



## **Shear Strength Properties of Ohio Embankment Soils (state job #134319)**

O TEC Presentation (Oct. 28,  
2008): Preliminary Results

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# Background

- Highway embankments in Ohio are often constructed from clay and silt soils with medium shear strengths.
- Some correlations between shear strength and in-situ/lab test results can be found in literature for soils from different regions of the county or from different countries.
- Design engineers in Ohio do not have full confidence in the published correlations. Thus, they tend to use overly conservative estimates of shear strengths for clay and silt fill materials.
- There is a great need to evaluate the applicability of the previously established empirical correlations to the Ohio soils and develop shear strength correlations for embankment soils found in Ohio.

# Background

- Laboratory shear strength tests must be performed on soils that are representative of fill soils utilized in Ohio. Shear strengths obtained from these tests must be correlated to the data produced from field and laboratory test techniques commonly employed by Ohio design engineers.
- The current research project aims at developing reliable correlations between shear strength and standard penetration test (SPT) data and index soil properties (such as Atterberg limits, gradation characteristics, density, **moisture content, ...)** for clay and silt fill soils sampled from several actual highway embankment sites located in Ohio.

# Project Tasks

- Task 1: Conduct a comprehensive literature review to catalog field and laboratory test results established previously for highway embankment soils in Ohio
- Task 2: Contact Ohio DOT Materials Testing Lab personnel and District geotechnical engineers to catalog additional data on the highway embankment soils in Ohio
- Task 3: Contact Ohio DOT District offices and select a total of nine (9) highway embankment sites suitable for the current study
- Task 4: Perform Standard Penetration tests (SPTs) and collect relatively undisturbed soil samples at each site

# Objectives & Project Tasks

- ~~Task 5~~: Conduct various laboratory tests on the soil samples recovered from the sites
- ~~Task 6~~: Analyze the field and laboratory test data together to develop correlations among basic index properties, SPT-N values, and shear strength properties for each major embankment soil type found in Ohio  
  
Formulate a set of guidelines concerning shear strength properties of cohesive soils commonly utilized in embankment constructions in Ohio

# Literature Review

Engineering Characteristics of Ohio Soil Series (by Johnson 1975: Report OHIO-DOT-12-75)

Parent Materials of Ohio Soils

- Bedrock & Residual Soils
- Glacial Deposits
- Alluvial Deposits

# Literature Review

Engineering Characteristics of Ohio Soil Series (by Johnson 1975: Report OHIO-DOT-12-75)

- **Bedrock & Residual Soils**
- Age -- Ordovician (525 million years old) to Permian (275 million years old)
- Western Half of Ohio – Limestone or dolomite with some calcareous shale
- Eastern Half of Ohio – Sandstone and calcareous shale with some limestone; Acidic
- Pure residual soils are only found at bedrock crest tops where gravity has not shifted the weathered materials down the slope

# Literature Review

## Bedrocks in Ohio

Western Ohio  
Limestone  
& Shale



Eastern Ohio  
Sandstone  
& Shale

# Literature Review

Engineering Characteristics of Ohio Soil Series (by Johnson 1975: Report OHIO-DOT-12-75)

- **Glacial Deposits**
- Descriptions – Excavated rock fragments in size ranging from clay particles to boulders; Composition reflects the type of bedrock excavated by the glacier
- Origin – Products of four major ice advances in the past 1,500 years
- Extensiveness -- Cover 60% of Ohio
- Depth – Vary from a few inches to 450 ft (along the western edge of Mercer County)

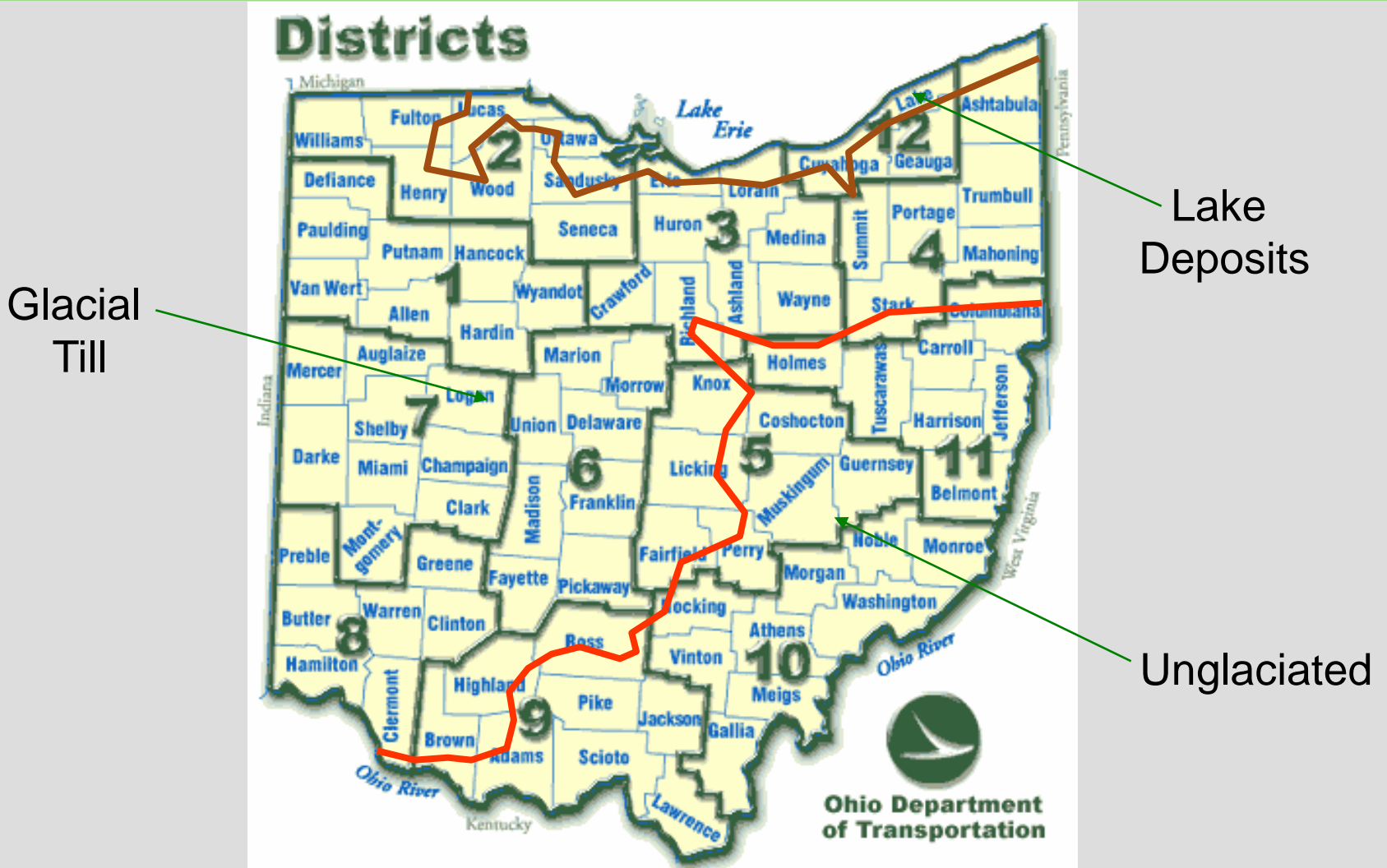
# Literature Review

Engineering Characteristics of Ohio Soil Series (by Johnson 1975: Report OHIO-DOT-12-75)

- **Alluvium Deposits**
- Descriptions – Fine-grained soils (mixtures of clay, silt, sand) deposited in stream and lake floors and upland during floods
- Origin – Sedimentation
- High bottom deposits – Older original alluvial fills; may be flooded by the 100-year flood
- Low bottom deposits – Newer alluvial fills produced by erosion of high bottom terraces; may be flooded every 2 to 3 years

# Literature Review

## Soil Deposits in Ohio



# Literature Review

## AASHTO Soil Types

- Based on soil classification system for highway constructions
- Granular Soils – Types A-1, A-2, A-3
- Fine-Grained Soils – Types A-4, A-5, A-6, A-7
- **A-4a** (moderately plastic silty soil)
- **A-4b** (plastic soil, silt  $\geq$  50%)
- **A-6a** (plastic clay soil, PI  $\leq$  15)
- **A-6b** (plastic clay soil, PI  $\geq$  16)
- **A-7-6** (clay, volume change)

**Focus of  
This Project**



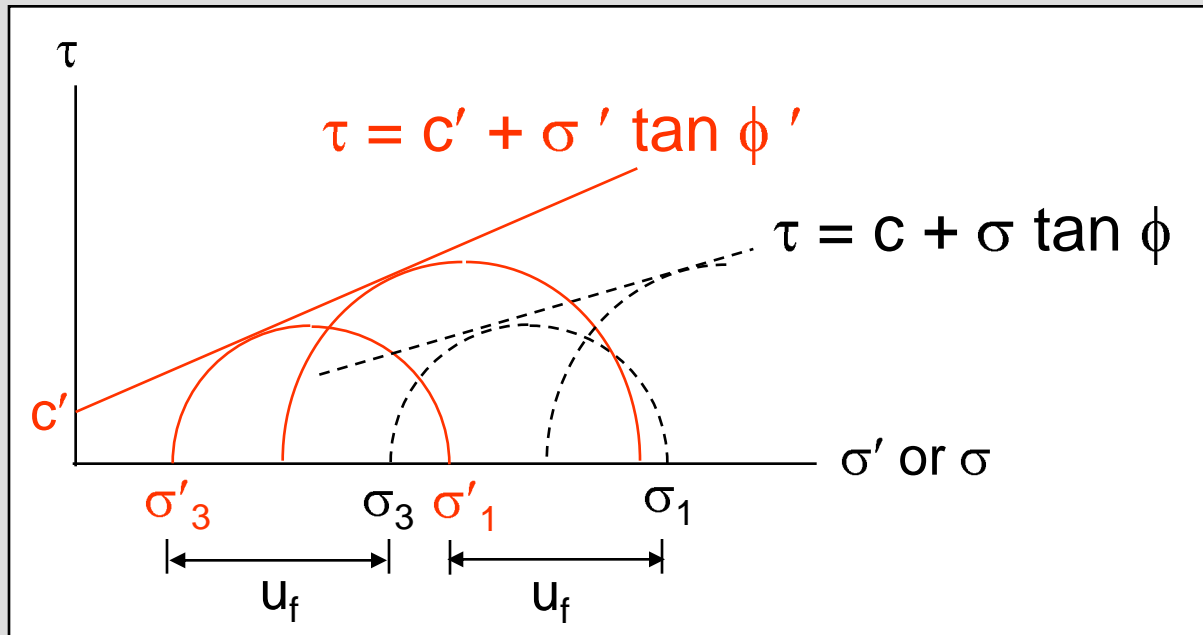
# Literature Review

- AASHTO Soil Classification System

	A-4	A-6	A-7-6
(-) No. 200	36 min.		
LL	40 max.	40 max.	41 min.
PI	10 max.	11 min.	11 min.
Description	Silty soils	Clayey soils	
Note			PI > (LL-30)

# Literature Review

- Shear Strength = maximum shear stress a soil mass can withstand along the potential failure surface.
- Mohr-Coulomb Failure Envelope (total or effective stress)



# Literature Review

- ~~Shear Strength Parameters ( $c'$ ,  $\phi'$ ,  $c$ ,  $\phi$ )~~
- **Internal Friction Angle ( $\phi'$ )** describes the frictional properties of individual particles and interlocking between particles. It is known to depend on soil mineral type, gradation, soil particle shape, and void ratio.
- **Cohesion ( $c'$ )** describes the bonding between soil particles due to cementation, electrostatic attractions, and covalent bonding.

# Literature Review

## Drained vs. Undrained Behavior

- Saturated soil under undrained loading – No volume change; Development of positive or negative pore pressure; Short-term stability of embankment slopes.
- Saturated soil under drained loading – Volume change; No excess pore pressure build-up; Long-term stability of embankment slopes

# Literature Review

## Laboratory Determination of Soil Shear Strength

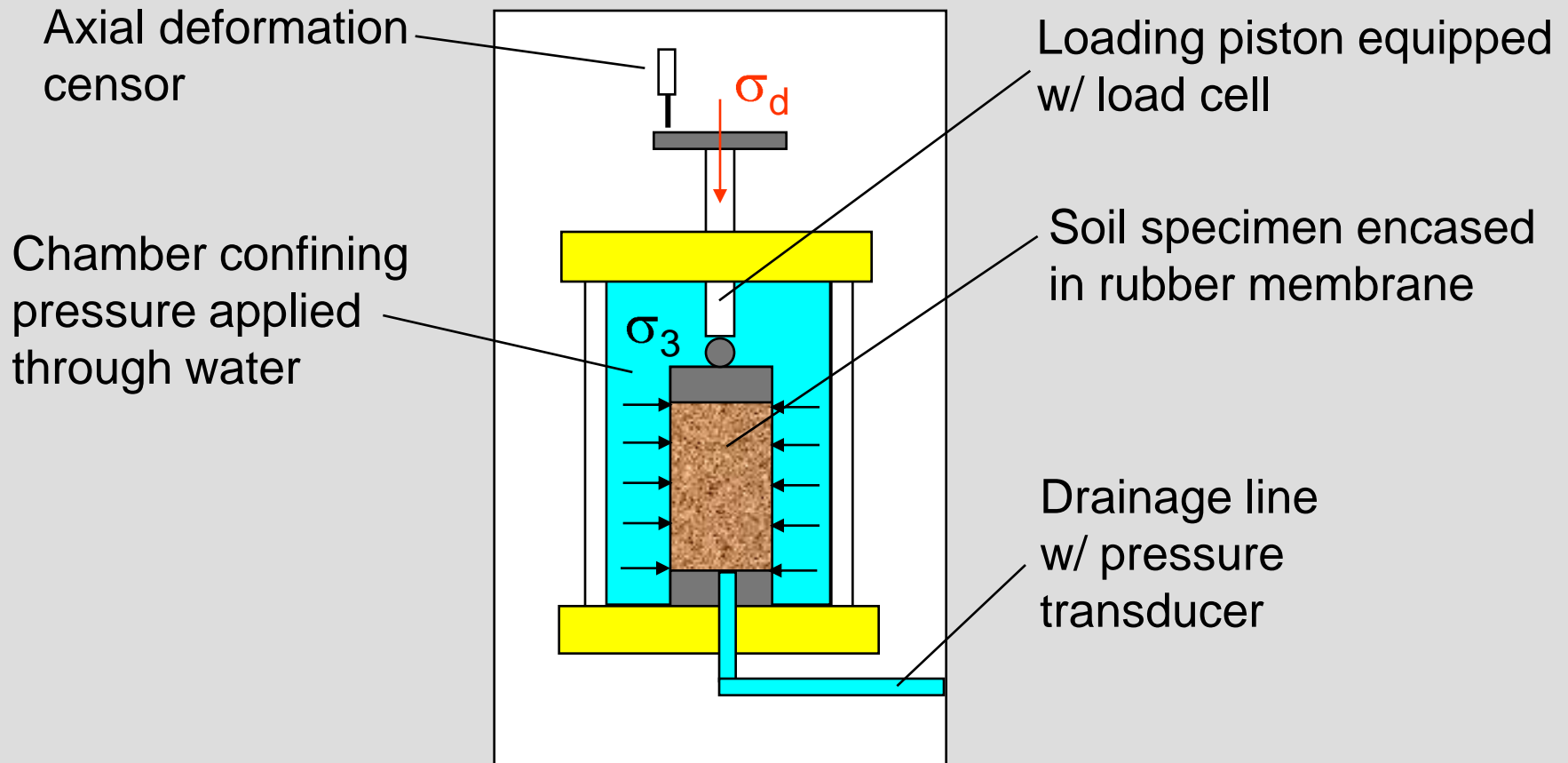
- **Triaxial Compression Test** equipment
- Stage 1 = specimen saturation by back-pressure
- Stage 2 = specimen consolidation by confining pressure and open drainage line
- Stage 3 = specimen axial loading (shearing) to failure
  
- Three test types --- Unconsolidated-Undrained (U-U or Q), Consolidated-Undrained (C-U or R), and Consolidated-Drained (C-D or S)
  
- **U-U (or Q) Test** --- End-of-construction shear strength; Fast loading rate; No pore pressure measurements; Results in total stresses

# Literature Review

## Laboratory Determination of Soil Shear Strength

- **C-U (or R) Test** --- Most common test; Long-term shear strength; Relatively slow loading rate; Pore pressure measurements; Results in both effective and total stresses.
- **C-D (or S) Test** --- Long-term shear strength; Very slow loading rate; Rarely performed (too time-consuming)

# Literature Review



## Components of Triaxial Test Set-Up

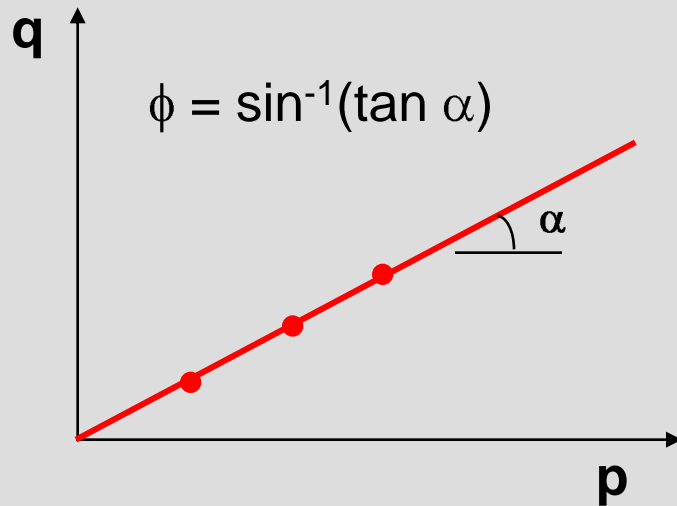
# Literature Review

## Laboratory Determination of Soil Shear Strength

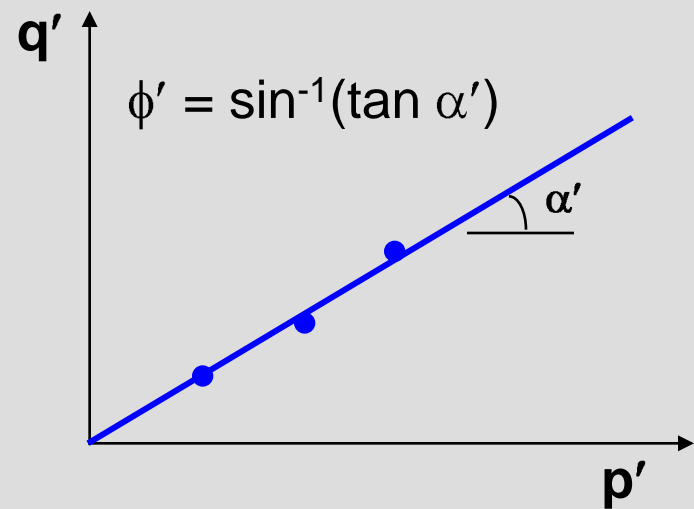
- Perform triaxial tests at three confining pressure levels
- Minimum confining pressure needs to be larger than overburden pressure to assure normally consolidated soil behaviors
- Plot the results from three tests in p-q and p'-q' diagrams, where  $p = (\sigma_{1f} + \sigma_3)/2$ ;  $q = (\sigma_{1f} - \sigma_3)/2$ ;  $p' = (\sigma'_{1f} + \sigma'_3)/2$ ; and  $q' = (\sigma'_{1f} - \sigma'_3)/2$

# Literature Review

- p-q and p'-q' Diagrams (for NC soils)



Using total stresses at failure



Using effective stresses at failure

# Literature Review

## Unconfined Compression Test

- Performed only on cohesive soils
- Rapid test to obtain undrained cohesion strength ( $c_u$ ):  
$$c_u = \sigma_1/2$$
- Considered as a special case of U-U test
- Involves no confining pressure; No drainage



# Literature Review

## Stability of Highway Embankments

- **Factors for stability** – shear strength of embankment soil; unit weight of embankment soil; height of embankment; steepness of embankment slope; pore pressures in embankment soil; and shear strength of subsoil
- **Stability of embankments on firm subsoils** – Sliding of soil mass over firm base; Both short-term and long-term conditions are critical
- **Stability of embankments on soft subsoils** – Shear failure deep within soft subsoil layer; Short-term conditions are more critical

# Literature Review

## ~~Stability of Highway Embankments~~

- Embankments constructed of a mixture of cohesive soils and rock fragments – Long-term stability may be a concern especially if the rock fragments were derived from sedimentary rock (ex. shale).

# Literature Review

## Standard Penetration Test (SPT)

- Oldest and most commonly used in-situ soil test method
- Drop a 140-lb (64-kg) hammer 30 inches (0.76 m) to drive a split-spoon barrel
- **SPT-N value** = number of hammer blows per 1-ft (0.3-m) penetration
- SPT-N value depends on several factors such as the hammer type, actual drop height, inclination of the hole, hole diameter, presence of liner inside barrel, and test depth.

# Literature Review

## Normalization of SPT-N value

- SPT-N values are normalized to an overburden pressure of 1 tsf (13.9 psi, 95.7 kPa) and to an energy transfer rate of 60% (= energy typically applied by the safety hammer in the U.S.)

$$(N_1)_{60} = C_N * N_{60}$$

where  $(N_1)_{60}$  = normalized  $N_{60}$  value;  $C_N$  = depth or overburden pressure correction factor; and  $N_{60}$  = N value measured with 60 % hammer efficiency

# Literature Review

## Normalization of SPT-N Value

- A few different methods proposed for evaluating  $C_N$
- Peck et al. (1974)

$$C_N = 0.77 \log \left( \frac{20}{\sigma'_0} \right)$$

where  $\sigma'_0$  = effective overburden pressure (tsf)

- Terzaghi et al. (1996)

$$C_N = \left( \frac{100}{\sigma'_0} \right)^{0.5}$$

where  $\sigma'_0$  = effective overburden pressure (kPa)

# Literature Review

## Normalization of SPT-N Value

- Bazarraa (1967)

$$C_N = \frac{4}{1 + 2\sigma'_0}$$

for  $\sigma'_0 \leq 1.5$  ksf; where  $\sigma'_0$  = effective overburden pressure (ksf)

$$C_N = \frac{4}{3.25 + 0.5\sigma'_0}$$

for  $\sigma'_0 > 1.5$  ksf

# Literature Review

## Normalization of SPT-N Values

- Seed et al. (1975)

$$C_N = 1 - 1.25 \log \left( \frac{\sigma'_0}{p_a} \right)$$

- Skempton (1986)

$$C_N = \frac{2}{1 + \sigma'_0 / p_a}$$

where  $\sigma'_0$  = effective overburden pressure (psf); and  $p_a$  = atmospheric pressure (= 2,000 psf = 1 tsf)

# Literature Review

## Empirical Correlations

- SPT-N Value vs. Unconfined Compression Strength  $q_u$  for Cohesive Soils – Terzaghi et al (1996)

SPT- $(N_{60})_1$	Stiffness	Strength (psi)
< 2	very soft	< 3.6
2-4	soft	3.6-7.3
4-8	medium stiff	7.3-14.5
8-15	stiff	14.5-29
15-30	very stiff	29-58
> 30	hard	> 58

# Literature Review

## Empirical Correlations

- Friction Angle  $\phi'$  vs. Plasticity Index PI – Terzaghi et al. (1996)

PI (%)	$\phi'$ (deg)	PI (%)	$\phi'$ (deg)
10	33.3	50	25.6
20	30.8	60	24.6
30	29.2	70	23.8
40	27.1	80	23.1

[Note] The actual  $\phi'$  value may be off by at least  $\pm 3$  degrees.

# Literature Review

## Empirical Correlations

- SPT-N Value vs. Unconfined Compression Strength  $q_u$  – Dept. of Navy (1982)

SPT- $N_{60}$	$q_u$ of clays (low plasticity) & clayey silts	$q_u$ of clays (med. plasticity)	$q_u$ of clays (high plasticity)
5	5.2 psi	10.4 psi	17.4 psi
10	10.4 psi	20.8 psi	34.7 psi
15	15.6 psi	31.3 psi	52.1 psi
20	20.8 psi	41.7 psi	69.4 psi
25	26.0 psi	52.1 psi	86.8 psi
30	31.2 psi	62.5 psi	104.1 psi

[Note] Low plasticity (LL < 40); Med. Plasticity (LL 40 to 60); and High plasticity (LL > 60).

# Literature Review

## Empirical Correlations

- Typical Properties of Compacted Soils

Soil Type	$\gamma_{d-max}$ (pcf)	OMC (%)	$C_{-moist}$ (psi)	$C_{-saturated}$ (psi)	$\phi'$ (deg.)
A-4	94-119	12-24	9	1	32
A-6	94-119	12-24	12	2	28
A-7-6	75-119	12-36	12-15	2	19-28

[Ref.] Design Manual 7.2 by U.S. Dept. of Navy (1982).

# Literature Review

## Shear Strength of Unsaturated Soil

- Shear strength of unsaturated soil has been studied by some (ex. Fredlund & Rahardjo 1993).

- According to Bishop et al. (1960):  $\sigma' = \sigma - u_a + \chi(u_a - u_w)$

where  $u_a$  = pore air pressure;  $\chi$  = a fraction of unit cross-sectional area of pore spaces occupied with water (= 0 for dry soil, = 1 for saturated soil); and  $u_w$  = pore water pressure.

- Shear strength of unsaturated soil is then expressed as:

$$\tau_f = c' + [\sigma - u_a + \chi(u_a - u_w)] \tan \phi'$$

# Literature Review

## Soil Shear Strength: Saturated vs. Unaturated

- Input  $\chi = 0.0$  (dry)  $\rightarrow \tau_f = c' + (\sigma - u_a) \tan\phi'$
- Input  $\chi = 0.5$  (**unsat'd**)  $\rightarrow \tau_f = c' + (\sigma - 0.5u_a - 0.5u_w) \tan\phi'$
- Input  $\chi = 1.0$  (saturated)  $\rightarrow \tau_f = c' + (\sigma - u_w) \tan\phi'$
  
- In general,  $u_a < 0$  and  $u_w > 0$ .
  
- [Comment] Shear strength of unsaturated soil is greater than that of the same soil in the saturated state. This has been verified experimentally by Casagrande & Hirschfeld (1960). Thus, it is conservative to design highway embankments using shear strength of saturated soil.

