-	0.06	0.4	#VALUE!	#VALUE!
402	41	19	22.0	18.0	16.4				75		0.029	0.001	0.01	0.049	49	2.04082

Record Numer	Void Ratio	Degree of Saturation	Percent Compaction (%)	G_s	Dispersion Ratio	pH	Electrical Conductivity (micro siemens)	Fluid Temperature (C)	Salinity (ppm)	Percent Clay (%)	Percent Silt (%)	Organic Content (%)	Soil Activity	Relative Density (%)	Density of Cracks
1															
75									500						
164				2.74											
167	44.2	94.6		2.69						20	40		0.53%		
251			95.50%		22%	7.3	109	23		48					
308			95.00%		25%	6.5	426	18.1		13					
402			93.00%		58%	6.7	239	19.9		14					


INTACT ROCK
CLAY
SILT
FINE SAND
COARSE SAND
GRAVEL
RIP-RAP & JOINTED ROCK
Critical Shear Stress, τ_c (Pa)
100000
10000
1000
100
10
1
0.1
0.01
High c'
Low c'
$\tau_c = 0.06 (D_{50})^{-2.3}$
$D_{50} = 0.3$ mm
50 kPa
25 kPa
10 kPa
5 kPa
1 kPa
0.1 kPa
5 mm
2 mm
1 mm
US Army Corps of Engineers
$\tau_c = D_{50}$
Curve proposed by Shields (1936)
$\tau_c = 0.05 (D_{50})^{-0.25}$
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
Mean Grain Size, D_{50} (mm)
Joint Spacing for Jointed Rock


Very High Erodibility I
High Erodibility II
Medium Erodibility III
Low Erodibility IV
Very Low Erodibility V
100000
10000
1000
100
10
1
0.1
EROSION RATE (mm/hr)
-Fine Sand
-Non-plastic Silt
-Medium Sand
-Low Plasticity Silt
-Jointed Rock (Spacing < 30 mm)
-Fine Gravel
-High Plasticity Silt
-Low Plasticity Clay
-All fissured Clays
-Jointed Rock (30-150 mm Spacing)
-Cobbles
-Coarse Gravel
-High Plasticity Clay
-Jointed Rock (150-1500 mm Spacing)
-Riprap
-Intact Rock
-Jointed Rock (Spacing > 1500 mm)
- Increase in Compaction (well graded soils)
- Increase in Density
- Increase in Water Salinity (clay)
GP
SW
SW-SM
GC
CH
SM
CL
SP-SM
ML
SP-SC
SP
MH
SC-SM
SC
ML-CL
Rock
0.1
1
10
100
1000
10000
100000
SHEAR STRESS (Pa)

SOME PUBICATIONS WHICH MAY BE OF INTEREST

- SHAFII I., MEDINA-CETINA Z., SHIDLOVSKAYA* A., BRIAUD J.-L., 2022, "Relationship between Soil Erodibility and Soil Properties" Journal of Geotechnical and Geoenvironmental Engineering, Vol. 149, Issue 1, ASCE.
- SHIDLOVSKAYA A., BRIAUD J.-L., 2023, "Erosion Mitigation Using Grass, Riprap, Lime, and Enzymes, Journal of Geotechnical and Geoenvironmental Engineering, Vol. 149, Issue 4, ASCE.