TEXAS A&M ENGINEERING

Design of Drilled Shafts in Expansive Soils

Robert L. Lytton

Professor, Fred J. Benson Endowed Chair
Zachry Department of Civil Engineering
Texas A&M University

Foundation Performance Association
Houston, Texas
December 14, 2011

Question:

How do you convert the usual data from a Soils Lab report into information you can use to design a drilled shaft?

What kind of data is in the usual Soils Lab report?

Answer:

- Atterberg limits,
  - Liquid limit, LL
  - Plasticity index, PI
- Water content, w
- Dry unit weight (density) of the soil, γ_d
- Strength
  - Unconfined compressive strength, psi, tsf
  - Pocket penetrometer, tsf
  - Vane shear strength, tsf

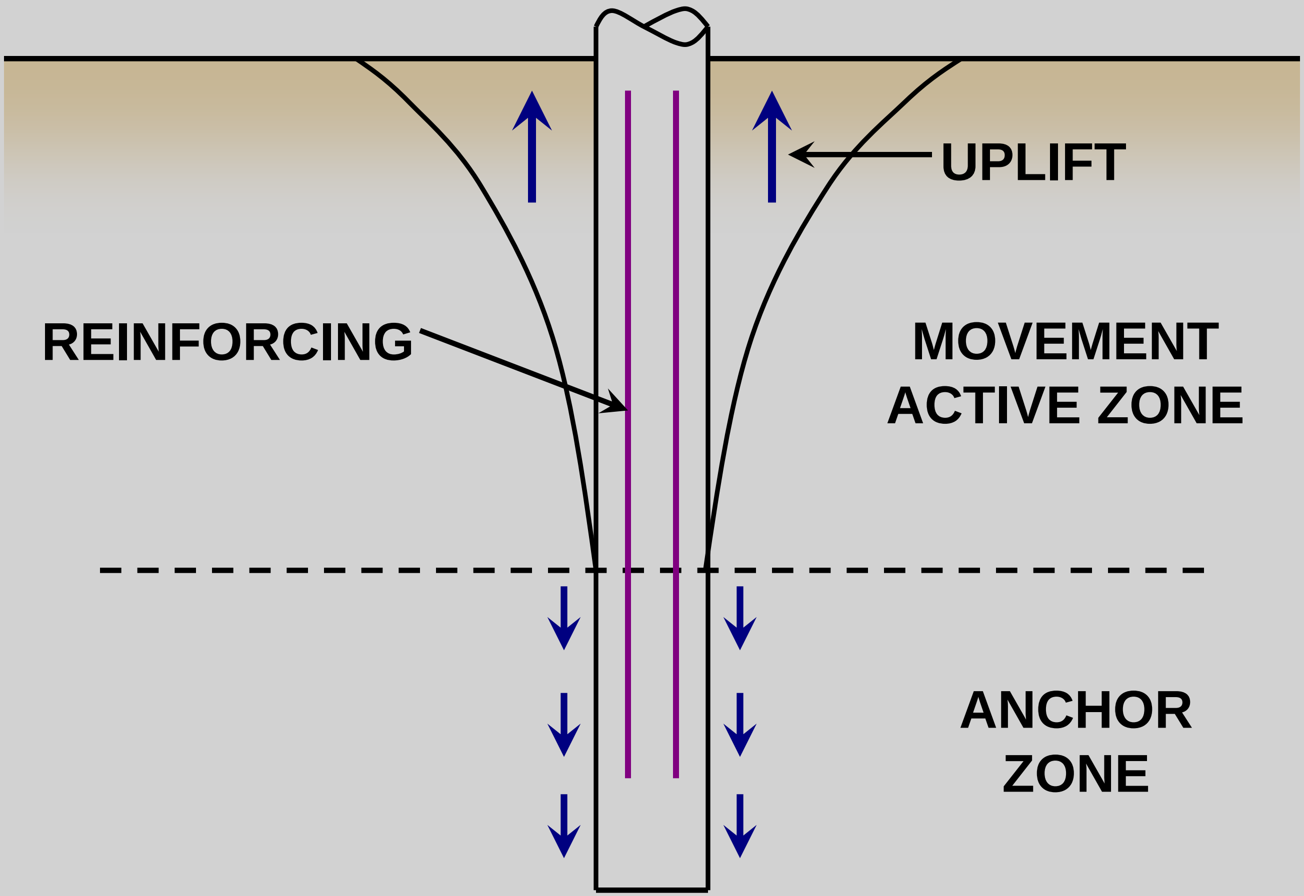
What kind of information do you need to design a drilled shaft?