# Literature Review

## Soil Shear Strength: Saturated vs. Unsaturated

- The additional shear strength possessed in the unsaturated state is tenuous and can be lost easily upon wetting.
- It is a sound practice to design embankments with the assumption that unsaturated soils can become saturated over time. This eventual saturation can be caused by a rising water table, poor surface drainage, an unusually wet season, and leaking underground structures.

# Tasks 1 & 2

- Field and laboratory test results established previously for highway embankment soils in Ohio
- Only some limited amount of data are available. There are no statewide database of embankment soil properties.

# Task 3

## Site Selection Criteria

- Embankment fill height over 25 ft
- Site located on major highway
- Site recommended by ODOT or subcontractor
- Unique geographical or geological location within state
- Favorable soil type(s) based on prior subsurface data
- A lack of gravel size particles and rock fragments
- No guardrails
- Relatively level grassed area

[Note] Major soil types (AASHTO A-4, A-6, and A-7-6)

# Task 3

- Example of Ideal Site (ATH-33)



# Site Locations

## Locations of Embankment Sites



# Site Locations

- List of Field Sites

Site No.	Site I.D.	Site Location Descriptions
1	HAM-275	I -275 in Hamilton County; North of Blue Rock Road Exit; Northwest of downtown; District 8
2	FAY-35	At junction of new & old USR 35 in Fayette County; Near Jeffersonville; District 6
3	LAK-2	USR 2 in Lake County; Close to Junction of USR 2 & SR 815; District 12
4	ATH-33	New USR 33 in Athens County; 2.2 Miles South of CR 21; District 10
5	MRW-71	Approx. 150 ft South of Bridge MRW-71-1766 (I-71 over CR-22 & Kokosing River) in Morrow County; District 6
6	ERI-2	A site located right by Edison Bridge on SR 2 in District 2

# Site Locations

- List of Field Sites

Site No.	Site I.D.	Site Location Descriptions
7	HAN-75	I-75 in Hancock County; Approx. 0.5 miles north of Exit 142 (Bluffton Exit); District 1
8	JAC-32	USR 32 in Jackson County; Approx. 245 ft SW of rear abutment of JAC-32-1129 Bridge; District 9
9	MUS-70	I-70 in Muskingum County; Approx. 0.5 miles west of Exit 153 in Zanesville; District 5
10	NOB-77	I-77 in Noble County; Approx. 2850 ft north of CR37 overpass; North of Bell Valley; District 10

# Site Locations

## Distributions of Field Sites

- Two (2) sites (east, west) in the lake deposits area
- Four (4) sites in the glaciated region
- Four (4) sites in the unglaciated region
- Three (3) sites in northern Ohio
- Four (4) sites in central Ohio
- Three (3) sites in southern Ohio
- Eight (8) ODOT districts

# Task 4

## Subsurface Exploration Work

- Use of automatic SPT hammer
- Calibration of SPT equipment
- Dedicated equipment and personnel
- Continuous SPT to 25-ft depth in center hole
- Direct visual logging of soil layers
- Pocket penetrometer reading on each soil sample
- Four (4) surrounding holes to provide twelve (12) Shelby tube soil samples at three (3) selected depth ranges

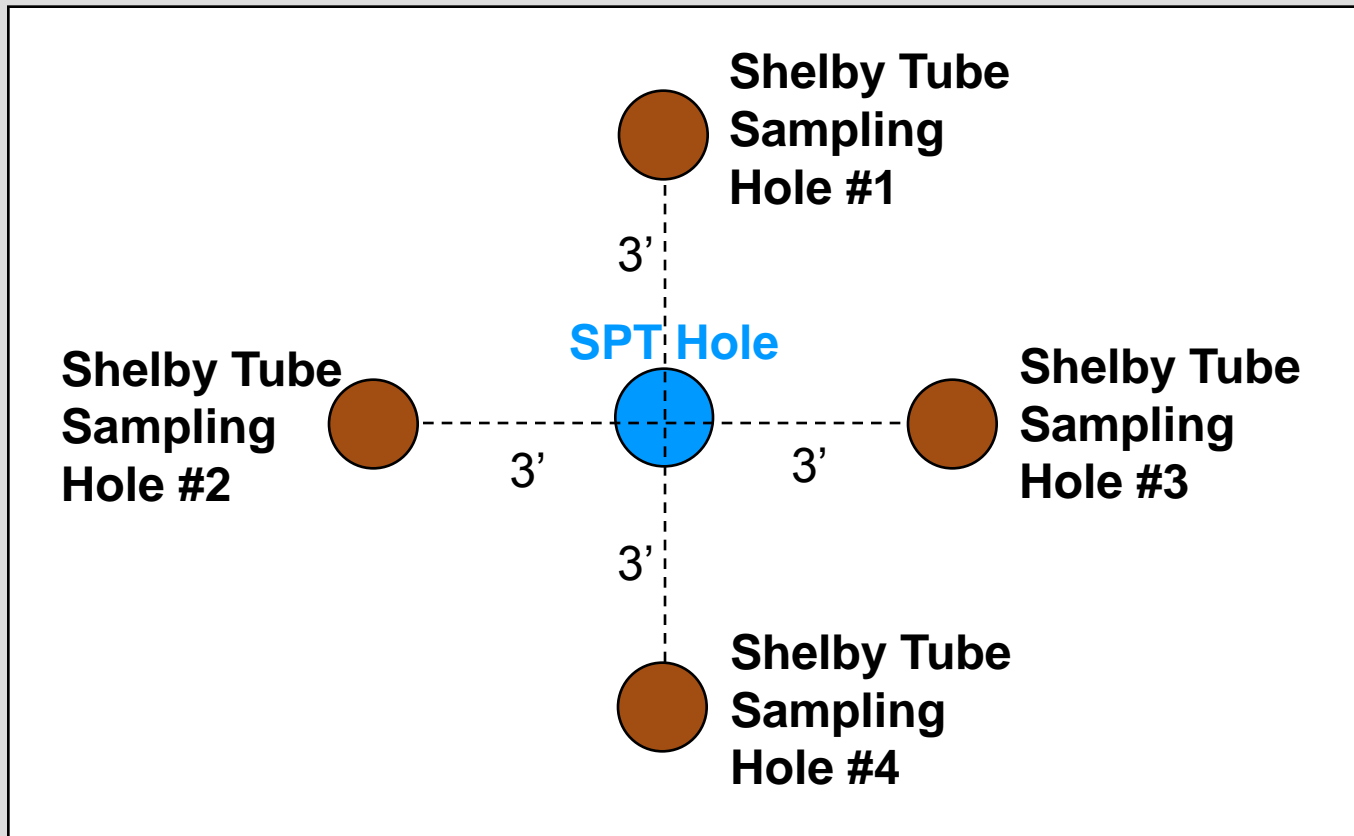
# Task 4

~~Subsurface Exploration Work~~

~~Selection of Three Shelby Tube Sampling Depths~~

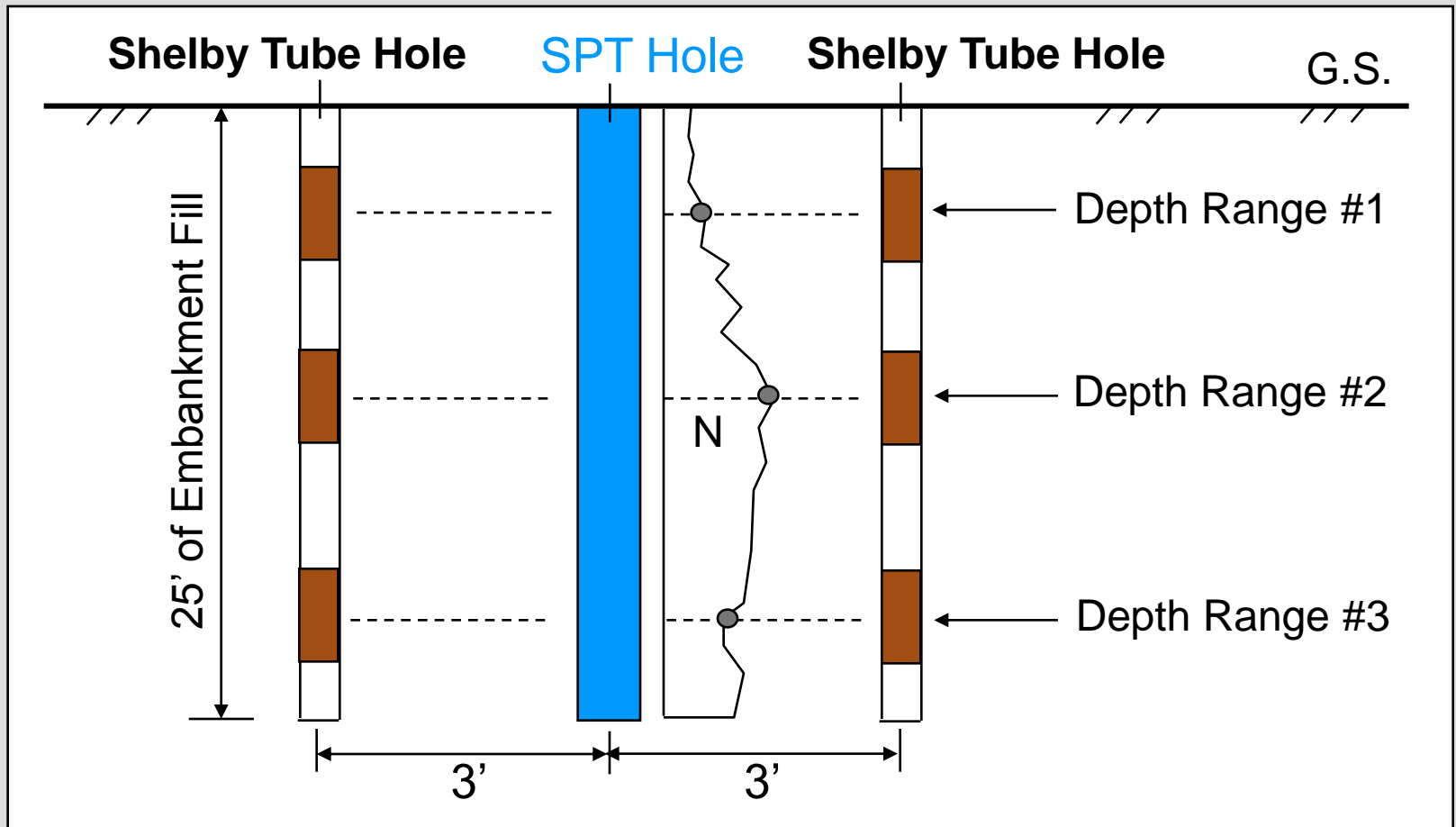
- Variations of SPT-N value
- Soil types encountered

# Task 4



Plan View of Master Plan

# Task 4



Side View of Master Plan

# Task 4



BBCM's Truck #55 performing Continuous SPT with automatic SPT hammer

# Task 4

## SPT Automatic Hammer Calibration

- Calibration by GRL Engineering, Inc. (Cleveland, OH; Tel. 216-292-3076)
- Truck #55 with CME automatic hammer & AWJ rods; Sample depth 1 to 25.5 ft
- Energy measurements in 18-inch depth intervals
- PAK model pile driving analyzer

# Task 4

## SPT Automatic Hammer Calibration

- Maximum Energy Transferred to Rods (EMX):

$$EMX = \int F \cdot \bar{V}(t) dt$$

where  $F(t)$  = force measured at time  $t$ ; and  $V(t)$  = velocity measured at time  $t$ .

- Energy transfer ratio (ETR) =  $EMX / (\text{Theoretical SPT Hammer Energy}) = EMX / (0.35 \text{ kip-ft})$
- Results: ETR = 78.8 to 84.4% (ave. 81.6%) for Truck #55
- $N_{60} = (ETR/60) * N_m$  where  $N_m$  = measured SPT-N value.

# Task 4



Logging of soils by split-spoon sampler

# Task 4



Shelby tube getting ready to be used for relatively undisturbed soil sampling

# Task 4



**Sealing of soil sample by melted wax**

# Task 4

- Field Test Data from Site 1 (HAM I-275)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	7	10.0-11.5	20
2.5-4.0	7	11.5-13.0	29
4.0-5.5	13	13.0-14.5	37
5.5-7.0	24	14.5-16.0	29
7.0-8.5	22	16.0-17.5	30
8.5-10.0	31	17.5-19.0	45

[Note] Soils = stiff, silty material with some clay, some gravel, and trace sand.

# Task 4

- Field Test Data from Site 2 (FAY-35)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	18	13.0-14.5	14
2.5-4.0	14	14.5-16.0	10
4.0-5.5	21	16.0-17.5	21
5.5-7.0	18	17.5-19.0	16
7.0-8.5	21	19.0-20.5	23
8.5-10.0	23	20.5-22.0	32
10.0-11.5	21	22.0-23.5	43
11.5-13.0	13	23.5-25.0	20

# Task 4

- Field Test Data from Site 3 (LAK-2)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	10	13.0-14.5	9
2.5-4.0	17	14.5-16.0	16
4.0-5.5	25	16.0-17.5	12
5.5-7.0	30	17.5-19.0	18
7.0-8.5	21	19.0-20.5	14
8.5-10.0	12	20.5-22.0	22
10.0-11.5	13	22.0-23.5	13
11.5-13.0	28	23.5-25.0	28

# Task 4

- Field Test Data from Site 4 (ATH-33)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	27	13.0-14.5	20
2.5-4.0	40	14.5-16.0	40
4.0-5.5	16	16.0-17.5	45
5.5-7.0	33	17.5-19.0	36
7.0-8.5	16	19.0-20.5	21
8.5-10.0	17	20.5-22.0	32
10.0-11.5	25	22.0-23.5	21
11.5-13.0	19	23.5-25.0	32

# Task 4

- Field Test Data from Site 5 (MRW-71)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	11	13.0-14.5	17
2.5-4.0	10	14.5-16.0	25
4.0-5.5	9	16.0-17.5	15
5.5-7.0	13	17.5-19.0	31
7.0-8.5	14	19.0-20.5	16
8.5-10.0	16	20.5-22.0	30
10.0-11.5	9	22.0-23.5	16
11.5-13.0	21	23.5-25.0	35

# Task 4

- Field Test Data from Site 6 (ERI-2-0.23)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	NA	13.0-14.5	11
2.5-4.0	7	14.5-16.0	17
4.0-5.5	8	16.0-17.5	20
5.5-7.0	12	17.5-19.0	14
7.0-8.5	6	19.0-20.5	14
8.5-10.0	8	20.5-22.0	24
10.0-11.5	11	22.0-23.5	18
11.5-13.0	14	23.5-25.0	39

# Task 4

- Field Test Data from Site 7 (HAN-75)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	19	13.0-14.5	12
2.5-4.0	13	14.5-16.0	25
4.0-5.5	14	16.0-17.5	17
5.5-7.0	16	17.5-19.0	33
7.0-8.5	15	19.0-20.5	10
8.5-10.0	23	20.5-22.0	21
10.0-11.5	9	22.0-23.5	21
11.5-13.0	20	23.5-25.0	25

# Task 4

- Field Test Data from Site 8 (JAC-32)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	19	13.0-14.5	12
2.5-4.0	13	14.5-16.0	25
4.0-5.5	14	16.0-17.5	17
5.5-7.0	16	17.5-19.0	33
7.0-8.5	15	19.0-20.5	10
8.5-10.0	23	20.5-22.0	21
10.0-11.5	9	22.0-23.5	21
11.5-13.0	20	23.5-25.0	32

# Task 4

- Field Test Data from Site 9 (MUS-70)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	15	13.0-14.5	46
2.5-4.0	17	14.5-16.0	53
4.0-5.5	20	16.0-17.5	38
5.5-7.0	42	17.5-19.0	53
7.0-8.5	36	19.0-20.5	44
8.5-10.0	13	20.5-22.0	49
10.0-11.5	19	22.0-23.5	42
11.5-13.0	48	23.5-25.0	61

[Note] Soils = medium dense to dense sand at most depths; silty clay layer detected at 9.5 through 11.0 ft.

# Task 4

- Field Test Data from Site 10 (NOB-77)

Depth (ft)	N Value	Depth (ft)	N Value
1.0-2.5	11	13.0-14.5	14
2.5-4.0	10	14.5-16.0	22
4.0-5.5	14	16.0-17.5	44
5.5-7.0	15	17.5-19.0	22
7.0-8.5	9	19.0-20.5	12
8.5-10.0	15	20.5-22.0	20
10.0-11.5	17	22.0-23.5	26
11.5-13.0	18	23.5-25.0	26

[Note] Soils = Medium stiff to stiff silty clay (resembling weathered shale).

# Task 5

- Laboratory Testing Shared by OU and Sub-contractor (BBCM)
- Nine (9) Shelby Tube Samples for OU
- Three (3) Shelby Tube Samples for BBCM

# Task 5

## List of Laboratory Tests by Subcontractor (BBCM)

- Visual soil descriptions
- Moisture contents & Dry unit weight
- Atterberg limits (plastic; liquid → plasticity index)
- Grain size analysis (mechanical sieve; hydrometer)
- Soil classifications by AASHTO method
- Specific gravity
- Unconfined compression strength

# Task 5

## List of Laboratory Test by ORITE (Ohio Univ.)

- Consolidated-undrained (C-U) triaxial compression test with pore pressure measurement
- **ASTM D-4767-04: "Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils"**

# Task 5

## Key Specifications of ASTM D-4767-04

- Specimen (Height/Diameter) ratio of 2.0 to 2.5
- Back pressure 5 psi (35 kPa) less than chamber pressure
- Saturation to minimum B value of 0.95, where  $B = \Delta u / \sigma_3$
- Consolidation stage to follow the procedure outlined in ASTM D-2435. Determine  $t_{50}$
- Loading rate set at  $4\% / (10 * t_{50})$  so that pore pressure can achieve equilibrium
- Load specimen to 15% axial strain, a 20% drop in deviator stress, or 5% additional strain beyond deviator stress peak.
- Check for presence of large stones after test

# Task 5



**Cutting of Shelby Tube into Shorter Sections**

# Task 5



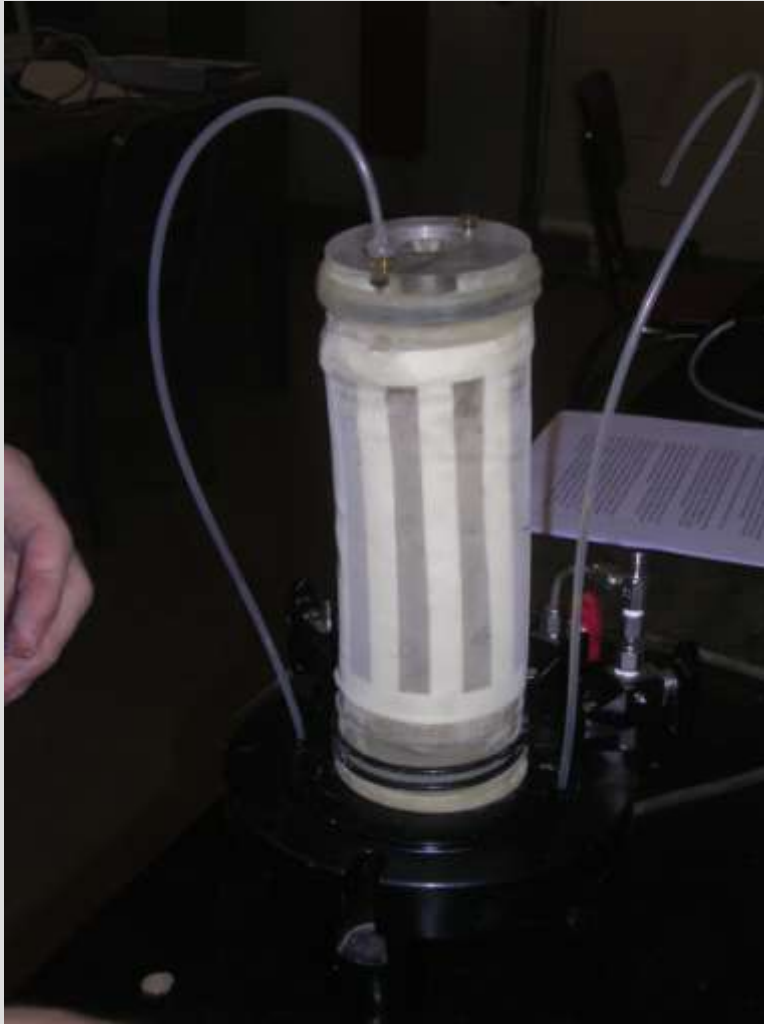
Hydraulic Jacking of  
Soil Sample Out of  
Shortened Shelby  
Tube

# Task 5



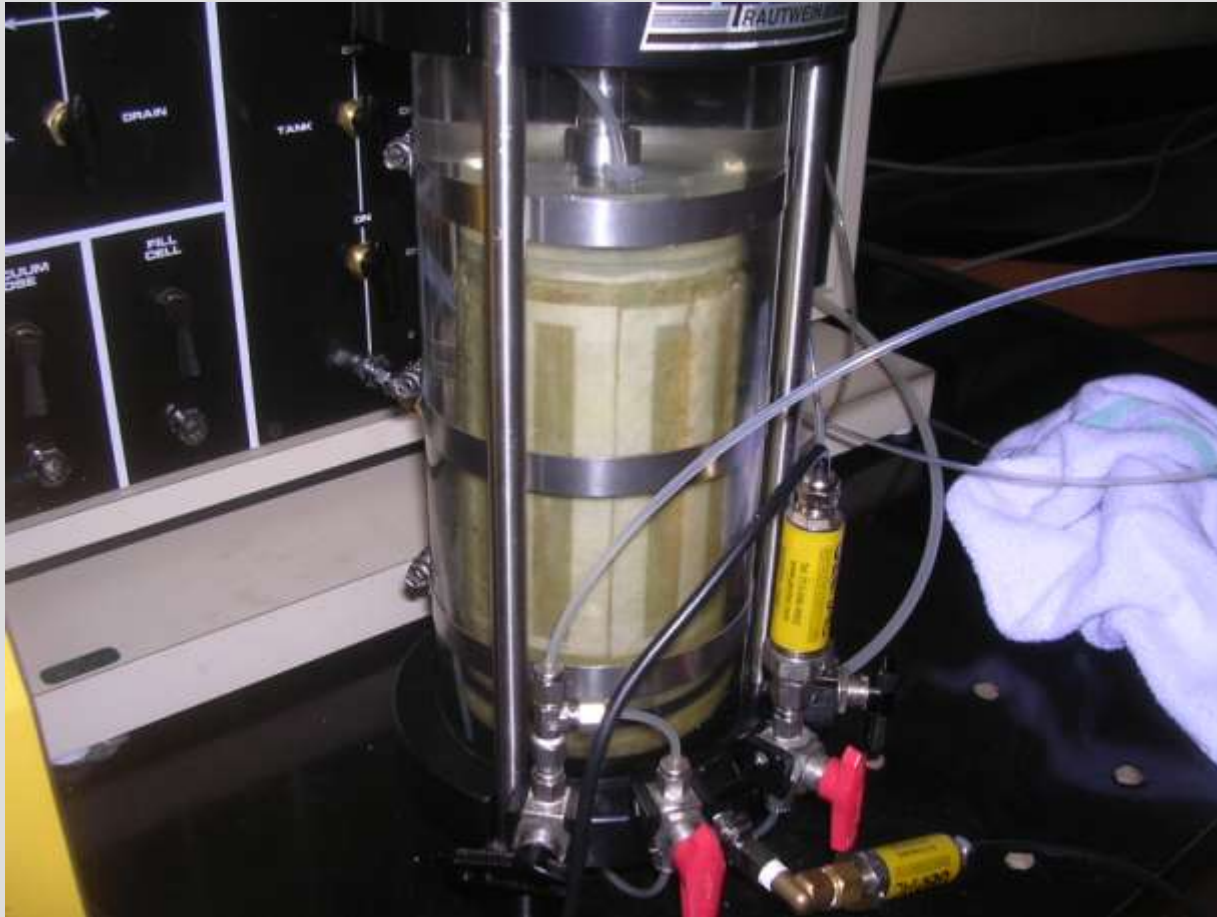
Extracted Soil Specimen  
being Examined Before  
Test

# Task 5



Mounting of Soil Specimen

# Task 5



Soil Specimen Going Through Initial Saturation

# Task 5



Triaxial Compression Test in Progress

# Task 5

- Laboratory Test Results for Site 1 (HAM I-275) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
2.5-3.0	A-1	2.74	41	19	22	A-7-6
3.1-3.6	A-1	2.74	58	21	37	A-7-6
2.5-3.0	D-1	2.74	41	19	22	A-7-6
5.1-5.6	A-2	2.70	50	20	30	A-7-6
4.9-5.4	C-2	2.70	50	20	30	A-7-6
4.6-5.1	D-2	2.70	50	20	30	A-7-6
10.3-10.8	A-3	2.66	43	22	21	A-7-6
10.2-10.6	D-3	2.66	43	22	21	A-7-6

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 1 (HAM I-275) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
2.5-3.0	A-1	11	14	30	46
3.1-3.6	A-1	10	13	26	51
2.5-3.0	D-1	11	14	30	46
5.1-5.6	A-2	7	11	34	48
4.9-5.4	C-2	7	11	34	48
4.6-5.1	D-2	7	11	34	48
10.3-10.8	A-3	6	12	30	51
10.2-10.6	D-3	6	12	30	51

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 1 (HAM I-275) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
2.5-3.0	A-1	15.7	112.7	24.8	18
3.1-3.6	A-1	22.0	104.4	30.6	18
2.5-3.0	D-1	15.7	112.7	24.8	18
5.1-5.6	A-2	17.6	107.8	18.7	28
4.9-5.4	C-2	17.6	107.8	18.7	28
4.6-5.1	D-2	17.6	107.8	18.7	28
10.3-10.8	A-3	15.4	111.7	46.9	31
10.2-10.6	D-3	15.4	111.7	46.9	31

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 1 (HAM I-275) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
2.5-3.0	A-1	105.2	21.3	35.0	51.6	27.1
3.1-3.6	A-1	112.5	23.6	45.1	65.6	33.6
2.5-3.0	D-1	107.4	24.4	60.1	90.0	40.0
5.1-5.6	A-2	123.2	16.7	39.0	63.4	26.4
4.9-5.4	C-2	112.4	25.0	44.8	64.7	33.5
4.6-5.1	D-2	117.0	21.0	59.9	86.3	41.2
10.3-10.8	A-3	116.8	20.5	42.6	66.3	27.8
10.2-10.6	D-3	120.7	21.1	46.4	78.5	26.9

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 1 (HAM I-275) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\epsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
2.5-3.0	A-1	20.0	13.4	11.1	30.8
3.1-3.6	A-1	35.0	10.2	10.6	28.0
2.5-3.0	D-1	18.0	14.9	11.5	25.3
5.1-5.6	A-2	30.0	15.1	13.7	29.2
4.9-5.4	C-2	15.0	15.1	10.5	27.9
4.6-5.1	D-2	12.0	15.0	10.4	24.5
10.3-10.8	A-3	24.0	15.0	12.6	26.4
10.2-10.6	D-3	30.0	15.0	14.9	26.8

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 2 (FAY-35) – Part 1

Depth (ft)	Tube	G <sub>s</sub>	LL (%)	PL (%)	PI (%)	Type
5.7-6.2	A-1	2.68	32	17	15	A-6a
6.6-7.1	D-1	2.68	32	17	15	A-6a
6.3-6.7	E-1	2.68	32	17	15	A-6a
5.5-6.0	E-1	2.68	32	17	15	A-6a
9.2-9.7	A-2	2.70	21	13	8	A-4a
9.2-9.7	D-2	2.70	21	13	8	A-4a
9.2-9.7	E-2	2.70	21	13	8	A-4a
14.7-15.2	B-3	2.65	21	13	8	A-4a
15.4-15.8	B-3	2.65	21	13	8	A-4a

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 2 (FAY-35) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
5.7-6.2	A-1	6	24	40	30
6.6-7.1	D-1	6	24	40	30
6.3-6.7	E-1	6	24	40	30
5.5-6.0	E-1	6	24	40	30
9.2-9.7	A-2	15	27	39	19
9.2-9.7	D-2	15	27	39	19
9.2-9.7	E-2	15	27	39	19
14.7-15.2	B-3	16	28	38	18
15.4-15.8	B-3	16	28	38	18

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 2 (FAY-35) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
5.7-6.2	A-1	15.3	113.6	36.6	35
6.6-7.1	D-1	15.3	113.6	36.6	35
6.3-6.7	E-1	15.3	113.6	36.6	35
5.5-6.0	E-1	15.3	113.6	36.6	35
9.2-9.7	A-2	9.1	129.0	41.0	36
9.2-9.7	D-2	9.1	129.0	41.0	36
9.2-9.7	E-2	9.1	129.0	41.0	36
14.7-15.2	B-3	9.2	130.3	45.1	13
15.4-15.8	B-3	9.2	130.3	45.1	13

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 2 (FAY-35) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
5.7-6.2	A-1	131.4	14.6	37.7	79.3	24.5
6.6-7.1	D-1	112.0	17.0	45.3	83.1	29.4
6.3-6.7	E-1	118.9	18.9	52.3	101.3	28.5
5.5-6.0	E-1	114.7	18.9	59.9	113.4	42.0
9.2-9.7	A-2	135.9	9.3	45.1	149.6	5.5
9.2-9.7	D-2	138.0	10.3	52.7	167.0	9.7
9.2-9.7	E-2	137.4	10.6	60.2	205.3	1.9
14.7-15.2	B-3	127.9	10.0	47.9	104.8	24.7
15.4-15.8	B-3	137.1	11.1	54.1	141.8	20.0

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 2 (FAY-35) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\varepsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
5.7-6.2	A-1	3.7	15.0	20.8	37.8
6.6-7.1	D-1	10.2	13.8	17.1	32.9
6.3-6.7	E-1	30.5	15.0	18.6	30.5
5.5-6.0	E-1	10.1	15.1	18.0	36.8
9.2-9.7	A-2	1.3	15.1	32.5	34.7
9.2-9.7	D-2	1.1	15.2	31.3	34.8
9.2-9.7	E-2	3.4	15.0	33.1	33.6
14.7-15.2	B-3	1.8	15.0	21.9	33.5
15.4-15.8	B-3	3.6	15.0	26.6	34.2

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 3 (LAK-2) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
1.6-2.1	A-1	2.76	29	18	11	A-6a
1.0-1.5	A-1	2.76	29	18	11	A-6a
1.1-1.6	D-1	2.76	29	18	11	A-6a
4.1-4.6	A-2	2.70	28	18	10	A-4a
4.0-4.5	D-2	2.70	28	18	10	A-4a
4.7-5.2	D-2	2.70	29	19	10	A-4a
14.7-15.2	C-3	2.70	25	18	7	A-4a
14.6-15.1	A-3	2.70	25	18	7	A-4a
14.6-15.1	D-3	2.70	25	18	7	A-4a

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 3 (LAK-2) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
1.6-2.1	A-1	7	23	37	33
1.0-1.5	A-1	7	23	37	33
1.1-1.6	D-1	7	23	37	33
4.1-4.6	A-2	5	27	35	33
4.0-4.5	D-2	5	27	35	33
4.7-5.2	D-2	4	23	37	36
14.7-15.2	C-3	8	24	37	30
14.6-15.1	A-3	8	24	37	30
14.6-15.1	D-3	8	24	37	30

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 3 (LAK-2) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
1.6-2.1	A-1	14.0	122.8	57.3	32
1.0-1.5	A-1	14.0	122.8	57.3	32
1.1-1.6	D-1	14.0	122.8	57.3	32
4.1-4.6	A-2	12.0	123.9	79.0	55
4.0-4.5	D-2	12.0	123.9	79.0	55
4.7-5.2	D-2	12.5	125.2	71.3	55
14.7-15.2	C-3	13.1	125.3	30.2	21
14.6-15.1	A-3	13.1	125.3	30.2	21
14.6-15.1	D-3	13.1	125.3	46.1	21

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 3 (LAK-2) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
1.6-2.1	A-1	128.2	14.7	35.1	68.4	20.2
1.0-1.5	A-1	127.6	13.3	45.2	119.9	10.8
1.1-1.6	D-1	124.8	14.3	59.8	150.6	16.6
4.1-4.6	A-2	125.1	13.0	37.8	77.9	24.9
4.0-4.5	D-2	126.5	14.0	44.9	96.6	27.9
4.7-5.2	D-2	127.2	18.2	59.9	153.5	9.5
14.7-15.2	C-3	126.0	14.4	48.0	104.0	21.0
14.6-15.1	A-3	124.2	14.0	54.0	116.4	24.2
14.6-15.1	D-3	132.5	12.0	59.8	173.2	3.7

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 3 (LAK-2) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\varepsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
1.6-2.1	A-1	8.0	15.0	18.8	31.9
1.0-1.5	A-1	10.5	14.9	26.9	31.4
1.1-1.6	D-1	9.0	14.9	25.5	30.8
4.1-4.6	A-2	2.2	15.0	20.3	37.4
4.0-4.5	D-2	2.1	15.0	21.4	37.1
4.7-5.2	D-2	10.1	14.9	26.0	28.8
14.7-15.2	C-3	10.2	14.9	21.6	30.6
14.6-15.1	A-3	4.1	15.0	21.5	30.8
14.6-15.1	D-3	7.2	14.9	29.1	30.2

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 4 (ATH-33) – Part 1

Depth (ft)	Tube	G <sub>s</sub>	LL (%)	PL (%)	PI (%)	Type
5.9-6.1 & 6.1-6.4	A-1 & B-1	2.72	29	18	11	A-6a
5.5-6.0	B-1	2.72	29	18	11	A-6a
5.9-6.4	D-1	2.72	29	18	11	A-6a
8.8-9.3	B-2	2.70	29	18	11	A-6a
9.0-9.5	D-2	2.70	29	18	11	A-6a
9.5-9.5 & 9.6-10.0	B-2 & D-2	2.70	29	18	11	A-6a
20.0-20.5	A-3	2.70	45	21	24	A-7-6
20.0-20.5	B-3	2.70	45	21	24	A-7-6
20.0-20.5	D-3	2.70	45	21	24	A-7-6

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 4 (ATH-33) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
5.9-6.1 & 6.1-6.4	A-1 & B-1	4	26	37	33
5.5-6.0	B-1	4	26	37	33
5.9-6.4	D-1	4	26	37	33
8.8-9.3	B-2	5	23	40	32
9.0-9.5	D-2	5	23	40	32
9.5-9.5 & 9.6-10.0	B-2 & D-2	5	23	40	32
20.0-20.5	A-3	1	23	32	44
20.0-20.5	B-3	1	23	32	44
20.0-20.5	D-3	1	23	32	44

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 4 (ATH-33) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
5.9-6.1 & 6.1-6.4	A-1 & B-1	12.7	119.7	38.0	61
5.5-6.0	B-1	12.7	119.7	38.0	61
5.9-6.4	D-1	12.7	119.7	38.0	61
8.8-9.3	B-2	12.0	109.2	25.8	27
9.0-9.5	D-2	12.0	109.2	25.8	27
9.5-9.5 & 9.6-10.0	B-2 & D-2	12.0	109.2	25.8	27
20.0-20.5	A-3	22.0	105.1	41.8	25
20.0-20.5	B-3	22.0	105.1	41.8	25
20.0-20.5	D-3	22.0	105.1	41.8	25

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 4 (ATH-33) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
5.9-6.1 & 6.1-6.4	A-1 & B-1	120.2	15.8	37.6	86.5	19.3
5.5-6.0	B-1	125.1	16.7	45.1	108.1	21.4
5.9-6.4	D-1	122.0	17.5	60.1	142.2	27.7
8.8-9.3	B-2	125.6	18.0	44.9	114.8	17.6
9.0-9.5	D-2	118.7	18.8	52.3	103.4	31.9
9.5-9.5 & 9.6-10.0	B-2 & D-2	121.9	18.1	60.1	132.9	26.6
20.0-20.5	A-3	115.6	20.6	51.6	96.3	25.3
20.0-20.5	B-3	117.1	23.9	59.9	101.6	32.1
20.0-20.5	D-3	112.0	21.4	64.3	125.3	28.9

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 4 (ATH-33) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\epsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
5.9-6.1 & 6.1-6.4	A-1 & B-1	6.0	15.0	23.2	34.8
5.5-6.0	B-1	7.4	15.0	24.3	34.8
5.9-6.4	D-1	7.5	15.0	23.9	33.9
8.8-9.3	B-2	3.2	14.9	25.9	34.1
9.0-9.5	D-2	4.0	15.0	19.1	33.7
9.5-9.5 & 9.6-10.0	B-2 & D-2	2.9	15.0	22.2	31.4
20.0-20.5	A-3	50.0	15.0	17.6	27.4
20.0-20.5	B-3	25.0	12.7	15.0	25.4
20.0-20.5	D-3	53.0	15.0	18.8	27.6

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 5 (MRW-71) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
10.5-11.0	B-1	2.70	28	15	13	A-6a
10.5-11.0	C-1	2.70	28	15	13	A-6a
10.5-11.0	D-1	2.70	28	15	13	A-6a
13.3-13.8	D-2	2.70	30	17	13	A-4a
13.8-14.3	C-2	2.70	30	17	13	A-4a
13.3-13.7	C-2	2.70	30	17	13	A-4a
17.9-18.4	B-3	2.64	30	18	12	A-4a
18.2-18.6	D-3	2.64	30	18	12	A-4a
17.6-18.1	C-3	2.64	30	18	12	A-4a

[Note] Green Color = A-6 Soils; Pink = A-4 Soils

# Task 5

- Laboratory Test Results for Site 5 (MRW-71) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
10.5-11.0	B-1	8	27	40	25
10.5-11.0	C-1	8	27	40	25
10.5-11.0	D-1	8	27	40	25
13.3-13.8	D-2	3	23	47	27
13.8-14.3	C-2	3	23	47	27
13.3-13.7	C-2	3	23	47	27
17.9-18.4	B-3	8	24	44	25
18.2-18.6	D-3	8	24	44	25
17.6-18.1	C-3	8	24	44	25

[Note] Green Color = A-6 Soils; Pink = A-4 Soils

# Task 5

- Laboratory Test Results for Site 5 (MRW-71) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
10.5-11.0	B-1	11.4	128.2	47.8	13
10.5-11.0	C-1	11.4	128.2	47.8	13
10.5-11.0	D-1	11.4	128.2	47.8	13
13.3-13.8	D-2	14.8	111.4	19.1	23
13.8-14.3	C-2	14.8	111.4	19.1	23
13.3-13.7	C-2	14.8	111.4	19.1	23
17.9-18.4	B-3	16.0	110.0	20.8	38
18.2-18.6	D-3	16.0	110.0	20.8	38
17.6-18.1	C-3	16.0	110.0	20.8	38

[Note] Green Color = A-6 Soils; Pink = A-4 Soils

# Task 5

- Laboratory Test Results for Site 5 (MRW-71) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
10.5-11.0	B-1	129.6	13.2	45.2	100.4	24.0
10.5-11.0	C-1	131.6	13.5	52.5	110.7	29.2
10.5-11.0	D-1	127.2	13.6	60.0	112.4	38.3
13.3-13.8	D-2	125.4	15.1	45.0	112.6	18.0
13.8-14.3	C-2	131.3	13.1	52.4	129.5	19.7
13.3-13.7	C-2	123.4	16.8	60.2	127.7	31.4
17.9-18.4	B-3	126.0	14.7	50.1	114.9	24.7
18.2-18.6	D-3	123.8	20.5	60.0	122.2	39.2
17.6-18.1	C-3	114.4	20.6	64.8	110.7	44.3

[Note] Green Color = A-6 Soils; Pink = A-4 Soils

# Task 5

- Laboratory Test Results for Site 5 (MRW-71) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\epsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
10.5-11.0	B-1	2.7	15.0	22.3	34.4
10.5-11.0	C-1	5.0	15.0	20.9	33.7
10.5-11.0	D-1	9.0	15.0	17.7	33.2
13.3-13.8	D-2	5.1	15.0	25.4	33.8
13.8-14.3	C-2	5.3	15.0	25.1	32.7
13.3-13.7	C-2	4.0	15.1	21.1	32.7
17.9-18.4	B-3	6.8	14.9	23.1	34.1
18.2-18.6	D-3	3.1	15.0	20.0	36.9
17.6-18.1	C-3	4.7	15.1	15.1	31.8

[Note] Green Color = A-6 Soils; Pink = A-4 Soils

# Task 5

- Laboratory Test Results for Site 6 (ERI-2) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
2.95	B-1	2.68	49	22	27	A-7-6
3.25	B-1	2.68	60	24	36	A-7-6
3.50	D-1	2.68	60	24	36	A-7-6
6.50	D-2	2.68	48	22	26	A-7-6
7.05	D-2	2.68	55	23	22	A-7-6
7.15	B-2	2.68	55	23	22	A-7-6
11.75	B-3	2.71	61	24	37	A-7-6
11.75	C-3	2.71	61	24	37	A-7-6
11.75	D-3	2.71	61	24	37	A-7-6

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 6 (ERI-2) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
2.95	B-1	1	3	38	58
3.25	B-1	1	3	34	62
3.50	D-1	1	3	34	62
6.50	D-2	0	2	46	52
7.05	D-2	0	2	36	61
7.15	B-2	0	2	36	61
11.75	B-3	1	3	30	66
11.75	C-3	1	3	30	66
11.75	D-3	1	3	30	66

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 6 (ERI-2) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
2.95	B-1	25.4	98.0	21.3	9
3.25	B-1	26.0	97.7	18.9	11
3.50	D-1	26.0	97.7	18.9	11
6.50	D-2	24.6	101.0	24.3	8
7.05	D-2	28.1	97.1	21.2	11
7.15	B-2	28.1	97.1	21.2	11
11.80	B-3	25.7	97.6	16.9	19
11.80	C-3	25.7	97.6	16.9	19
13.15	D-3	25.7	97.6	16.9	19

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 6 (ERI-2) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
2.95	B-1	100.6	24.7	59.5	95.9	37.2
3.25	B-1	100.4	27.0	45.2	65.4	32.6
3.50	D-1	99.3	30.0	35.2	48.6	29.5
6.50	D-2	102.6	25.7	50.0	73.2	34.7
7.05	D-2	98.0	27.7	40.2	55.5	31.6
7.15	B-2	103.1	29.1	59.9	90.3	39.8
11.80	B-3	106.2	23.3	45.0	80.8	29.1
11.80	C-3	104.5	24.0	52.3	82.0	34.6
13.15	D-3	102.8	26.2	57.2	87.6	38.8

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 6 (ERI-2) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\varepsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
2.95	B-1	72.0	15.0	13.5	26.7
3.25	B-1	45.0	15.0	10.6	26.6
3.50	D-1	10.2	15.0	9.2	35.6
6.50	D-2	20.0	15.0	10.9	25.6
7.05	D-2	75.0	15.0	9.2	28.1
7.15	B-2	110.0	15.0	11.7	25.5
11.80	B-3	23.0	15.0	12.9	26.6
11.80	C-3	30.0	15.0	12.8	27.2
13.15	D-3	79.0	15.0	12.1	26.9

[Note] Blue Color = A-7-6 Soils

# Task 5

- Laboratory Test Results for Site 7 (HAN-75) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
6.55	D-1	2.69	41	19	22	A-7-6
6.75	C-1	2.69	41	19	22	A-7-6
7.00	A-1	2.69	45	21	24	A-7-6
10.95	A-2	2.69	47	22	25	A-7-6
10.95	B-2	2.69	47	22	25	A-7-6
11.05	D-2	2.69	38	20	18	A-6b
17.45	A-3	2.68	39	19	20	A-6b
17.45	B-3	2.68	39	19	20	A-6b
17.65	D-3	2.68	39	19	20	A-6b

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 7 (HAN-75) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
6.55	D-1	2	19	32	46
6.75	C-1	2	19	32	46
7.00	A-1	3	16	33	48
10.95	A-2	1	16	32	50
10.95	B-2	1	16	32	50
11.05	D-2	1	19	36	44
17.45	A-3	3	17	34	47
17.45	B-3	3	17	34	47
17.65	D-3	3	17	34	47

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 7 (HAN-75) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
6.55	D-1	20.0	110.1	24.6	34
6.75	C-1	20.0	110.1	24.6	34
7.00	A-1	21.4	107.2	39.4	34
10.95	A-2	21.4	107.2	39.4	15
10.95	B-2	21.6	105.1	34.4	15
11.05	D-2	20.1	108.8	35.9	30
17.45	A-3	18.5	111.3	61.2	23
17.45	B-3	18.5	111.3	61.2	42
17.65	D-3	18.5	111.3	61.2	42

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 7 (HAN-75) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
6.55	D-1	111.9	21.4	55.0	90.2	32.8
6.75	C-1	113.5	22.1	47.1	80.5	27.7
7.00	A-1	113.0	22.2	40.0	71.5	22.3
10.95	A-2	110.7	23.7	41.9	70.3	26.0
10.95	B-2	112.6	22.1	48.9	75.9	32.1
11.05	D-2	NA	NA	NA	NA	NA
17.45	A-3	113.5	19.7	45.1	92.1	20.3
17.45	B-3	114.9	17.5	52.3	109.6	23.5
17.65	D-3	116.7	18.2	61.3	128.6	23.9

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 7 (HAN-75) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\epsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
6.55	D-1	60.0	15.0	14.0	26.2
6.75	C-1	46.0	15.0	15.2	27.6
7.00	A-1	19.0	15.0	16.4	28.0
10.95	A-2	40.0	15.0	14.7	28.2
10.95	B-2	36.0	15.0	12.5	26.5
11.05	D-2	NA	NA	NA	NA
17.45	A-3	9.0	15.0	20.0	29.1
17.45	B-3	9.3	15.0	20.7	30.2
17.65	D-3	NA	15.0	20.7	28.3

[Note] Blue Color = A-7-6 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 8 (JAC-32) – Part 1

Depth (ft)	w (%)	G <sub>s</sub>	LL (%)	PL (%)	PI (%)	Type
2.90	11	2.66	NP	NP	NP	A-3a
3.90	14	2.66	23	15	8	A-4a
4.25	10	2.67	21	17	4	A-2-4
4.75	10	2.67	NP	NP	NP	A-3a
10.55	13	NA	NP	NP	NP	A-3a

# Task 5

- Laboratory Test Results for Site 8 (JAC-32) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
2.90	C-1	13	56	20	11
3.90	C-1	1	49	26	24
4.25	A-2	29	41	17	13
4.75	A-2	27	50	15	8
10.55	D-3	6	53	25	16

# Task 5

- Laboratory Test Results for Site 8 (JAC-32) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
2.90	C-1	11.0	121.3	7.7	37
3.90	C-1	14.0	118.1	25.2	33
4.25	A-2	9.5	127.4	12.1	33
4.75	A-2	10.5	122.2	10.3	33
10.55	D-3	12.7	120.0	16.2	14

# Task 5

- Laboratory Test Results for Site 8 (JAC-32) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)

**No High Quality Test Specimens Available**  
**Most Soil Samples Cohesionless**  
**No Good Triaxial Compression Tests Results Obtained**

# Task 5

- Laboratory Test Results for Site 8 (JAC-32) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\epsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)

**No Good Quality Test Specimens Available**  
**Most Soil Samples Cohesionless**  
**No Good Triaxial Compression Test Results Obtained**

# Task 5

- Laboratory Test Results for Site 9 (MUS-70) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
9.75		2.70	29	19	10	A-4b
9.75		2.70	29	19	10	A-4b
9.75		2.70	30	19	11	A-4b
10.25		2.66	30	19	11	A-6a
10.25		2.66	30	19	11	A-6a
10.25		2.66	30	19	11	A-6a

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 9 (MUS-70) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
9.75		8	22	50	20
9.75		0	17	59	24
9.75		0	17	59	24
10.25		10	29	42	19
10.25		10	29	42	19
10.25		10	29	42	19

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 9 (MUS-70) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
9.75		14.9	119.1	30.3	22
9.75		15.9	117.2	48.9	22
9.75		15.9	117.2	48.9	22
10.25		13.9	121.4	28.0	30
10.25		13.9	121.4	28.0	30
10.25		13.9	121.4	28.0	30

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 9 (MUS-70) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)

To Be Tested in Near Future

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 9 (MUS-70) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\varepsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)

**To Be Tested in Near Future**

[Note] Pink Color = A-4 Soils; Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 10 (NOB-77) – Part 1

Depth (ft)	Tube	$G_s$	LL (%)	PL (%)	PI (%)	Type
5.25		2.73	37	21	16	A-6b
5.25		2.73	37	21	16	A-6b
5.25		2.73	37	21	16	A-6b
7.75		2.73	39	22	17	A-6b
7.75		2.73	39	22	17	A-6b
8.25		2.73	39	22	17	A-6b
10.75		2.79	34	21	16	A-6a
11.25		2.79	36	21	15	A-6a
11.25		2.79	36	21	15	A-6a

[Note] Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 10 (NOB-77) – Part 2

Depth (ft)	Tube	% G	% S	% M	% C
5.25		13	11	48	28
5.25		13	11	48	28
5.25		13	11	48	28
7.75		4	12	50	34
7.75		7	17	46	30
8.25		7	17	46	30
10.75		15	18	42	25
11.25		12	15	43	30
11.25		12	15	43	30

[Note] Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 10 (NOB-77) – Part 3

Depth (ft)	Tube	w (%)	$\gamma_d$ (pcf)	$q_u$ (psi)	$(N_{60})_1$
5.25		14.0	124.5	20.2	33
5.25		14.0	124.5	20.2	33
5.25		14.0	124.5	20.2	33
7.75		15.2	117.3	18.4	17
7.75		13.5	123.2	21.2	17
8.25		13.5	123.2	21.2	17
10.75		12.5	123.8	20.8	27
11.25		12.5	126.8	30.3	27
11.25		12.5	126.8	30.3	27

[Note] Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 10 (NOB-77) – Part 4

Depth (ft)	Tube	$\gamma_d$ (pcf)	$w_f$ (%)	$\sigma_3$ (psi)	$\sigma_{1f}$ (psi)	$u_f$ (psi)
5.25						
5.25						
5.25						
7.75						
7.75						
8.25						
10.75						
11.25						
11.25						

**To Be Tested in Near Future**

[Note] Green Color = A-6 Soils

# Task 5

- Laboratory Test Results for Site 10 (NOB-77) – Part 5

Depth (ft)	Tube	$t_{50}$ (min)	$\epsilon_f$ (%)	$\phi$ (deg)	$\phi'$ (deg)
5.25					
5.25					
5.25					
7.75					
7.75					
8.25					
10.75					
11.25					
11.25					

To Be Tested in Near Future

[Note] Green Color = A-6 Soils

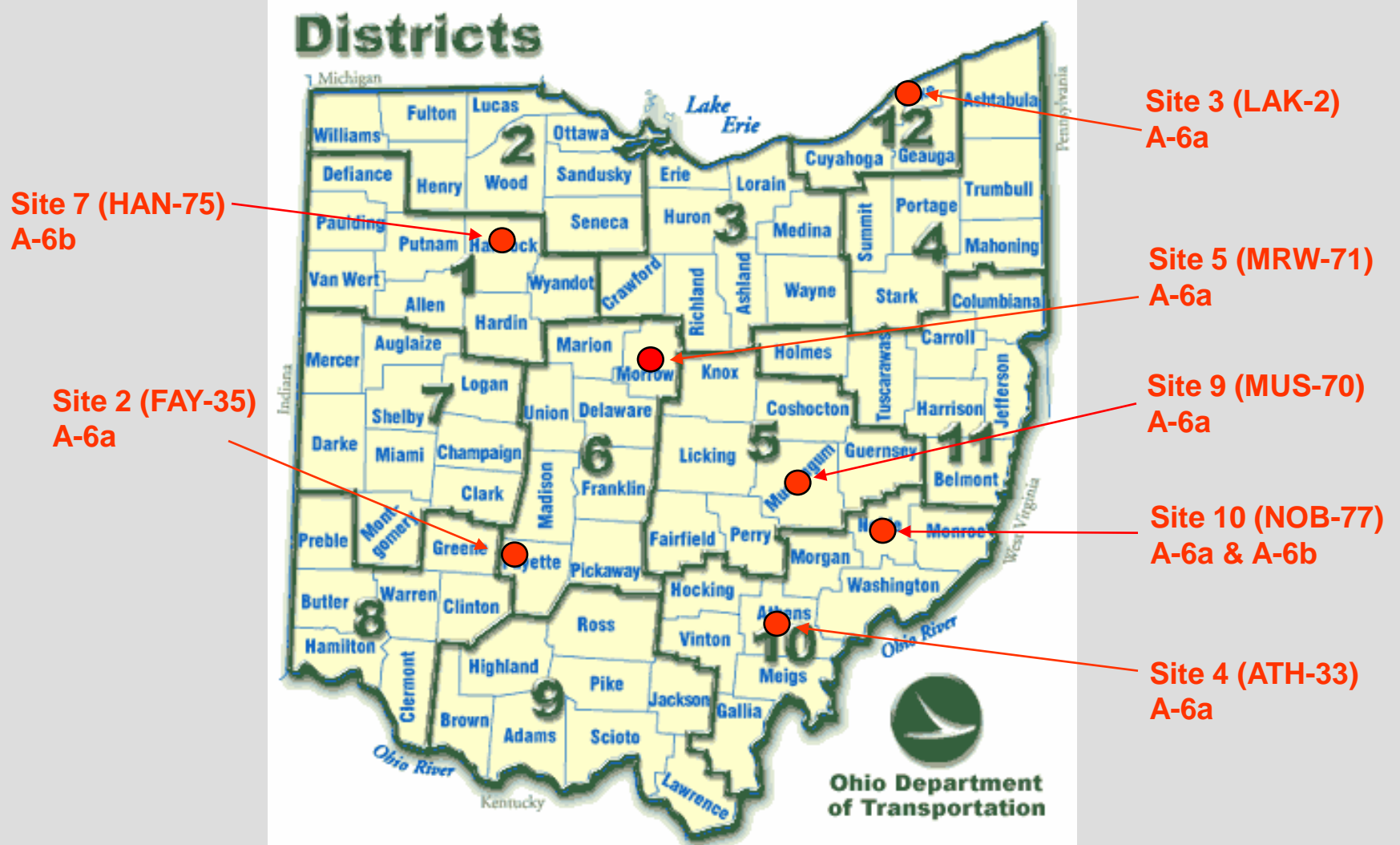
# Task 5

## A-4 Soils Encountered at Field Embankment Sites



# Task 5

## A-6 Soils Encountered at Field Embankment Sites



# Task 5

## A-7-6 Soils Encountered at Field Embankment Sites



# Task 6

## Empirical Correlations

- SPT-N Value vs. Unconfined Compression Strength  $q_u$  for Cohesive Soils – Terzaghi et al (1996)

SPT- $(N_{60})_1$	Strength (psi) Terzaghi: A-4	Strength (psi) Measured: A-4
< 2	< 3.6	(No data)
2-4	3.6-7.3	(No data)
4-8	7.3-14.5	(No data)
8-15	14.5-29	45.1
15-30	29-58	19.1, 30.2, 30.3, 46.1, 48.9
> 30	> 58	20.8, 25.2, 41.0, 71.3, 79.0

[Note] Values in red are well outside the range.