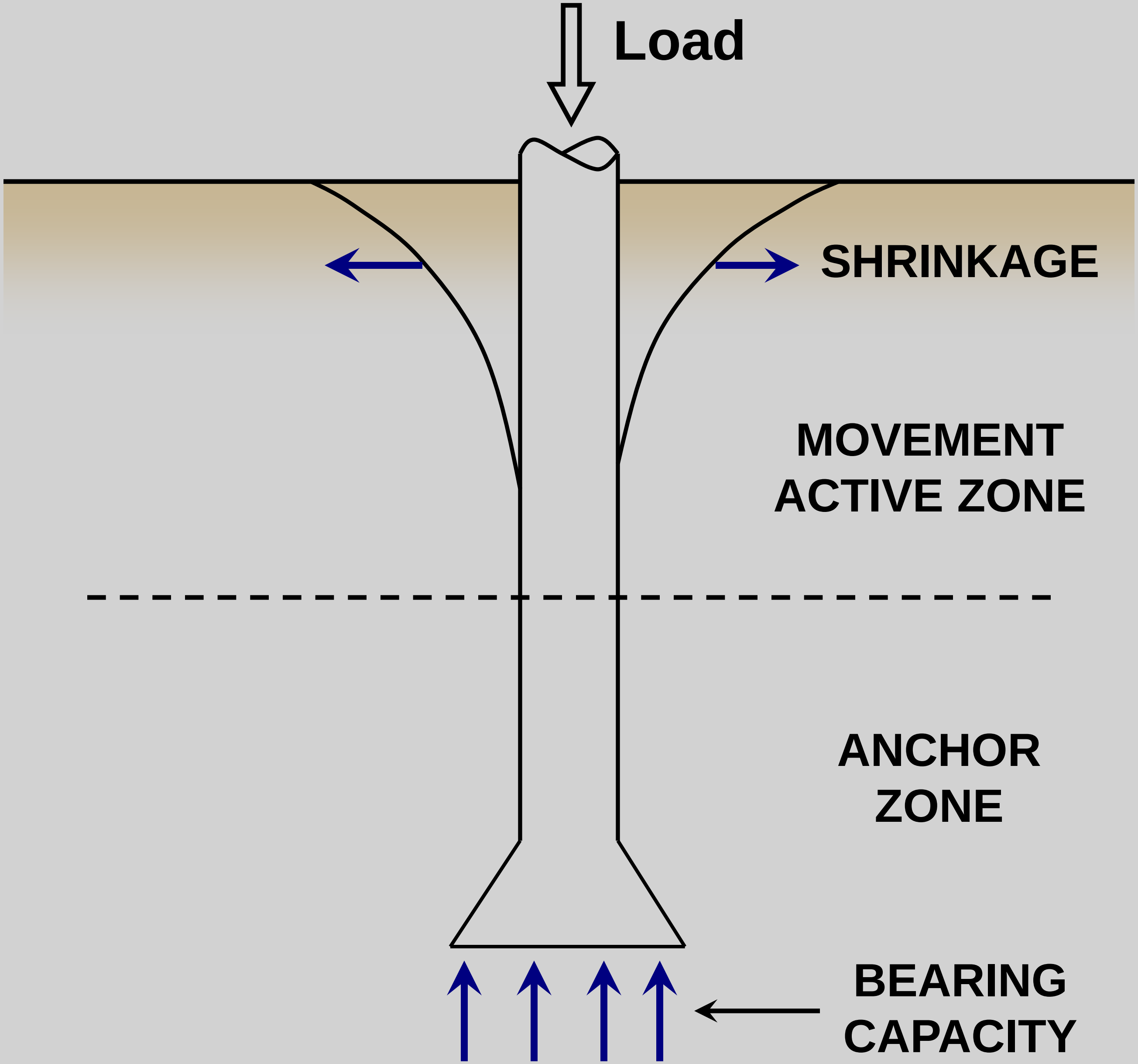
Answer:

- Volumetric water content, θ
- Effective friction angle, ϕ'
- Matric suction, pF
- Skin friction factor, α

Some in the movement active zone

Some in the anchor zone


UPLIFT
REINFORCING
MOVEMENT
ACTIVE ZONE
ANCHOR
ZONE



Load
SHRINKAGE
MOVEMENT
ACTIVE ZONE
ANCHOR
ZONE
BEARING
CAPACITY

What conditions do you need to design for?