# Task 6

## Empirical Correlations

- SPT-N Value vs. Unconfined Compression Strength  $q_u$  for Cohesive Soils – Terzaghi et al (1996)

SPT- $(N_{60})_1$	Strength (psi) Terzaghi: A-6	Strength (psi) Measured: A-6
< 2	< 3.6	(No data)
2-4	3.6-7.3	(No data)
4-8	7.3-14.5	(No data)
8-15	14.5-29	47.8
15-30	29-58	18.4, 20.8, 21.2, 25.8, 28.0, 30.3, 35.9, 61.2
> 30	> 58	20.2, 36.6, 38.0, 57.3, 61.2

[Note] Values in red are well outside the range.

# Task 6

## Empirical Correlations

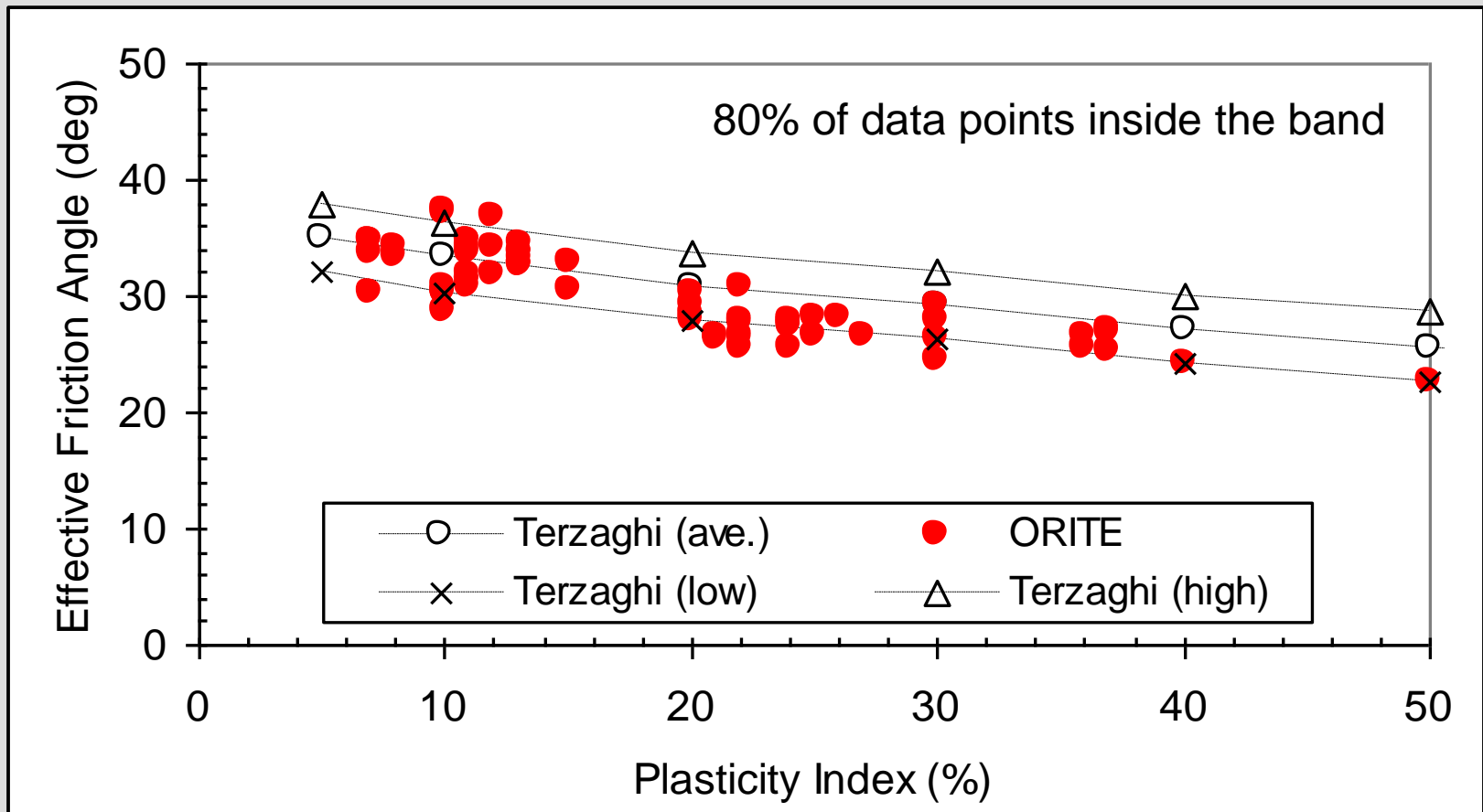
- SPT-N Value vs. Unconfined Compression Strength  $q_u$  for Cohesive Soils – Terzaghi et al (1996)

SPT- $(N_{60})_1$	Strength (psi) Terzaghi: A-7-6	Strength (psi) Measured: A-7-6
< 2	< 3.6	(No data)
2-4	3.6-7.3	(No data)
4-8	7.3-14.5	(No data)
8-15	14.5-29	18.9, 21.3, 21.2, 24.3
15-30	29-58	16.9, 18.7, 24.8, 30.6, 39.4, 41.8
> 30	> 58	24.6, 39.4, 46.9

[Note] Values in red are well outside the range.

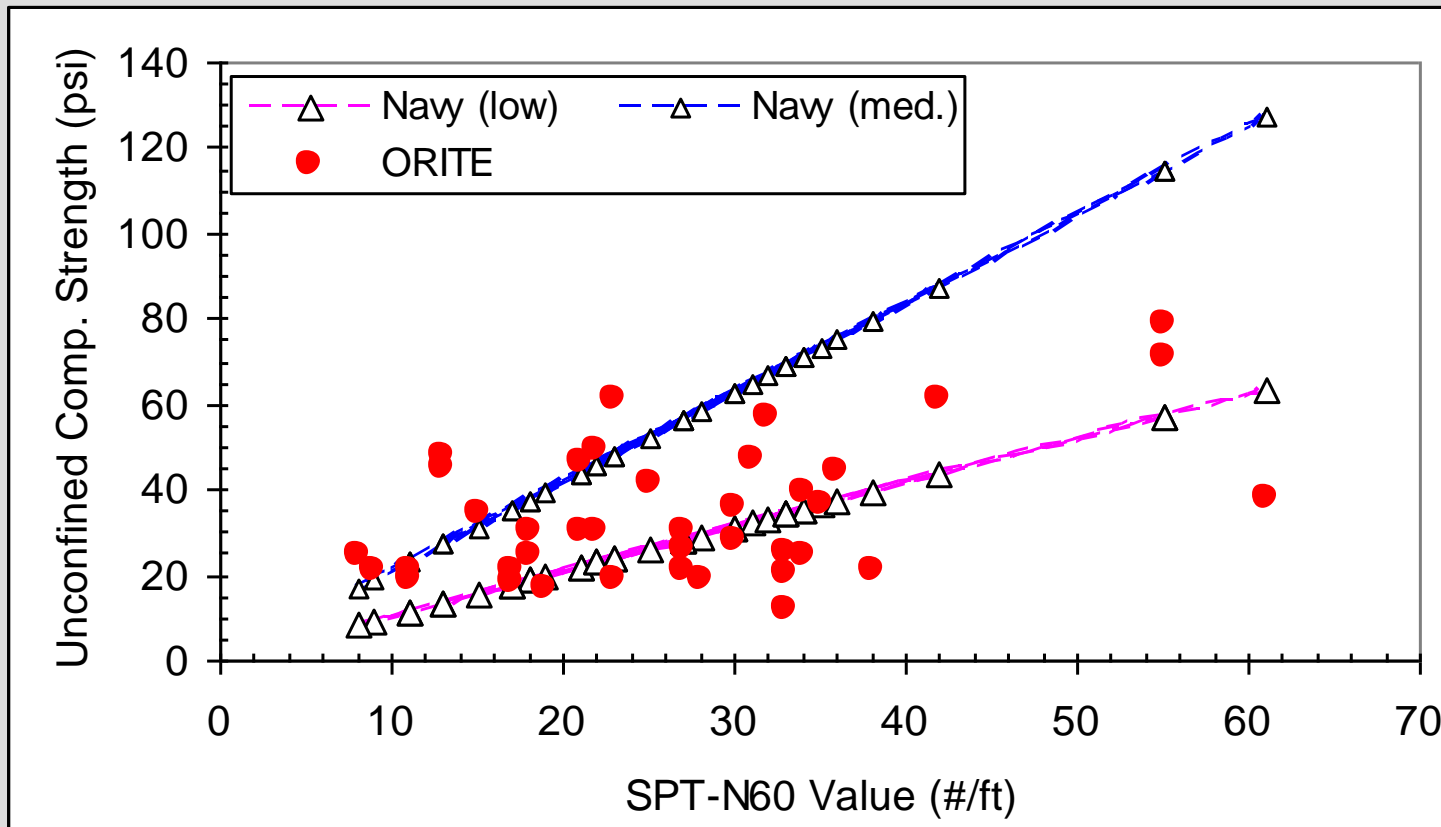
# Task 6

- Correlation Between PI and  $\phi'$  (previously investigated by Terzaghi)



# Task 6

- SPT-N Value vs. Unconfined Compression Strength (previously studied by the Dept. of Navy)



[Note] Total 36 data points; 20 points (51.3%) outside

# Task 6

- Soil Type vs. Effective Friction Angle (previously studied by the Dept. of Navy)

Soil Type	$\phi'$ (deg.) Dept. of Navy	$\phi'$ (deg.) Measured
A-4	32	28.8 to 37.4 (Ave. 33.4)
A-6	28	28.3 to 37.8 (Ave. 32.8)
A-7-6	19-28	24.6 to 35.6 (Ave. 27.3)

[Ref.] Design Manual 7.2 by U.S. Dept. of Navy (1982).

# Task 6

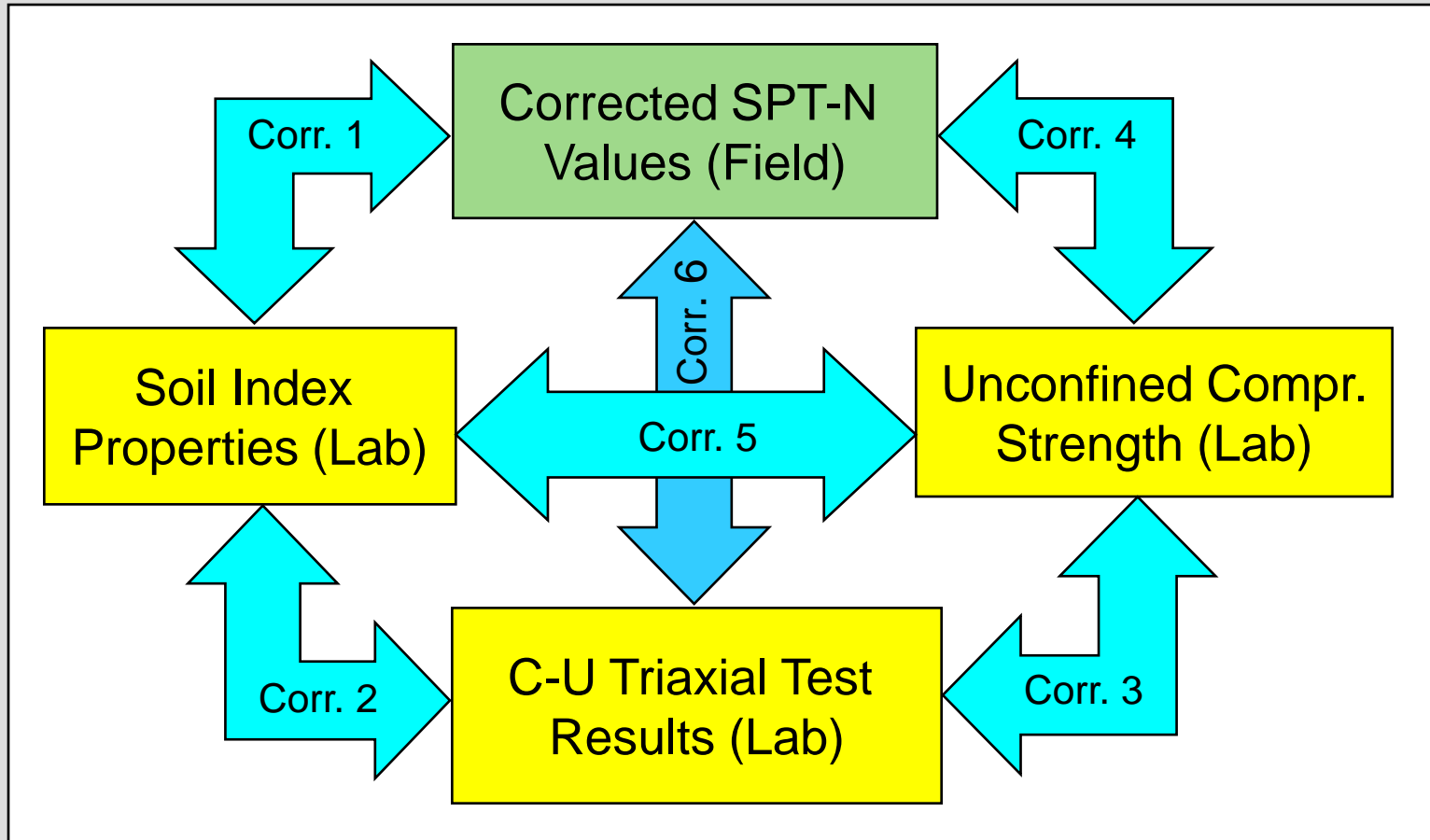


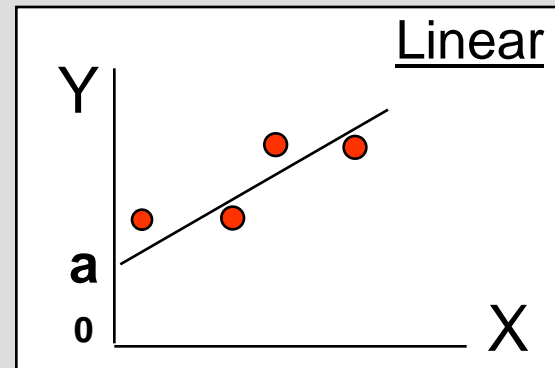
Diagram Showing Six Different Correlation Paths

# Task 6

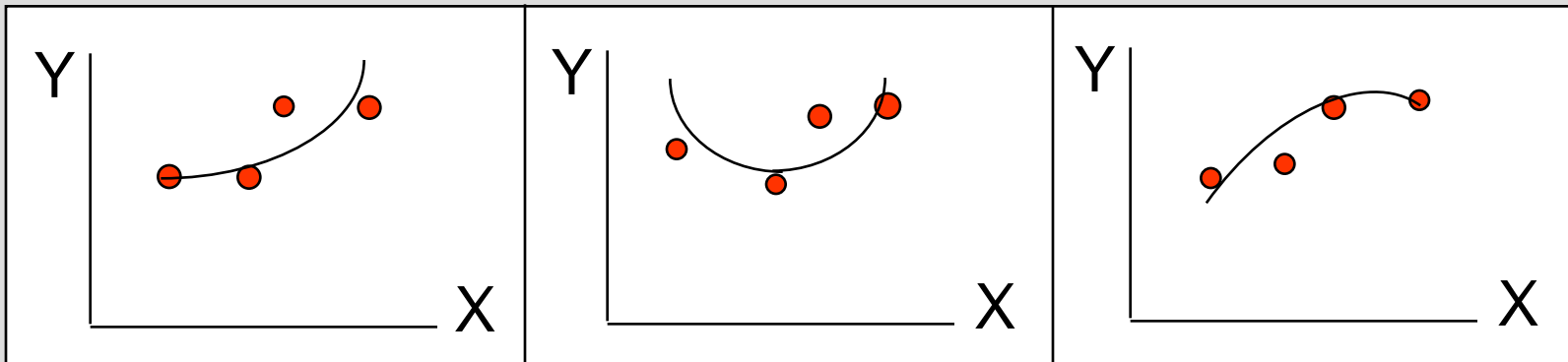
## Models for Statistical Analysis

- Simple Linear X-Y Correlation

$$Y = a_0 + a_1X$$



- Additional X-Y Correlations (higher polynomial, logarithmic, power, exponential, hyperbolic, reciprocal)



# Task 6

## Additional Models for Statistical Analysis

- Higher Polynomial

$$Y = a_0 + a_1X + a_2X^2 + \dots$$

- Logarithmic

$$Y = b + \text{Ln}(X)$$

- Exponential

$$Y = b e^{mX}$$

- Power

$$Y = b x^m$$

- Hyperbolic

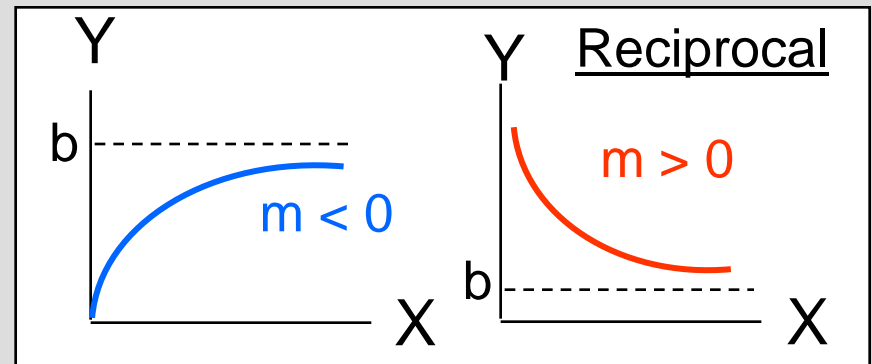
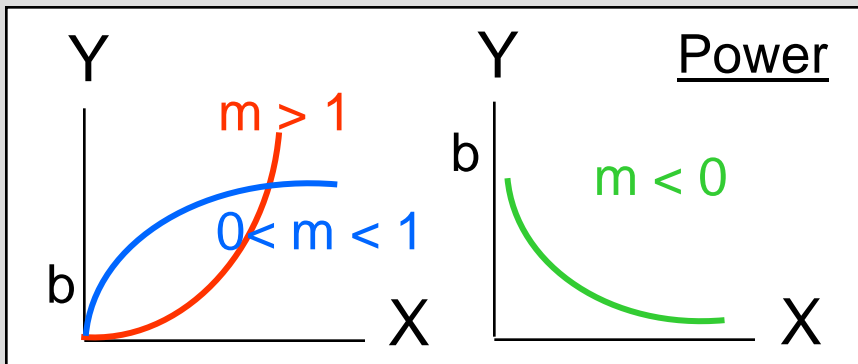
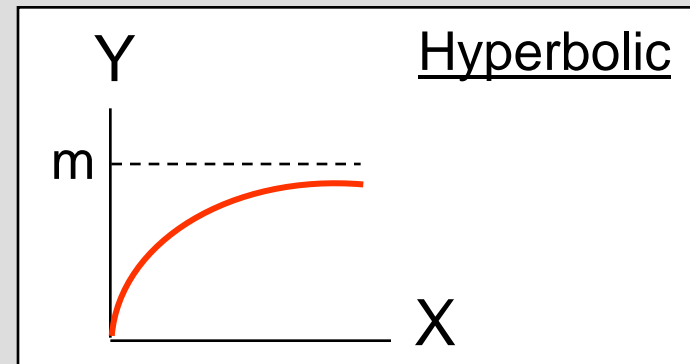
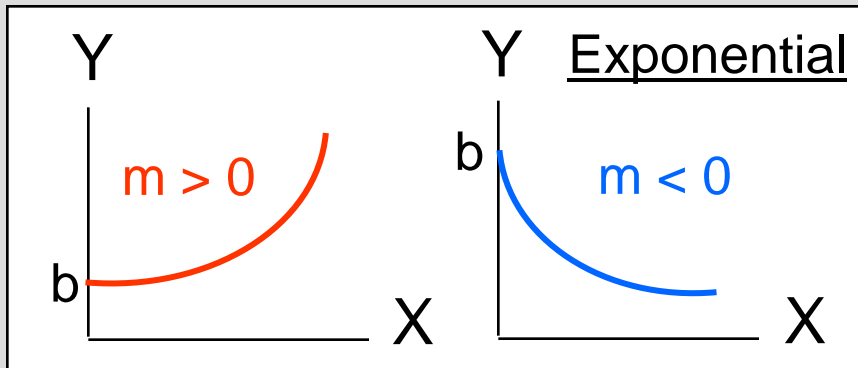
$$Y = (b + mX)/X$$

- Reciprocal

$$Y = b + m(1/X)$$

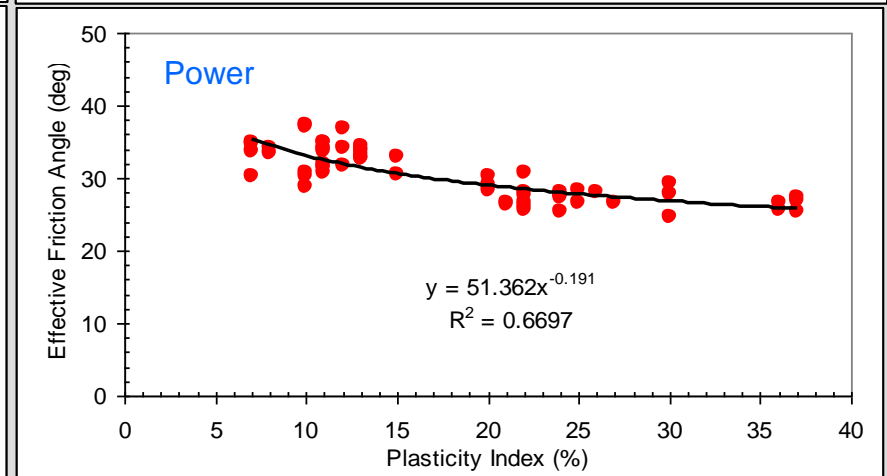
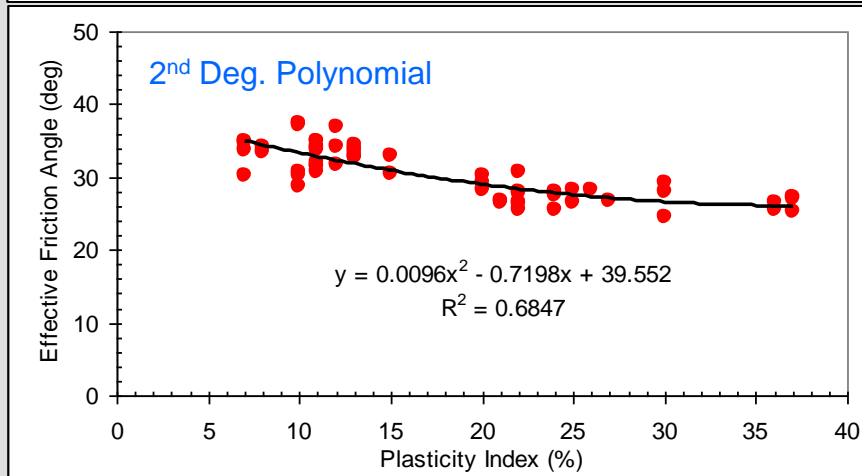
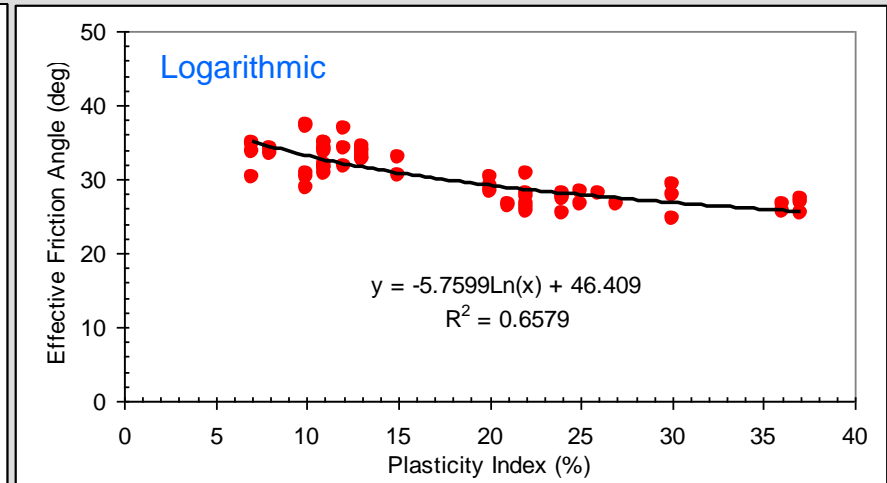
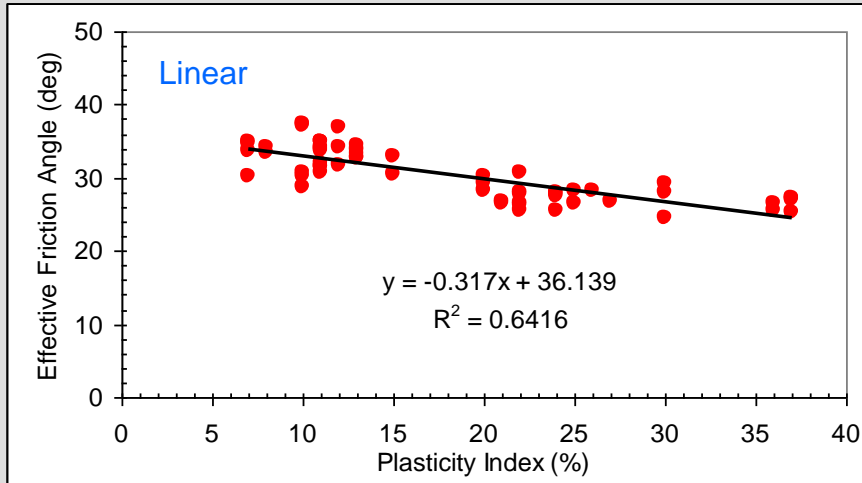
# Task 6

## Additional Models for Statistical Analysis



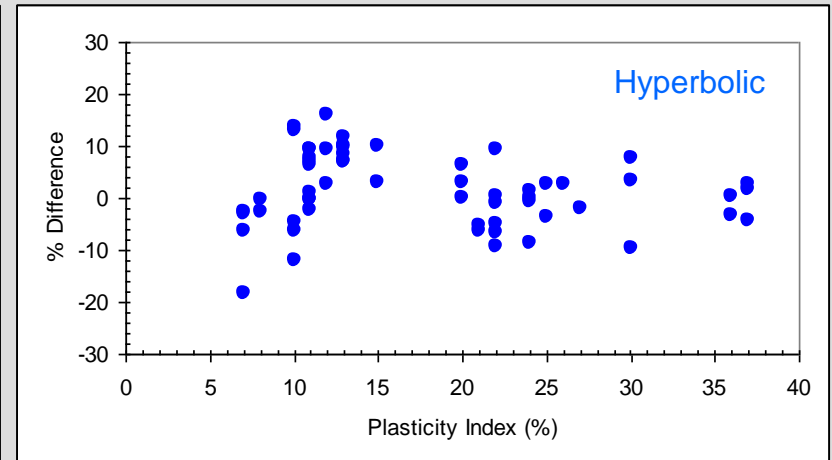
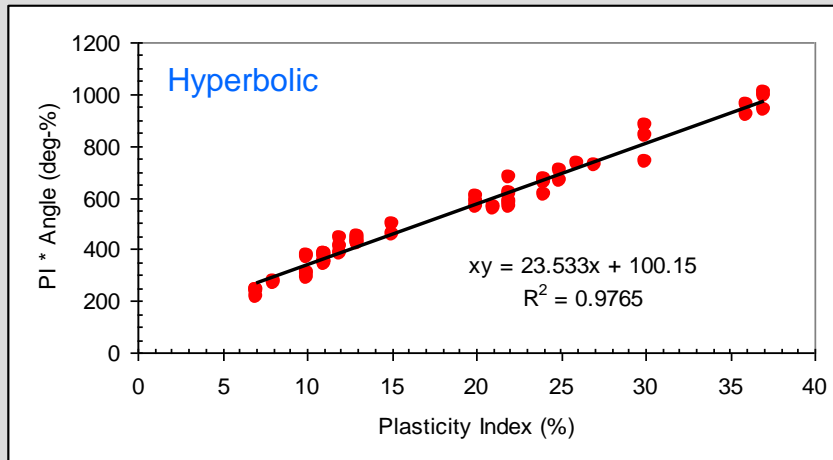
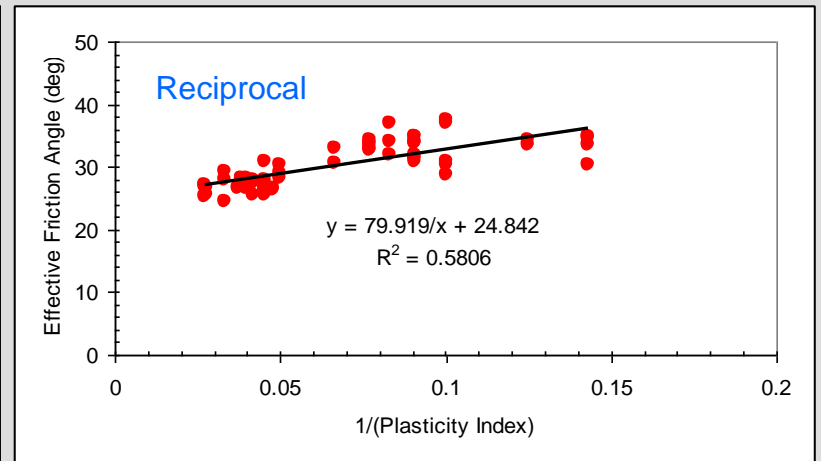
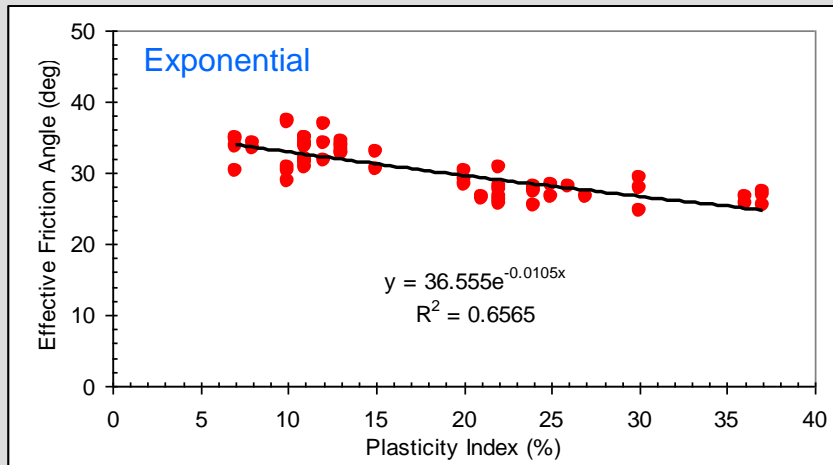
# Task 6

- Plasticity Index vs. Effective Friction Angle



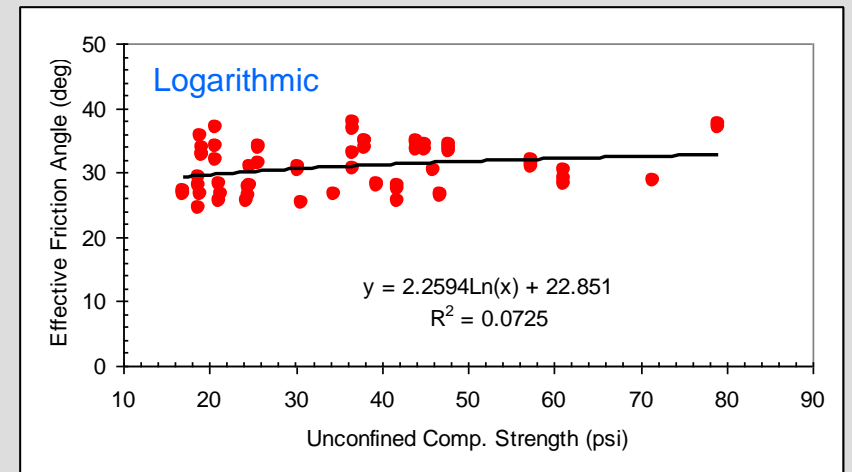
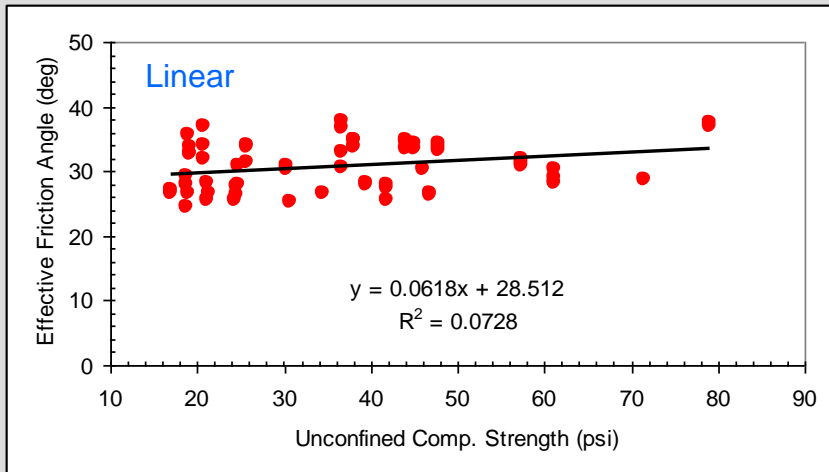
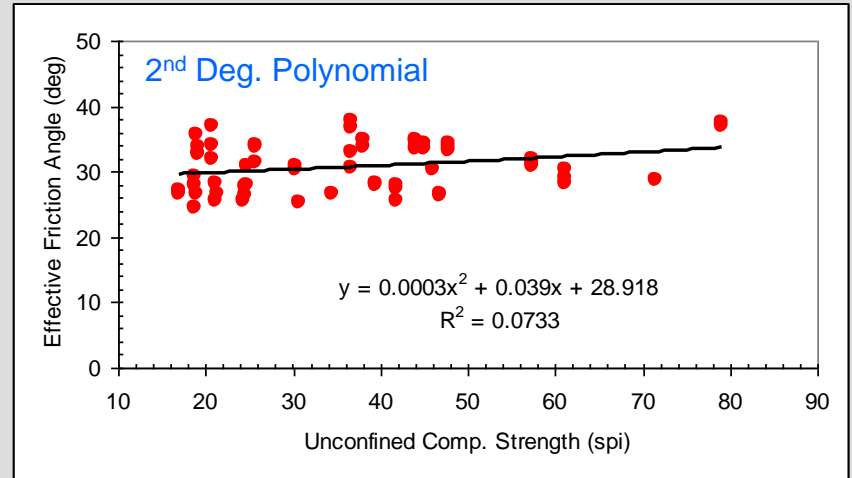
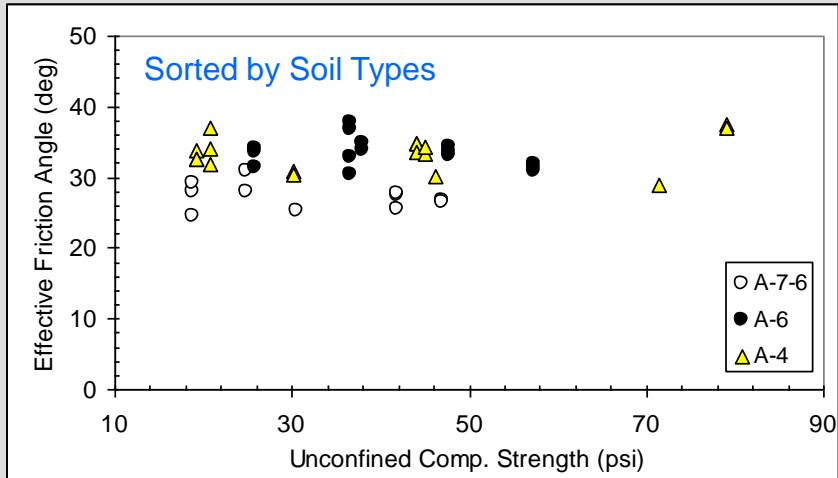
# Task 6

- Plasticity Index vs. Effective Friction Angle



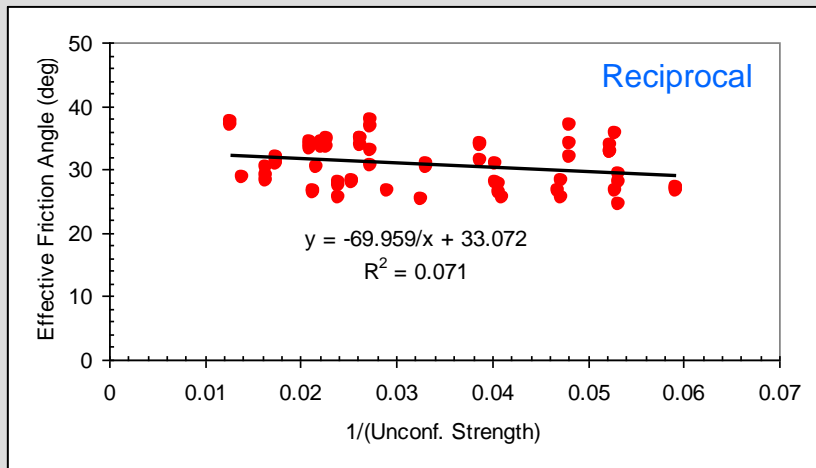
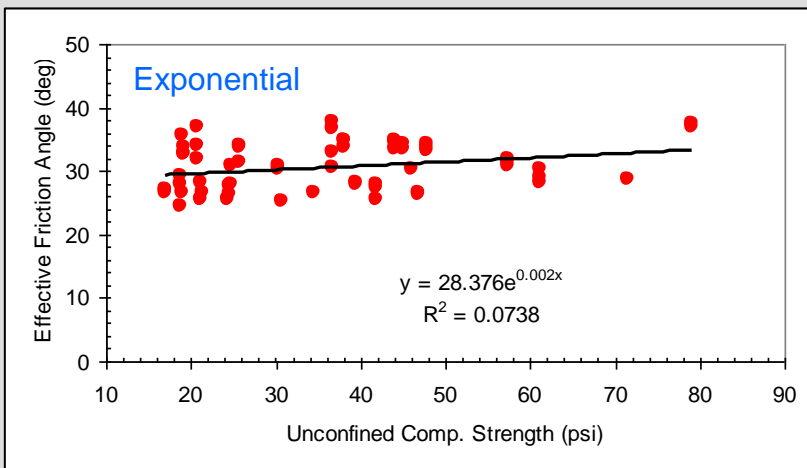
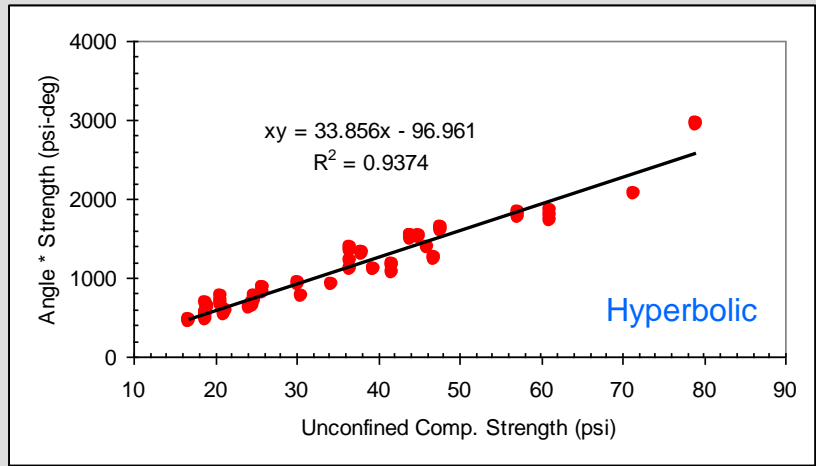
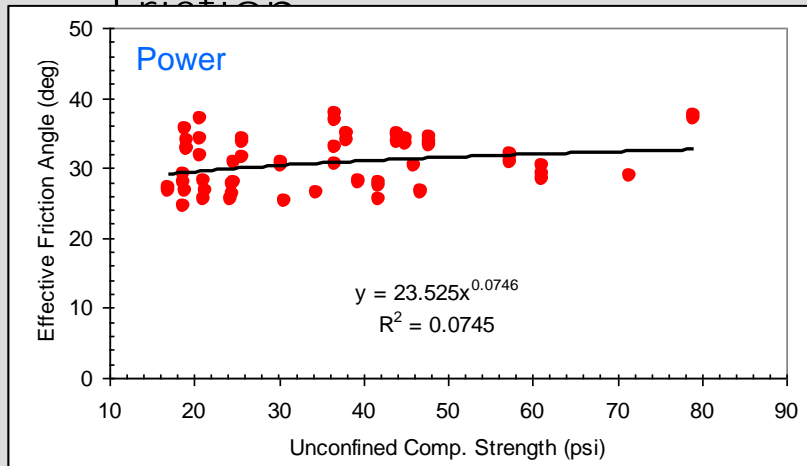
# Task 6

- Unconfined Compression Strength vs. Effective Angle of



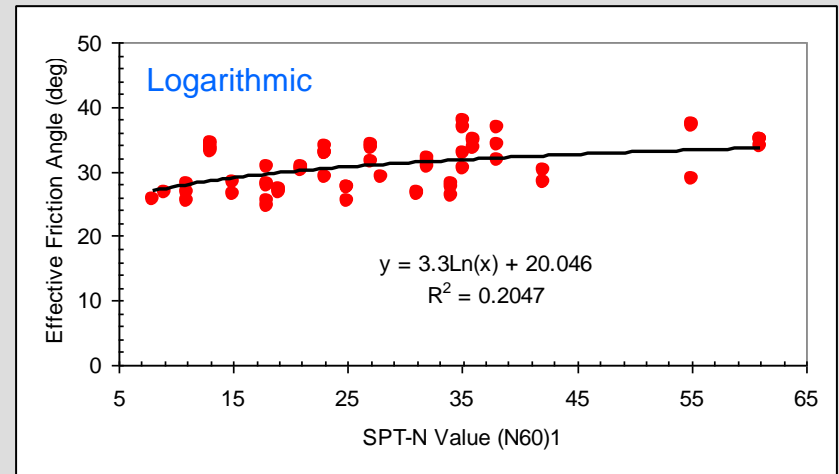
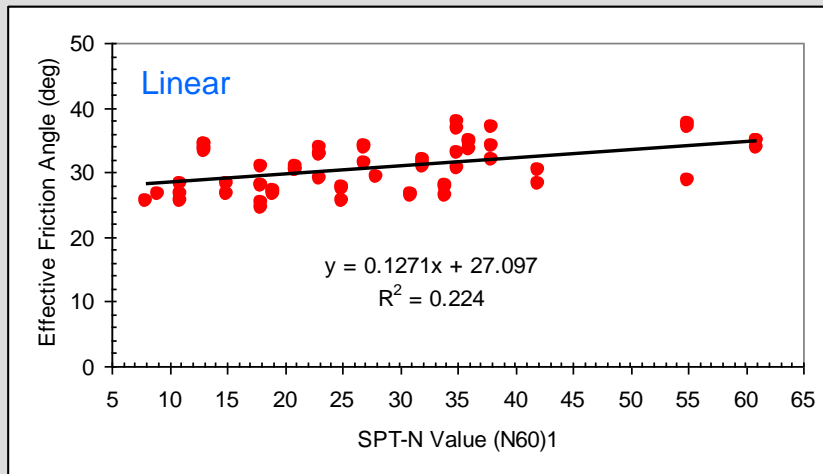
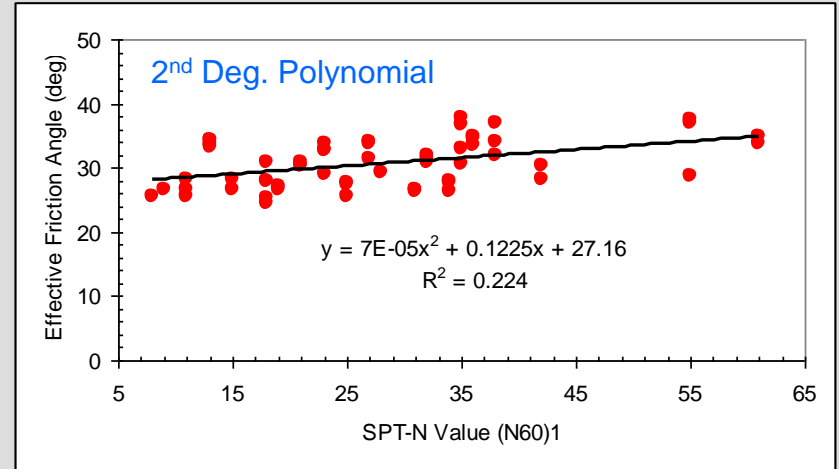
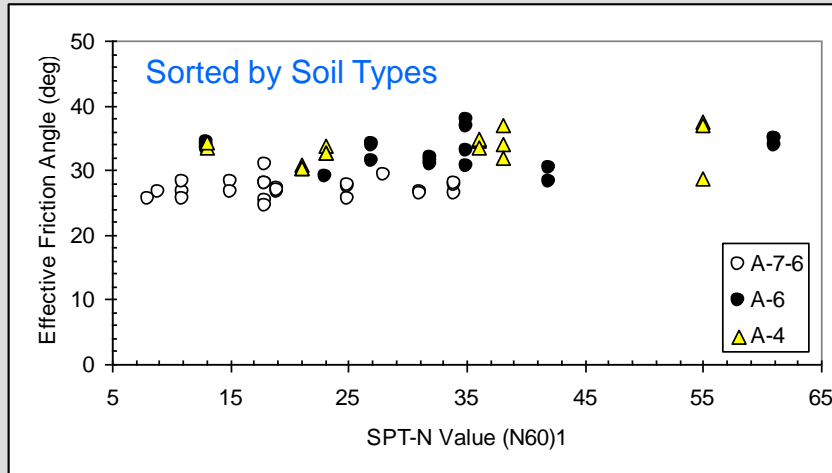
# Task 6

- Unconfined Compression Strength vs. Effective Angle of Friction



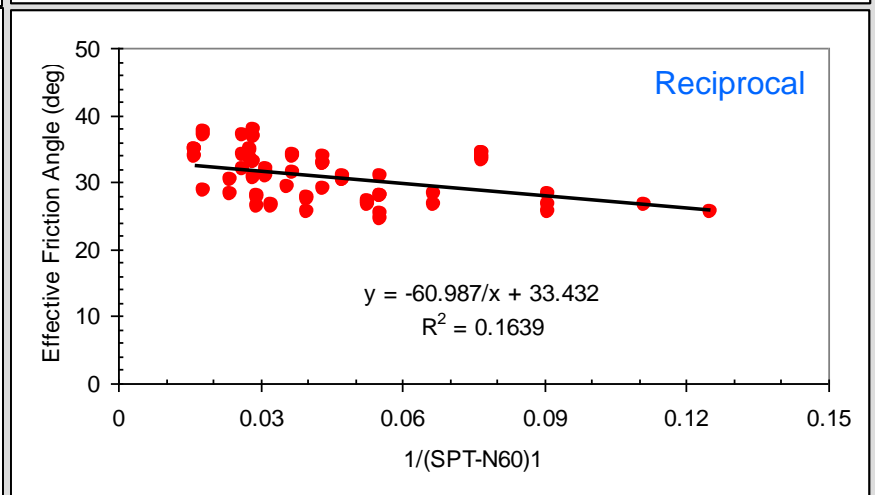
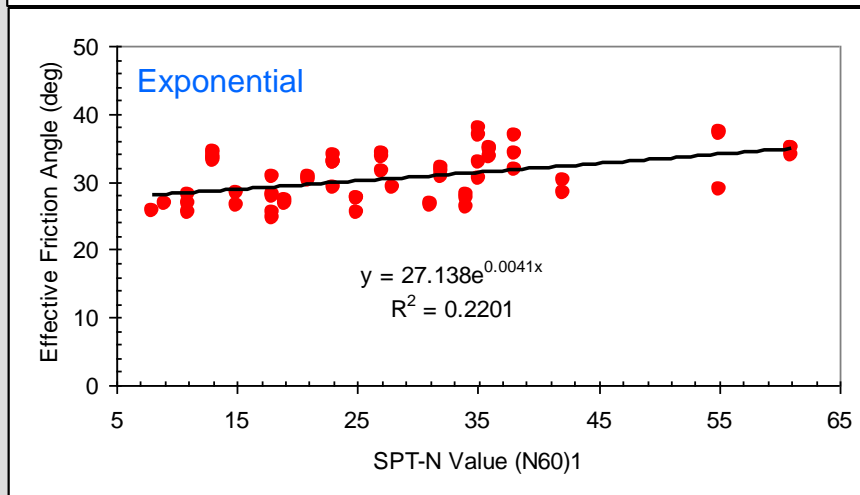
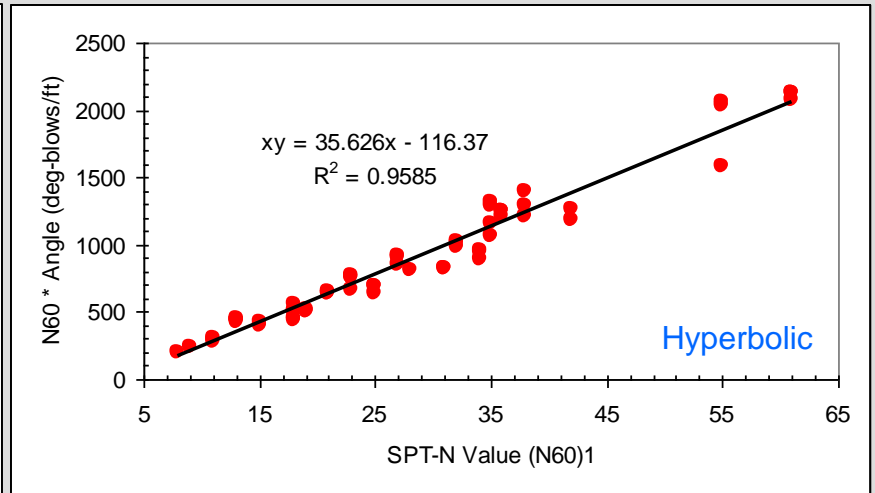
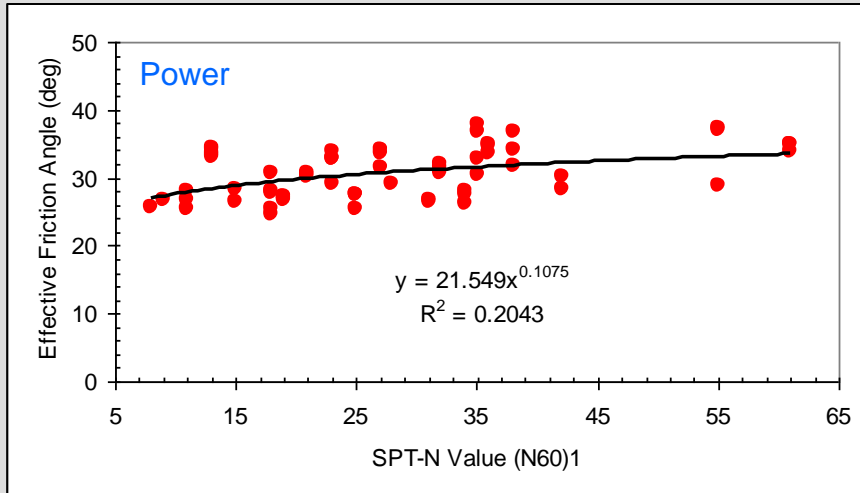
# Task 6