- Uplift (soil gets wetter)

- Bearing capacity (soil gets drier)

What other soils information will you need and where do you get it?

- Thornthwaite moisture index

  (for deep water tables)

  (map of TMI)

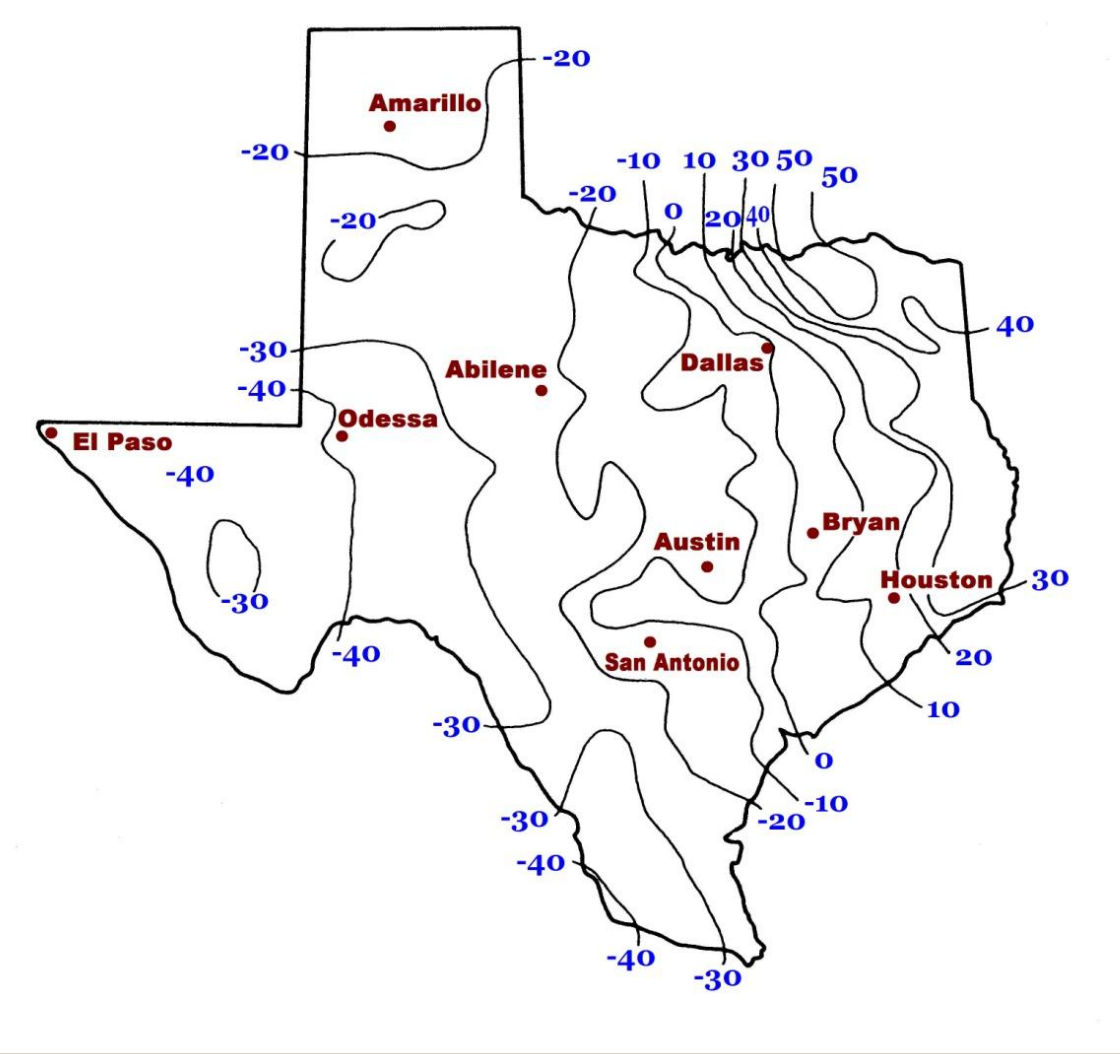
- Water content, Atterberg limits, dry unit weight, strength at or below the water table