- SPT-N ( $N_{60}$ )<sub>1</sub> Value vs. Effective Friction Angle



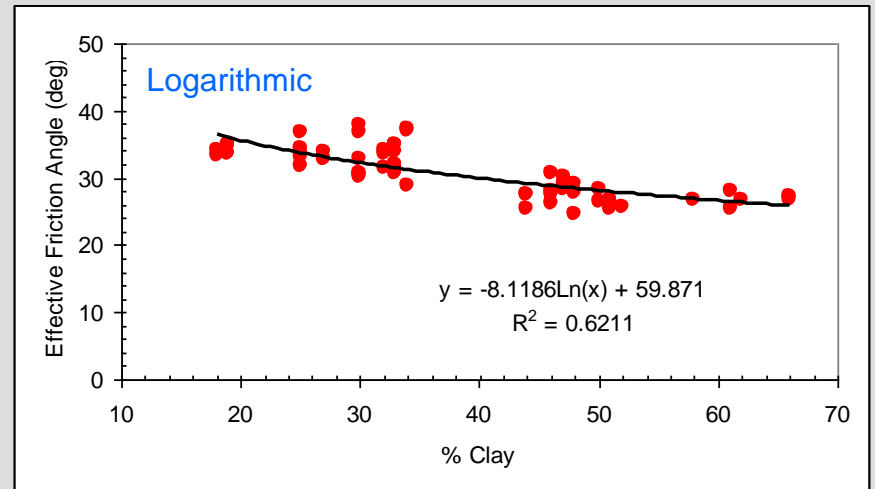
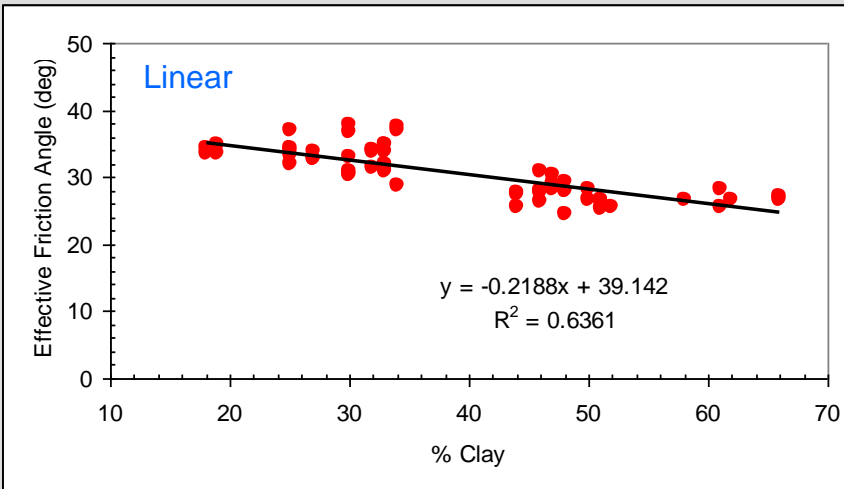
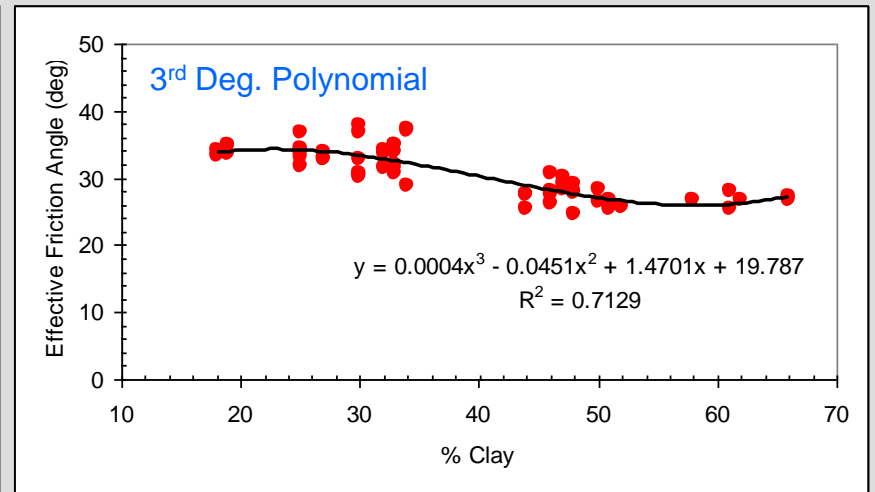
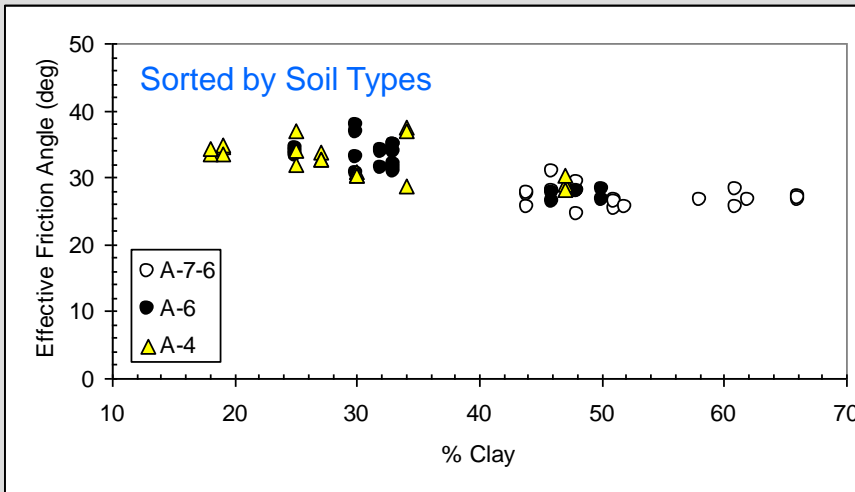
# Task 6

- SPT-N ( $N_{60}$ )<sub>1</sub> Value vs. Effective Friction Angle



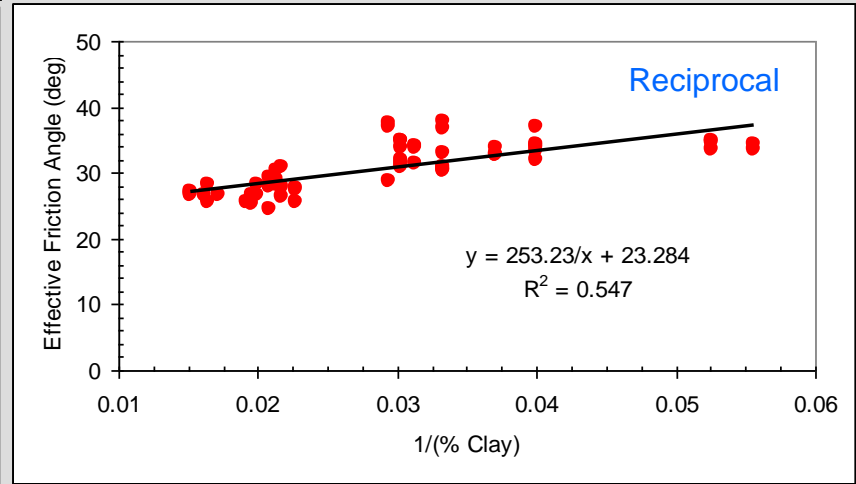
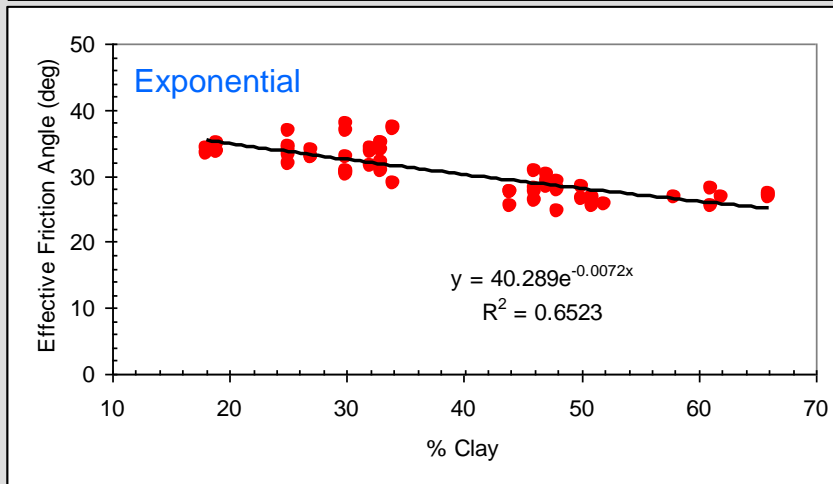
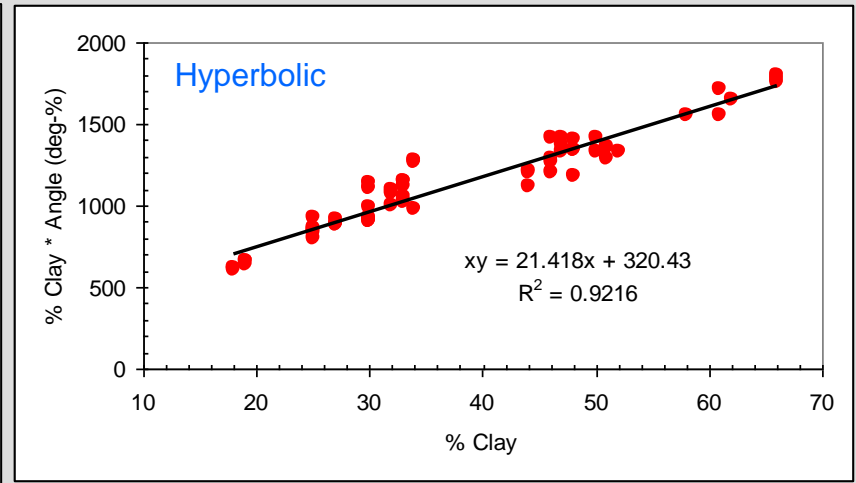
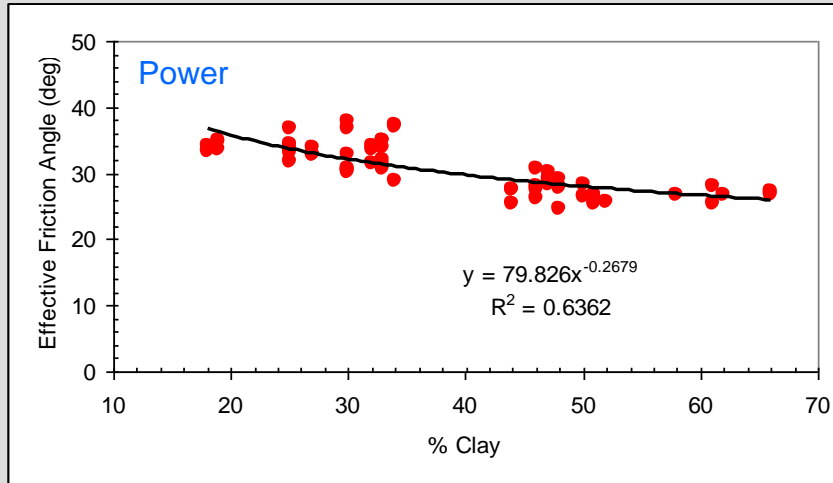
# Task 6

- (% Clay) vs. Effective Friction Angle



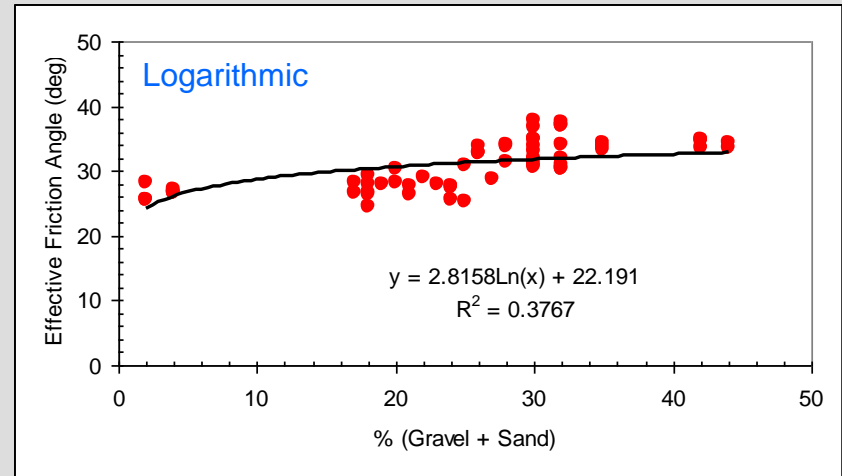
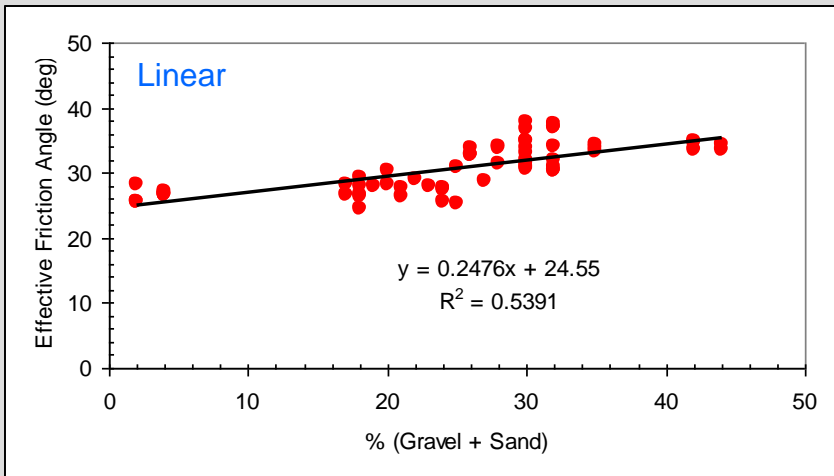
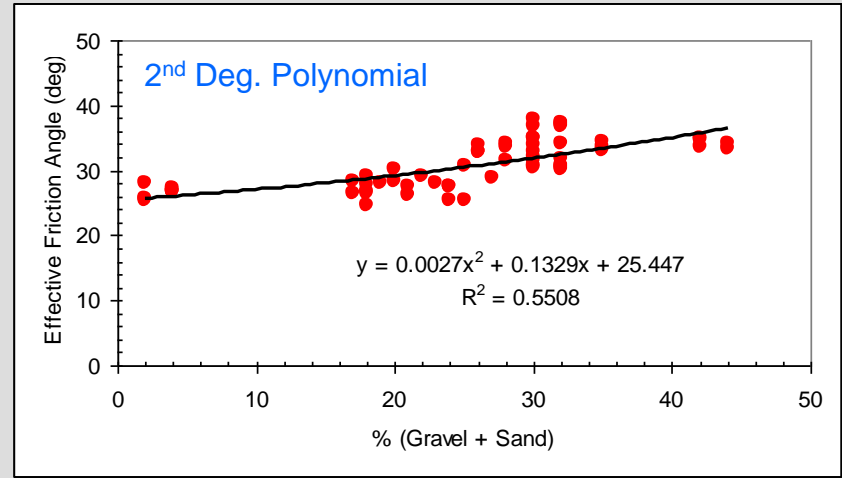
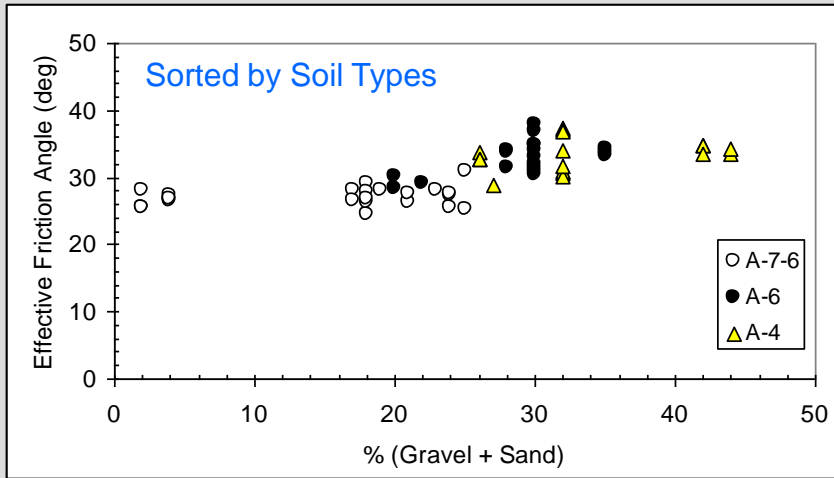
# Task 6

- (% Clay) vs. Effective Friction Angle



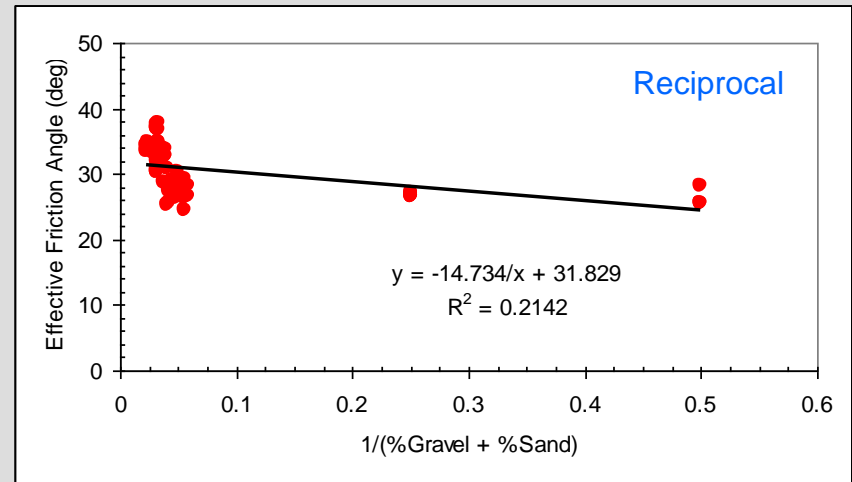
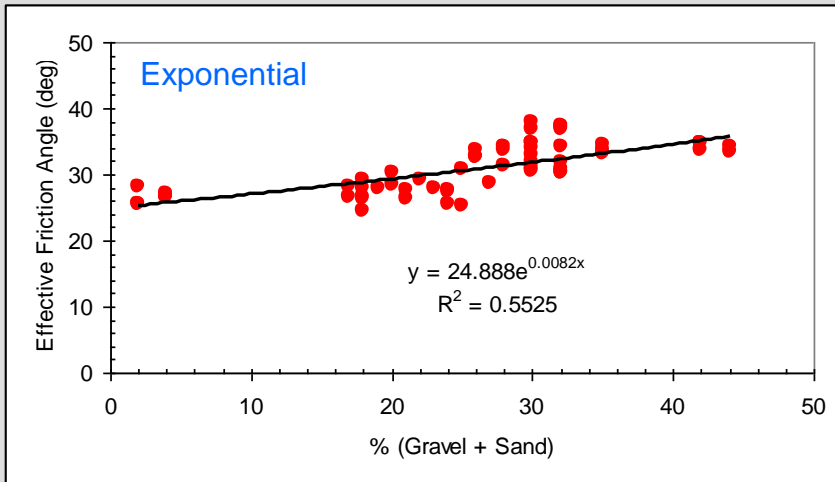
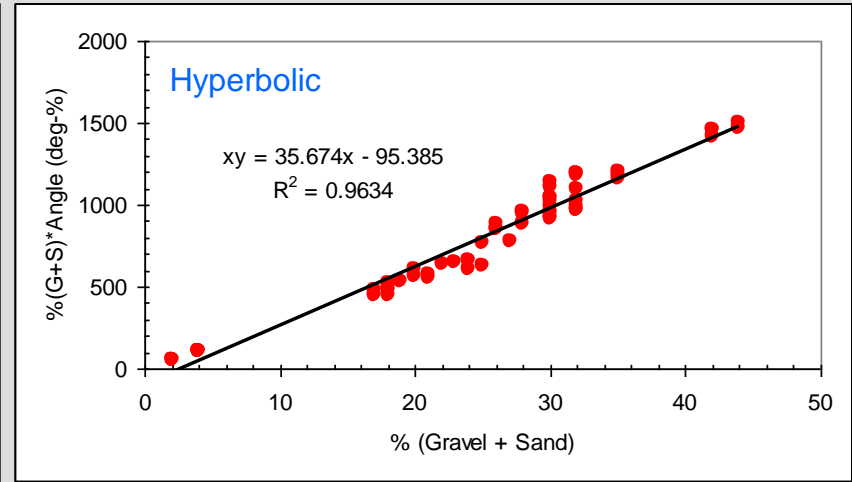
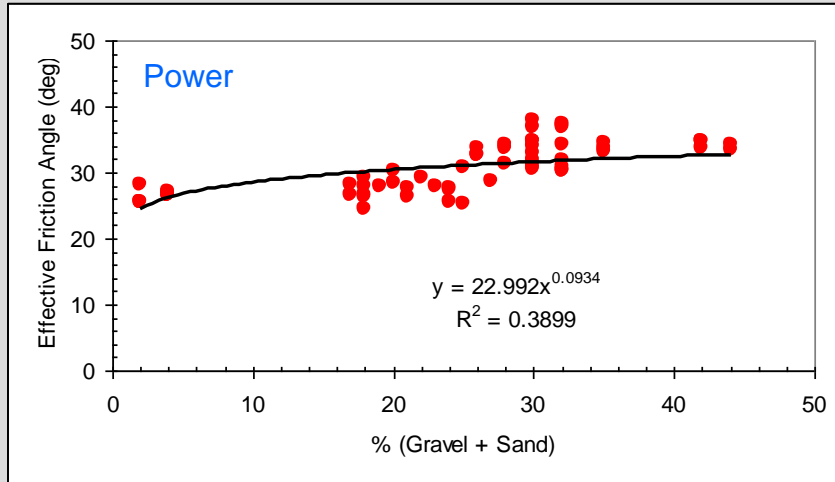
# Task 6

- (% Gravel + % Sand) vs. Effective Friction Angle



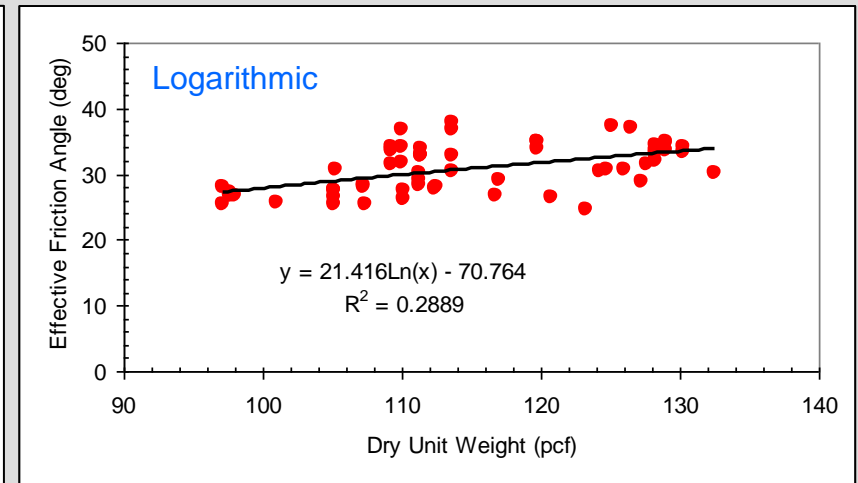
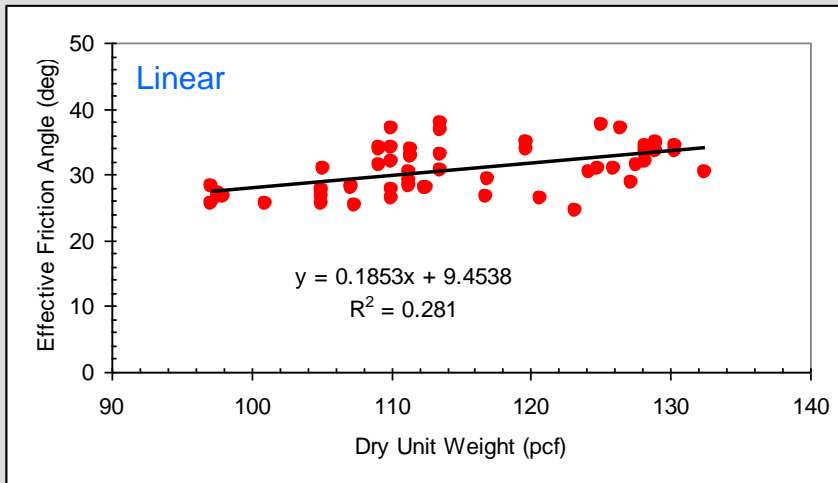
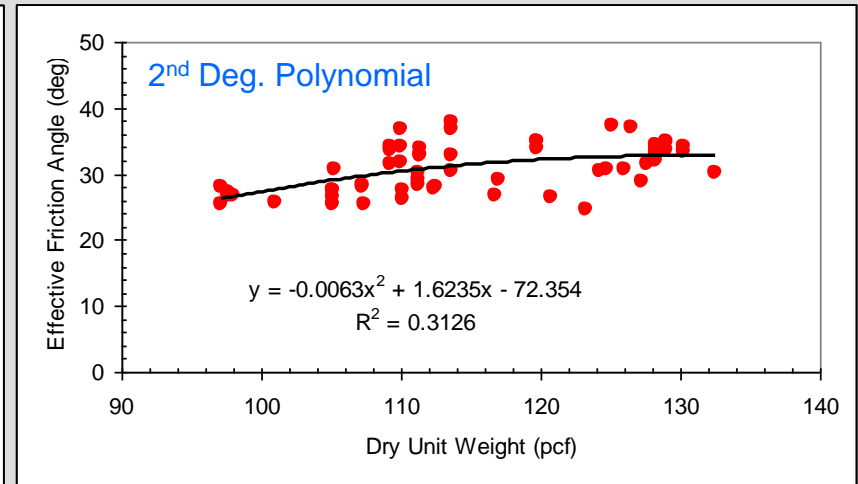
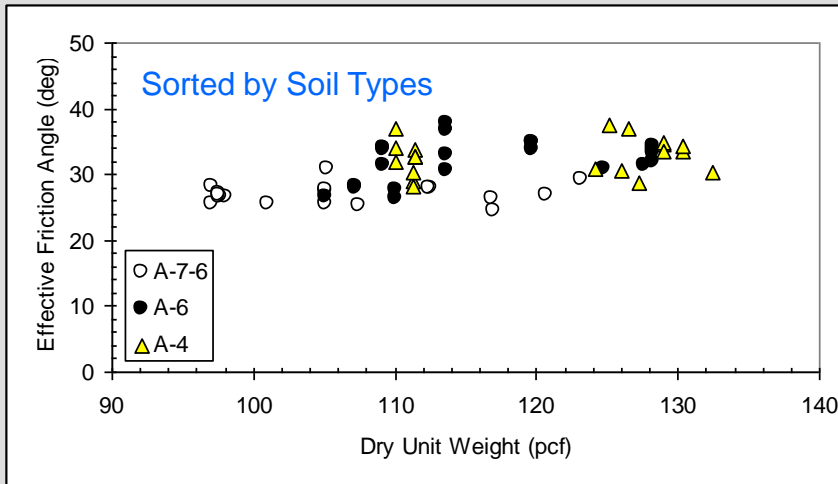
# Task 6

- (% Gravel + % Sand) vs. Effective Friction Angle



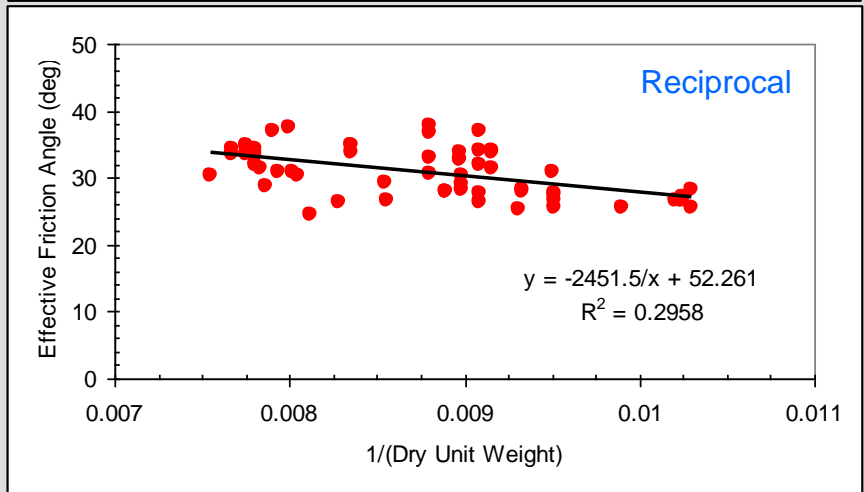
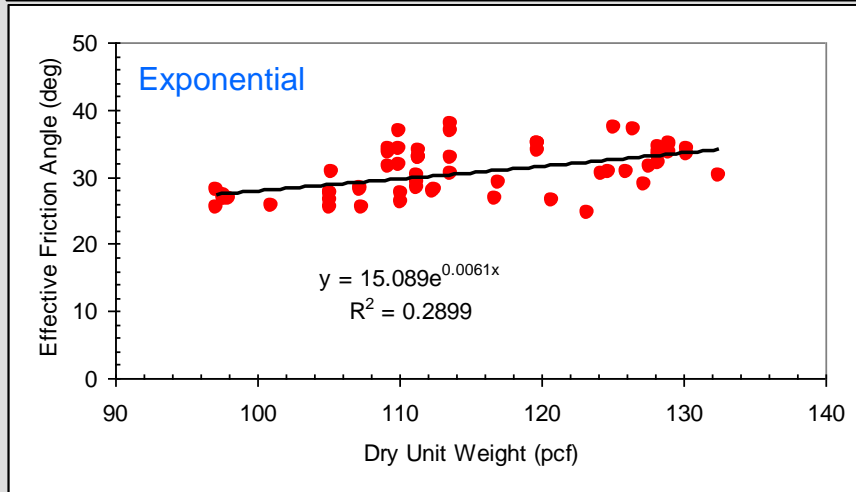
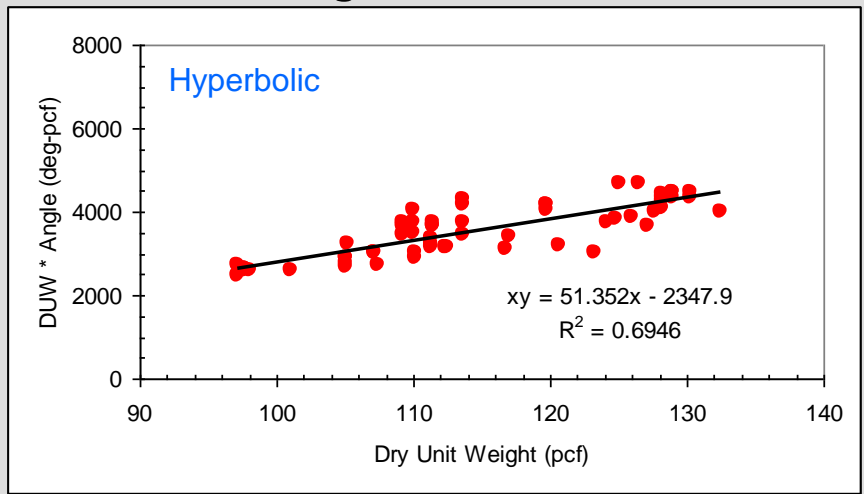
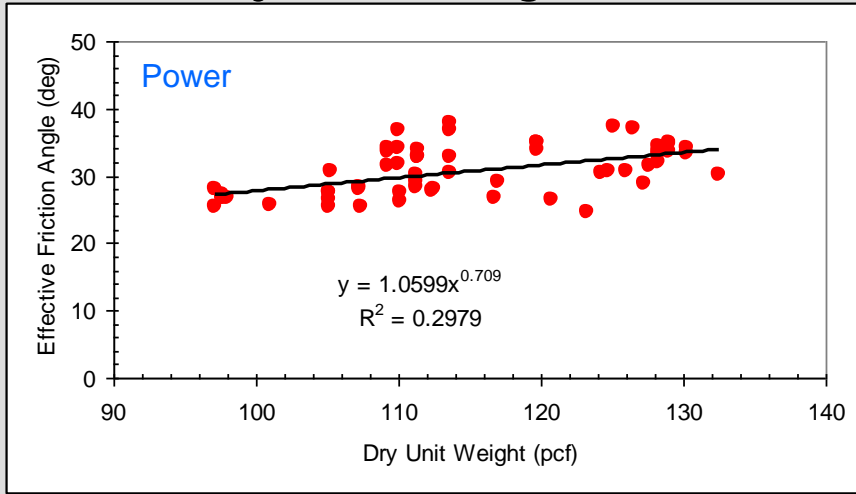
# Task 6

- Dry Unit Weight vs. Effective Friction Angle



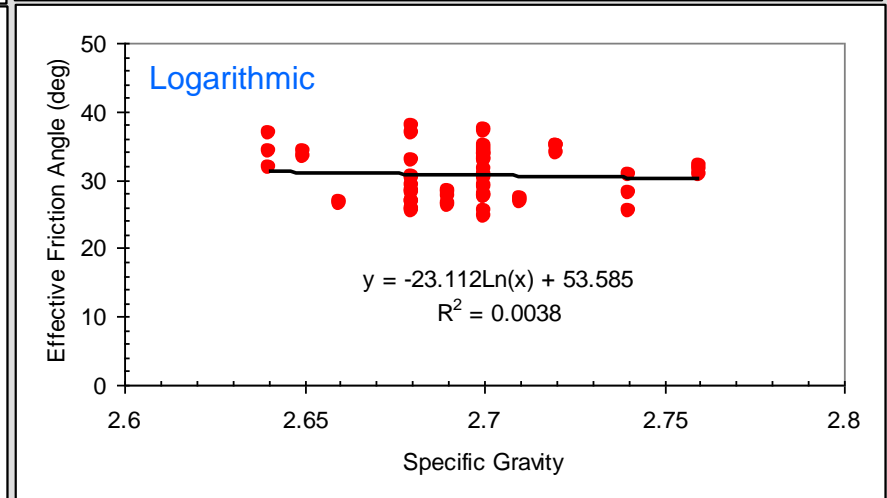
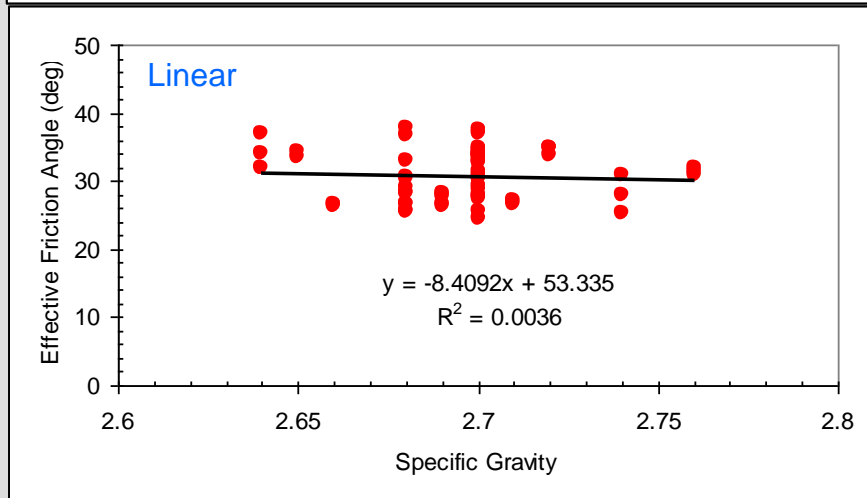
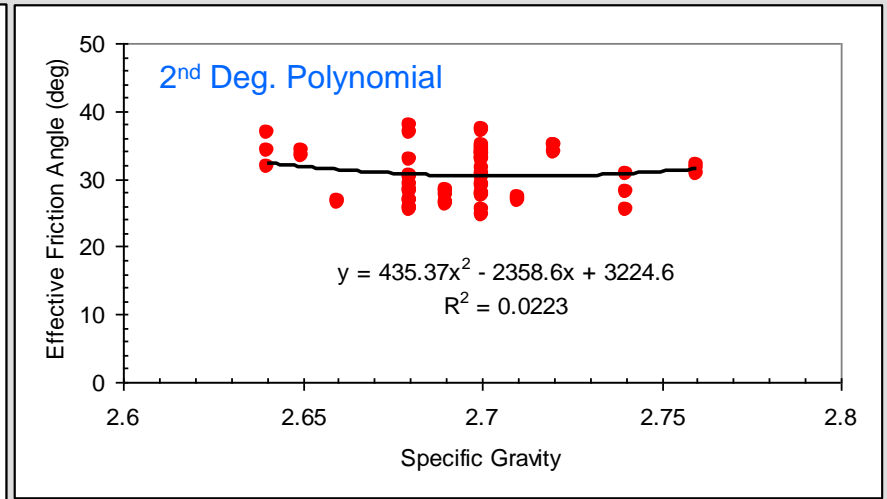
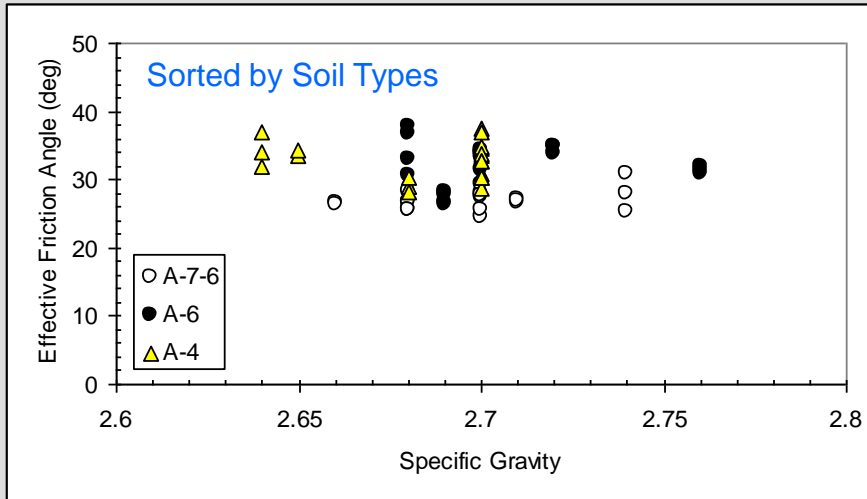
# Task 6

- Dry Unit Weight vs. Effective Friction Angle



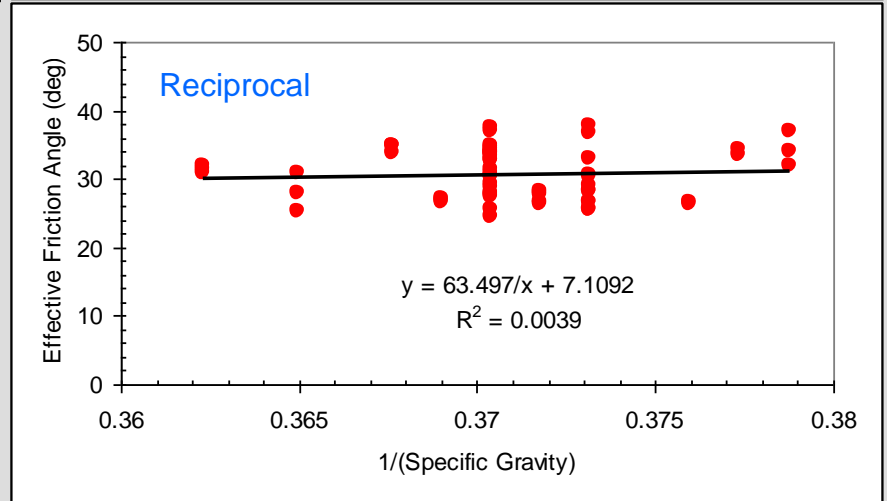
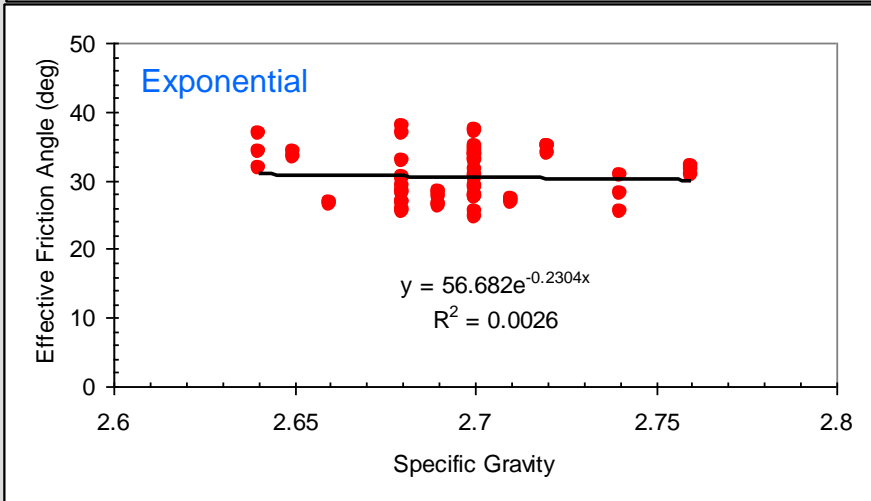
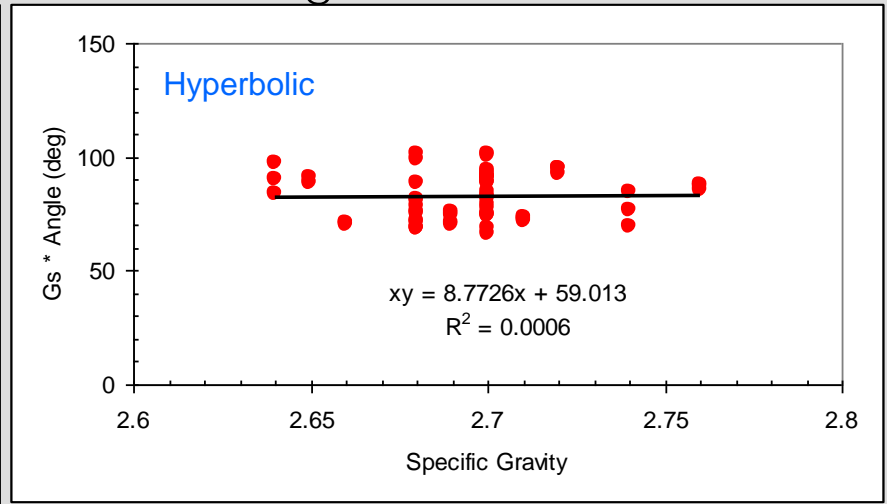
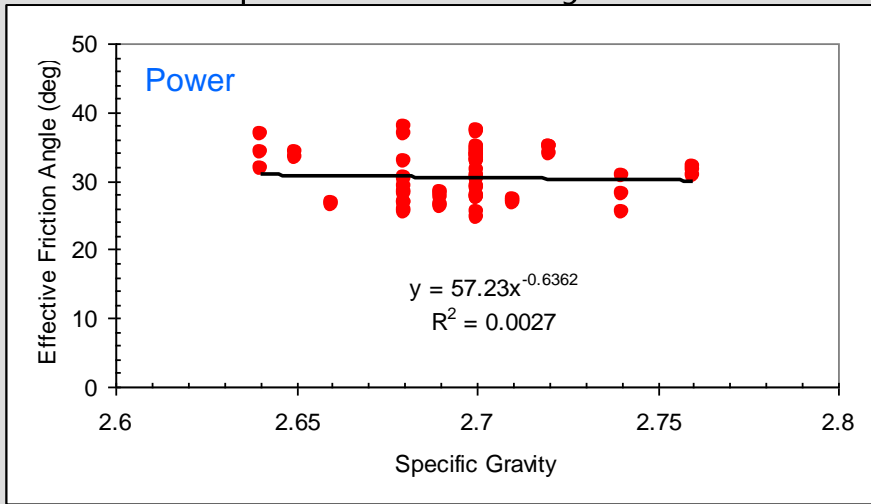
# Task 6

- Specific Gravity vs. Effective Friction Angle



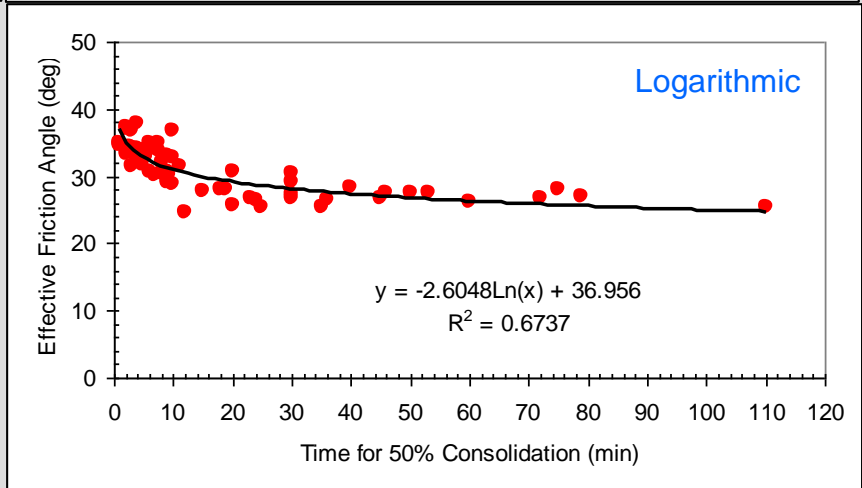
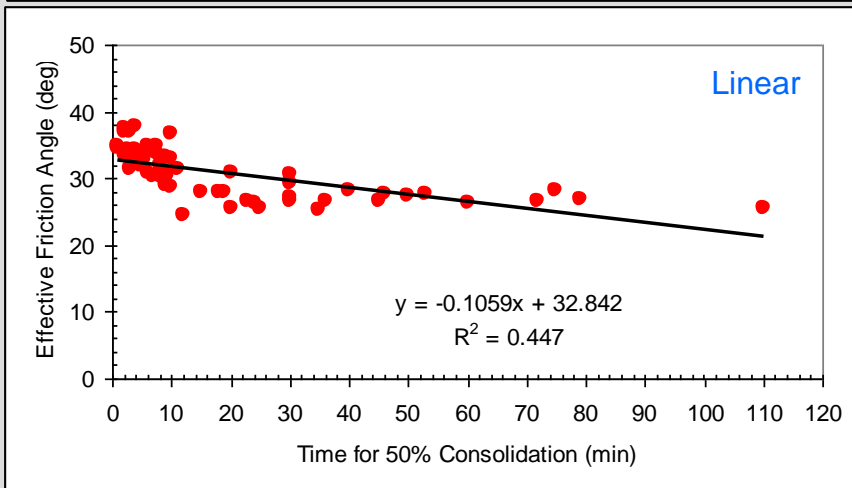
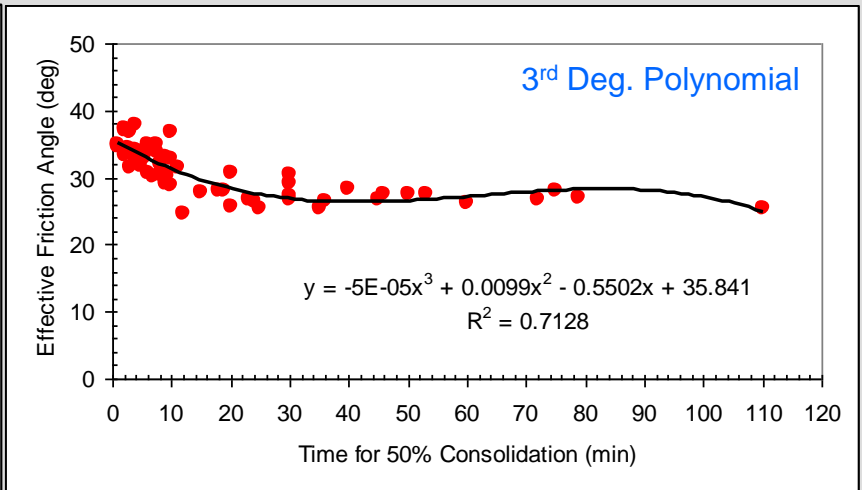
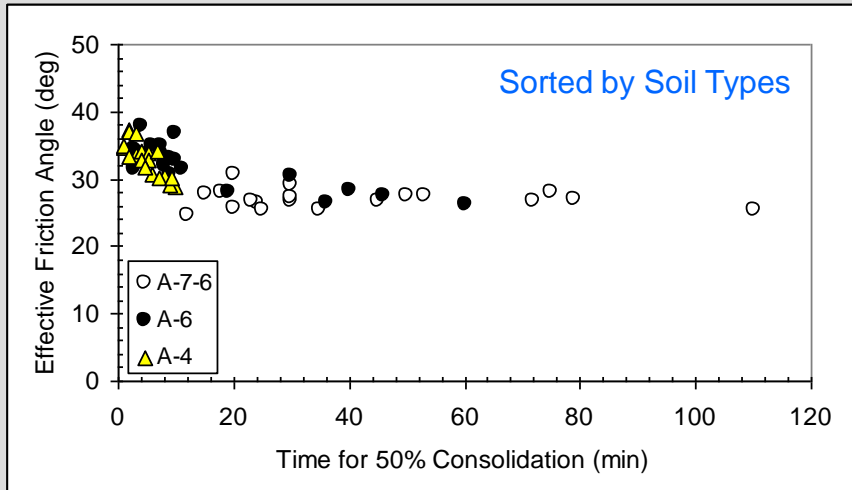
# Task 6

- Specific Gravity vs. Effective Friction Angle



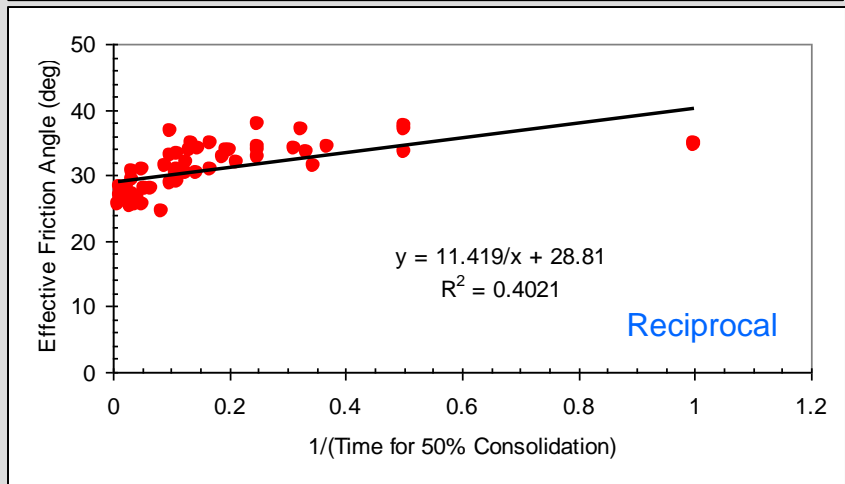
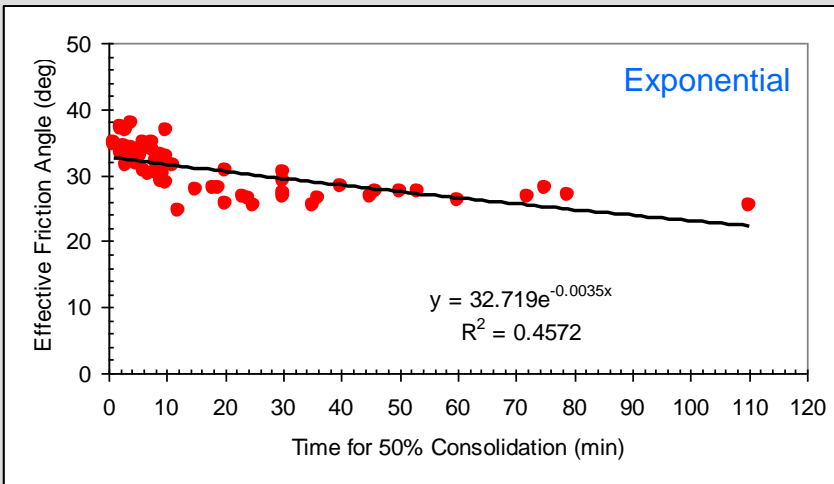
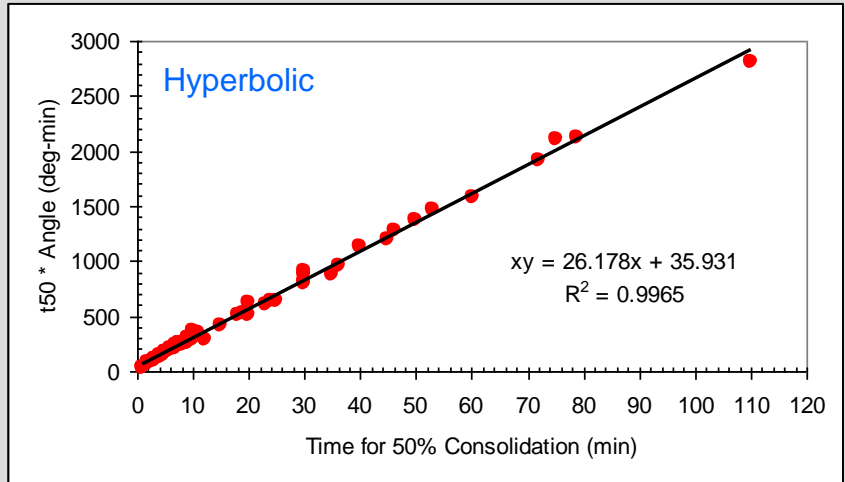
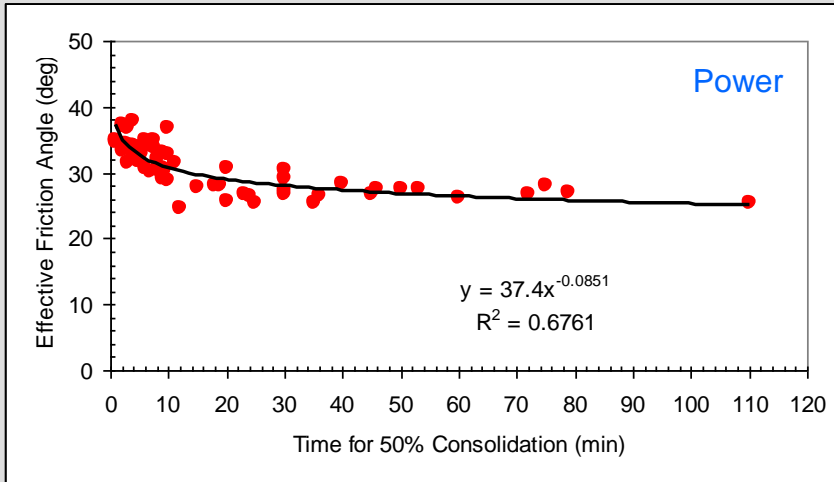
# Task 6

- Time for 50% Consolidation vs. Effective Friction Angle



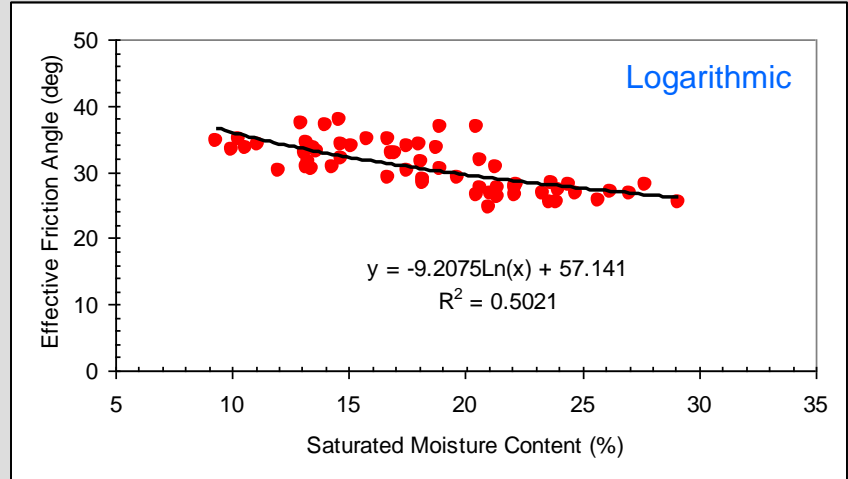
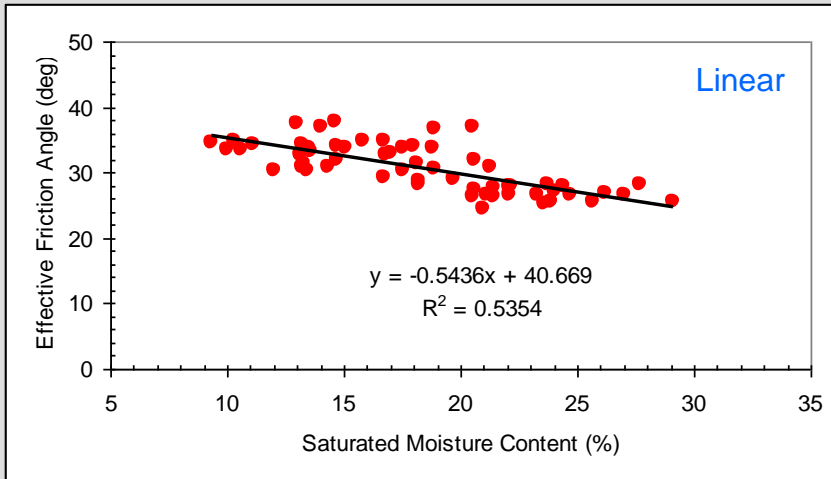
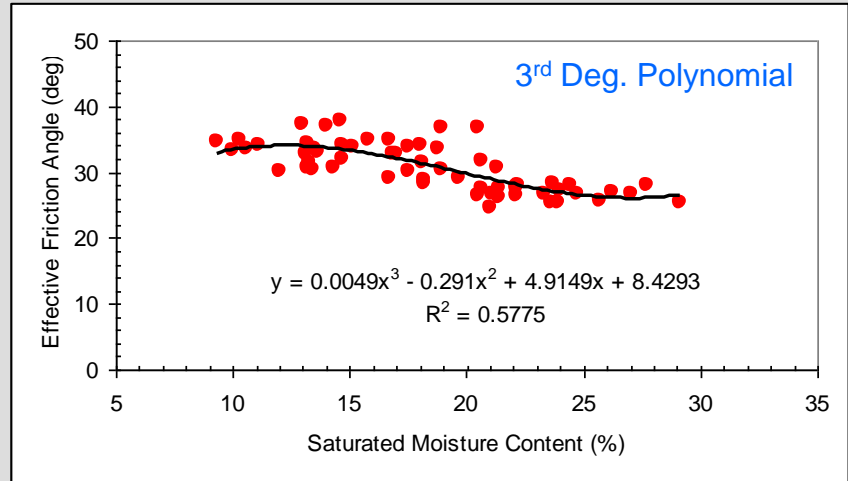
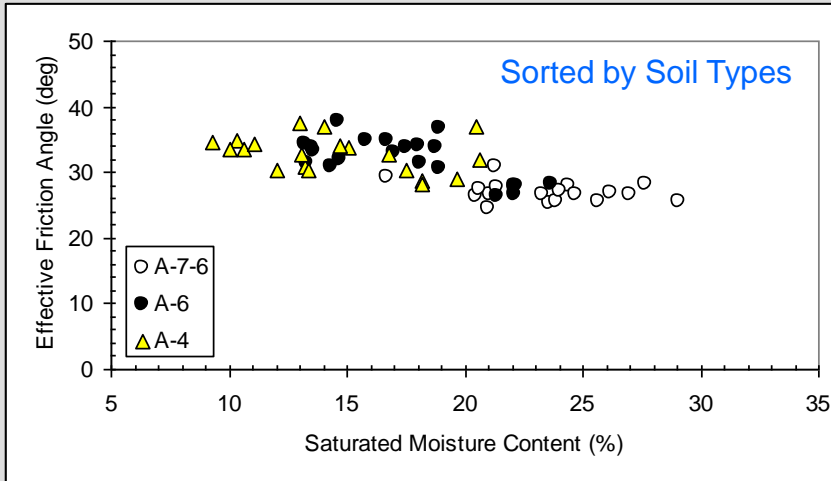
# Task 6

- Time for 50% Consolidation vs. Effective Friction Angle



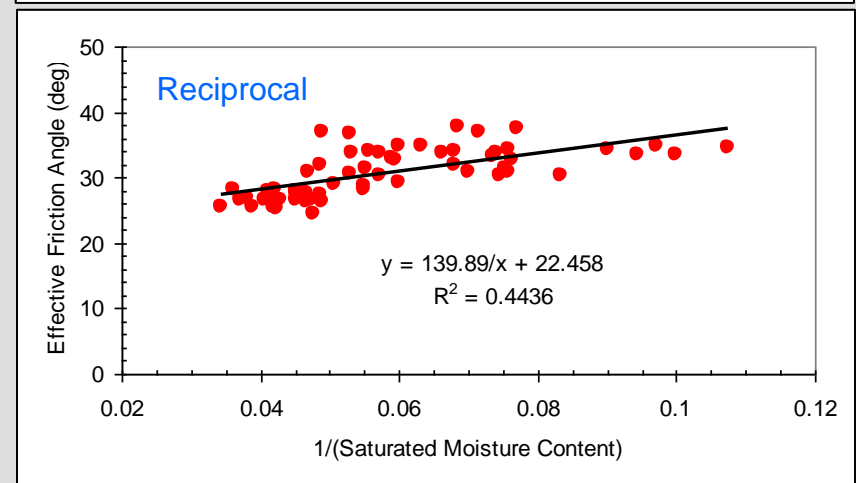
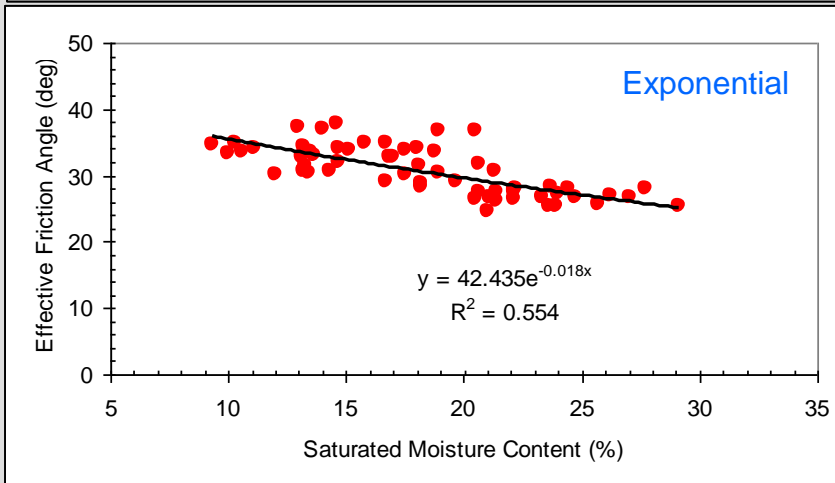
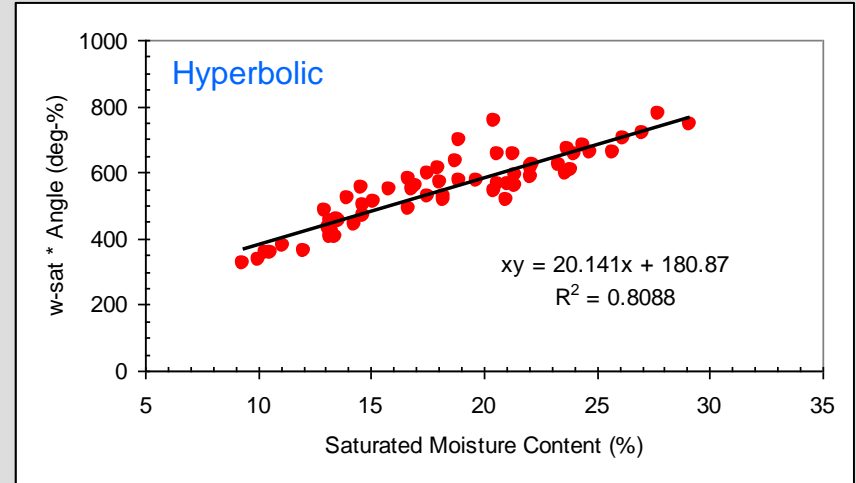
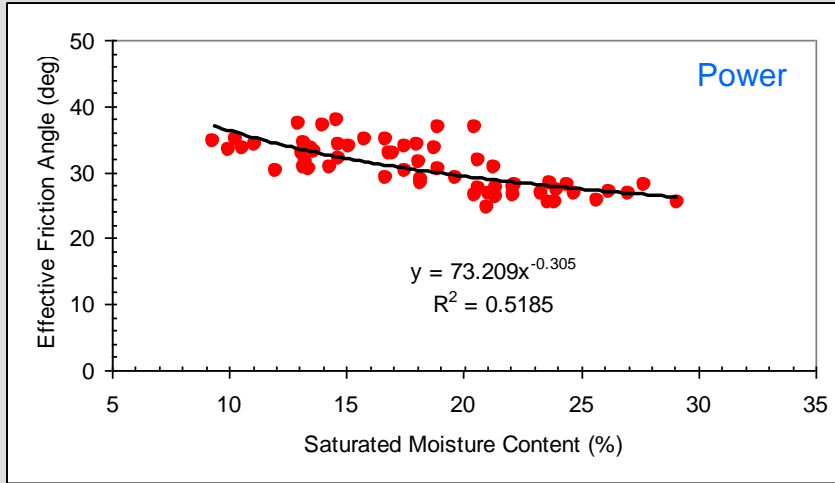
# Task 6

- Saturated Moisture Content vs. Effective Friction Angle



# Task 6

- Saturated Moisture Content vs. Effective Friction Angle



# Task 6

- Top Regression Analysis Results for  $\phi'$  of All Soil Types

Top	Independent Variable x	Model	Equation
1	Time for 50% consolidation	Hyperbolic	$\phi' = (26.18x + 35.93)/x$ ( $r^2 = 0.997$ )
2	Plasticity index (PI)	Hyperbolic	$\phi' = (23.53x + 100.15)/x$ ( $r^2 = 0.977$ )
3	% (gravel + sand)	Hyperbolic	$\phi' = (35.67x - 95.39)/x$ ( $r^2 = 0.963$ )
4	Corrected SPT-N value ( $N_{60}$ ) <sub>1</sub>	Hyperbolic	$\phi' = (35.63x - 116.37)/x$ ( $r^2 = 0.959$ )
5	Unconfined compr. strength	Hyperbolic	$\phi' = (33.86x - 96.96)/x$ ( $r^2 = 0.937$ )
6	% clay	Hyperbolic	$\phi' = (21.42x + 320.43)/x$ ( $r^2 = 0.922$ )
7	Saturated moisture content	Hyperbolic	$\phi' = (20.14x + 180.87)/x$ ( $r^2 = 0.809$ )

[Notes] Soil types include A-4, A-6, and A-7-6.

The above results based on analysis of first seven sites

# Task 6

- Top Regression Analysis Results for  $\phi'$  of A-4 Soils

Rank	Independent Variable x	Model	Equation
1	% gravel	Hyperbolic	$\phi' = (34.87x - 14.51)/x$ ( $r^2 = 0.990$ )
2	% sand	Hyperbolic	$\phi' = (64.92x - 819.50)/x$ ( $r^2 = 0.894$ )
3	% clay	Hyperbolic	$\phi' = (30.64x - 62.71)/x$ ( $r^2 = 0.860$ )
4	Plasticity index (PI)	Hyperbolic	$\phi' = (42.01x - 71.08)/x$ ( $r^2 = 0.817$ )
5	% sand	2 <sup>nd</sup> Polyn.	$\phi' = -0.53x^2 + 28.22x - 342.64$ ( $r^2 = 0.814$ )

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Top Regression Analysis Results for  $\phi'$  of A-6 Soils

Rank	Independent Variable x	Model	Equation
1	% gravel	Hyperbolic	$\phi' = (33.49x + 0.32)/x$ ( $r^2 = 0.959$ )
2	Plasticity index (PI)	Hyperbolic	$\phi' = (37.97x - 54.21)/x$ ( $r^2 = 0.840$ )
3	Natural moisture content	Hyperbolic	$\phi' = (35.21x - 0.23)/x$ ( $r^2 = 0.806$ )

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Top Regression Analysis Results for  $\phi'$  of A-7-6 Soils

Rank	Independent Variable x	Model	Equation
1	% gravel	Hyperbolic	$\phi' = (28.07x - 3.82)/x$ ( $r^2 = 0.978$ )
2	% sand	Hyperbolic	$\phi' = (26.29x + 12.72)/x$ ( $r^2 = 0.965$ )
3	Plasticity index (PI)	Hyperbolic	$\phi' = (28.60x - 35.41)/x$ ( $r^2 = 0.909$ )

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Multi-Variable Linear Regression Model

$$Y = a_0 + a_1X_1 + a_2X_2 + \dots + a_nX_n$$

- Multi-Variable Nonlinear Regression

$$Y = a_0(X_1)^{a_1}(X_2)^{a_2}\dots(X_n)^{a_n}$$

- Ranking of Correlations According to  $r^2$  values
- Backward Scheme or Forward Scheme

# Task 6

- Top Multi-Variable Linear Regression Analysis Results for  $\phi'$  of A-4 Soils

Rank	Independent Variables	Equation
1	% sand (= $x_1$ ), % silt (= $x_2$ ), PI (= $x_3$ ), dry unit weight (= $x_4$ )	$\phi' = 2.254x_1 + 1.342x_2 + 0.0172x_3 - 1.566x_4 + 122.484$ ( $r^2 = 0.983$ )
2	% gravel (= $x_1$ ), % silt (= $x_2$ ), PI (= $x_3$ ), $(N_{60})_1$ (= $x_4$ )	$\phi' = 1.299x_1 - 3.575x_2 - 0.0501x_3 + 0.131x_4 + 151.506$ ( $r^2 = 0.942$ )
3	% gravel (= $x_1$ ), % sand (= $x_2$ ), PI (= $x_3$ ), $(N_{60})_1$ (= $x_4$ )	$\phi' = -0.384x_1 + 2.208x_2 - 0.0502x_3 - 0.002x_4 - 17.479$ ( $r^2 = 0.942$ )
4	% sand (= $x_1$ ), % silt (= $x_2$ ), $(N_{60})_1$ (= $x_3$ )	$\phi' = 1.409x_1 + 3.390x_2 + 0.125x_3 - 101.352$ ( $r^2 = 0.917$ )
5	% sand (= $x_1$ ), $(N_{60})_1$ (= $x_2$ )	$\phi' = 1.325x_1 + 0.070x_2 - 3.515$ ( $r^2 = 0.859$ )
6	% sand (= $x_1$ ), % silt (= $x_2$ )	$\phi' = 1.426x_1 - 0.813x_2 + 26.552$ ( $r^2 = 0.855$ )

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Multi-Variable Linear Regression Analysis Results for  $\phi'$  of A-6 Soils

Rank	Independent Variables	Equation
1		
2		
3		
4		
5		

**None of the models for  $\phi'$  had  $r^2$  value larger than 0.799.**

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Multi-Variable Linear Regression Analysis Results for  $\phi'$  of A-7-6 Soils

Rank	Independent Variables	Equation
1		
2		
3		
4		
5		

**None of the models for  $\phi'$  had  $r^2$  value larger than 0.799.**

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Other Statistically Strong Correlations (A-4 Soils)

Dependent Variable	Independent Variable	Model	r <sup>2</sup> Value
Unconfined compr. strength	Plasticity index (PI)	2 <sup>nd</sup> Polynom.	0.975
Unconfined compr. strength	Effective Friction Angle $\phi'$	2 <sup>nd</sup> Polynom.	0.941
Unconfined compr. strength	% gravel	2 <sup>nd</sup> Polynom.	0.900
Unconfined compr. strength	Liquid limit (LL)	2 <sup>nd</sup> Polynom.	0.884
Unconfined compr. strength	% gravel	Hyperbolic	0.905
Friction angle $\phi$	% gravel	Hyperbolic	0.901
SPT ( $N_{60}$ ) <sub>1</sub>	Unconfined compr. strength	Hyperbolic	0.892
Unconfined compr. strength	Plasticity index (PI)	Hyperbolic	0.882
Unconfined compr. strength	Liquid limit (LL)	Hyperbolic	0.851
SPT ( $N_{60}$ ) <sub>1</sub>	Plasticity index (PI)	Hyperbolic	0.843
Unconfined compr. strength	% clay	Hyperbolic	0.814
Unconfined compr. strength	% gravel	Reciprocal	0.803

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Other Statistically Strong Correlations (A-6 Soils)

Dependent Variable	Independent Variable	Model	r <sup>2</sup> Value
SPT (N <sub>60</sub> ) <sub>1</sub>	50% consol. Time (t <sub>50</sub> )	Hyperbolic	0.842
Unconfined compr. strength	Dry unit weight	Hyperbolic	0.805

[Note] The above results based on analysis of data from the first five sites.

# Task 6

- Other Statistically Strong Correlations (A-7-6 Soils)

Dependent Variable	Independent Variable	Model	r <sup>2</sup> Value
Friction angle $\phi$	% gravel	Hyperbolic	0.954
Friction angle $\phi$	% sand	Hyperbolic	0.937
SPT ( $N_{60}$ ) <sub>1</sub>	Specific gravity	Linear	0.902
SPT ( $N_{60}$ ) <sub>1</sub>	Specific gravity	Log	0.900
SPT ( $N_{60}$ ) <sub>1</sub>	Specific gravity	Reciprocal	0.897
SPT ( $N_{60}$ ) <sub>1</sub>	Specific gravity	Hyperbolic	0.888
SPT ( $N_{60}$ ) <sub>1</sub>	Specific gravity	Exponential	0.881
SPT ( $N_{60}$ ) <sub>1</sub>	Specific gravity	Power	0.878
SPT ( $N_{60}$ ) <sub>1</sub>	50% consol. Time ( $t_{50}$ )	Hyperbolic	0.872
SPT ( $N_{60}$ ) <sub>1</sub>	Unconfined compr. strength	Hyperbolic	0.864
Unconfined compr. strength	% sand	Hyperbolic	0.854

[Note] The above results based on analysis of data from the first five sites.

# Task 7

- Geotechnical Guidelines (preliminary)
- The data and analytical results obtained in the current project can be used to formulate a set of guidelines so that geotechnical engineers in Ohio can estimate shear strength properties of highway embankment soils more confidently
- The guidelines must be given at multiple levels to allow varying degrees of sophistication

# Task 7

- Geotechnical Guidelines (preliminary)
- Level 1
- Use the following default effective friction angle for each of the three major soil types found in Ohio:
  - A-4 soils .....  $\phi' = 32$
  - A-6 soils .....  $\phi' = 28$
  - A-7-6 soils .....  $\phi' = 24$

# Task 7

- Geotechnical Guidelines (preliminary)
- Level 2
- Determine liquid and plastic limits of the soil. Compute plasticity index (PI). Estimate the effective friction angle **using the Terzaghi's empirical  $\phi'$  vs. PI correlation chart**. For A-4 and A-6 soils, use the average  $\phi'$  value resulting from the chart. For A-7-6 soils, the lower the average  $\phi'$  value shown in the chart by 3

# Task 7

- Geotechnical Guidelines (preliminary)
- Level 3
- Take advantage of some index property data available from laboratory tests. Use any of the correlation equations previously shown in Slides #172, 173, 174, 175, and 177.

# Preliminary Conclusions

- Literature review identified a general lack of guidance available to geotechnical engineers concerning engineering properties of embankment soils found in Ohio.
- Literature review indicated that lake deposits (A-4 soils) are abundant in the northern areas of Districts 2, 3, 4, and 12 (along the shores of Lake Erie). Literature review also indicated that cohesive (A-6, A-7-6) soils may be common in the remaining areas of Ohio.
- Terzaghi et al. (1996) established a relationship between the corrected SPT-N values  $(N_{60})_1$  and unconfined compression strength for cohesive soils.

# Preliminary Conclusions

- Terzaghi established a relationship between plasticity index (PI) and effective friction angle for a wide range of cohesive soils found outside the U.S.
- The relationship between the corrected SPT-N value and unconfined compression strength previously established by Terzaghi et al. (1996) was not reliable in about 50% of the data for the Ohio soils recovered from all ten sites.
- The relationship between plasticity index and effective friction angle previously established by Terzaghi et al. (1996) was a slightly off for the Ohio soils tested for the first seven sites.

# Preliminary Conclusions

- The field and laboratory test data collected for the Ohio embankment soils did not fit well to the relationships between SPT- $N_{60}$  value and unconfined compression strength previously established by the U.S. Dept. of Navy (1982). About 51% of the data points fell outside the range specified by the U.S. Dept. of Navy.
- The range of typical  $\phi'$  values cited by the U.S. Dept. of Navy was low for A-4 and A-6 soils and somewhat reasonable for A-7-6 soils.
- Several mathematical (linear, 2<sup>nd</sup> or 3<sup>rd</sup> degree polynomial, power, exponential, logarithmic, hyperbolic, and reciprocal) models were utilized to describe the relationships that exist among the field and laboratory test results accumulated for the Ohio embankment soils.

# Preliminary Conclusions

- Among these models, hyperbolic model appears to be the most successful in describing the relationships existing for effective friction angle. According to the statistical results, the time for 50% consolidation and plasticity index were highly correlated hyperbolically to the effective friction angle of all three cohesive soil types.
- Other properties that showed good correlations to effective friction angle were % (gravel + sand), % clay, unconfined compression strength, saturated moisture content, and corrected SPT- $N_{60}$  value. These outcomes are somewhat surprising. This may be reflecting a high degree of quality control measures implemented in every facet of the current project. For example, a SPT rig, equipped with a calibrated automatic hammer, was operated by the same operators at each field test site.

# Preliminary Conclusions

- Dry unit weight and specific gravity showed much weaker correlations to effective friction angle.
- Multi-variable linear regression analysis yielded several reliable prediction models for the effective friction angle of A-4 soils.
- Multi-variable linear regression analysis produced no reliable prediction models for A-6 and A-7-6 soil types.
- A set of preliminary geotechnical guidelines was established for cohesive soils in Ohio.

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**Thank you for listening to my presentation!**

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