  (for shallow water tables)

- Boring Log

- Natural resources conservation service county soil map

Thornthwaite Moisture Index (TMI, 1948)



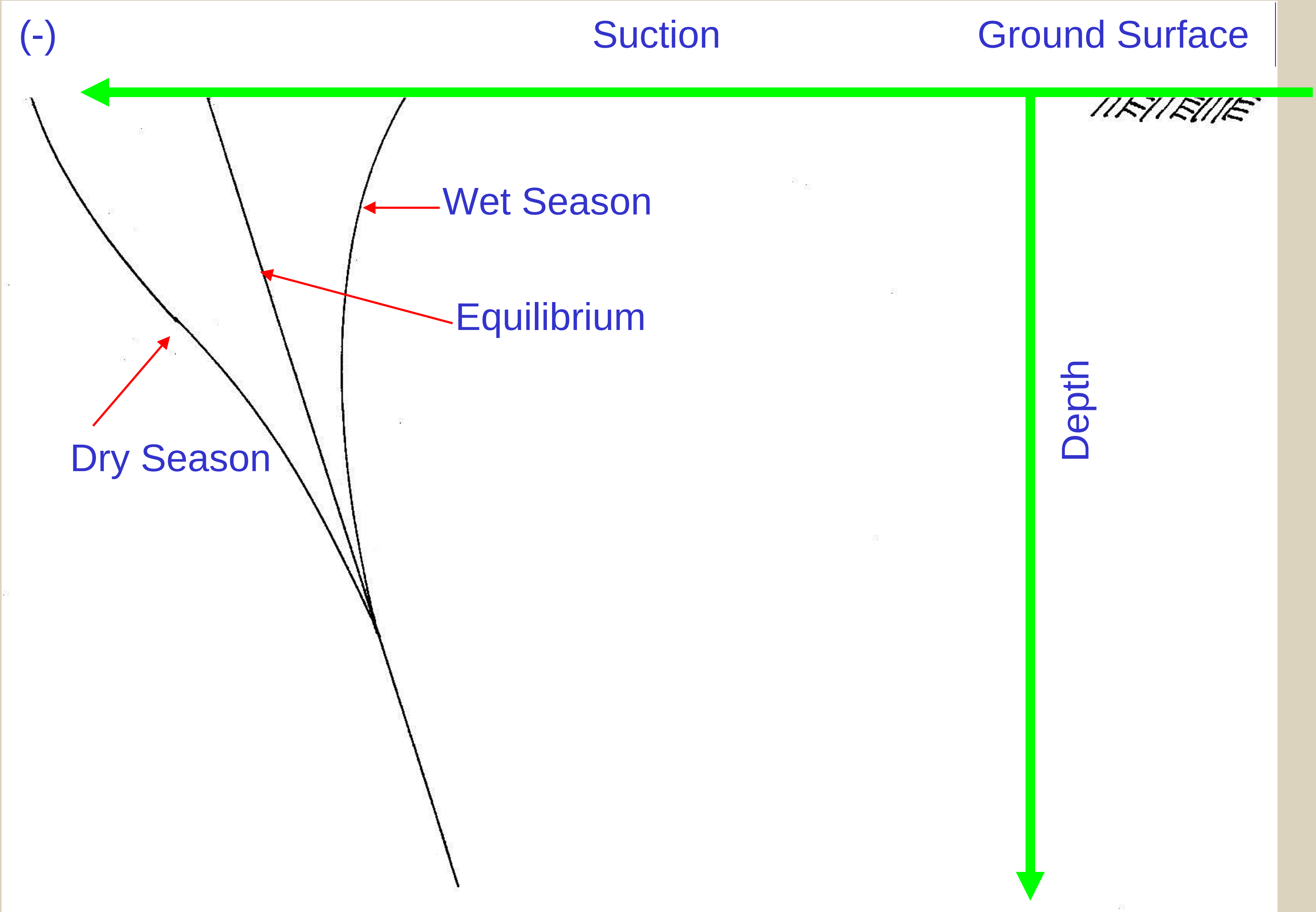
$$TMI = \frac{100R - 60DEF}{E_p}$$

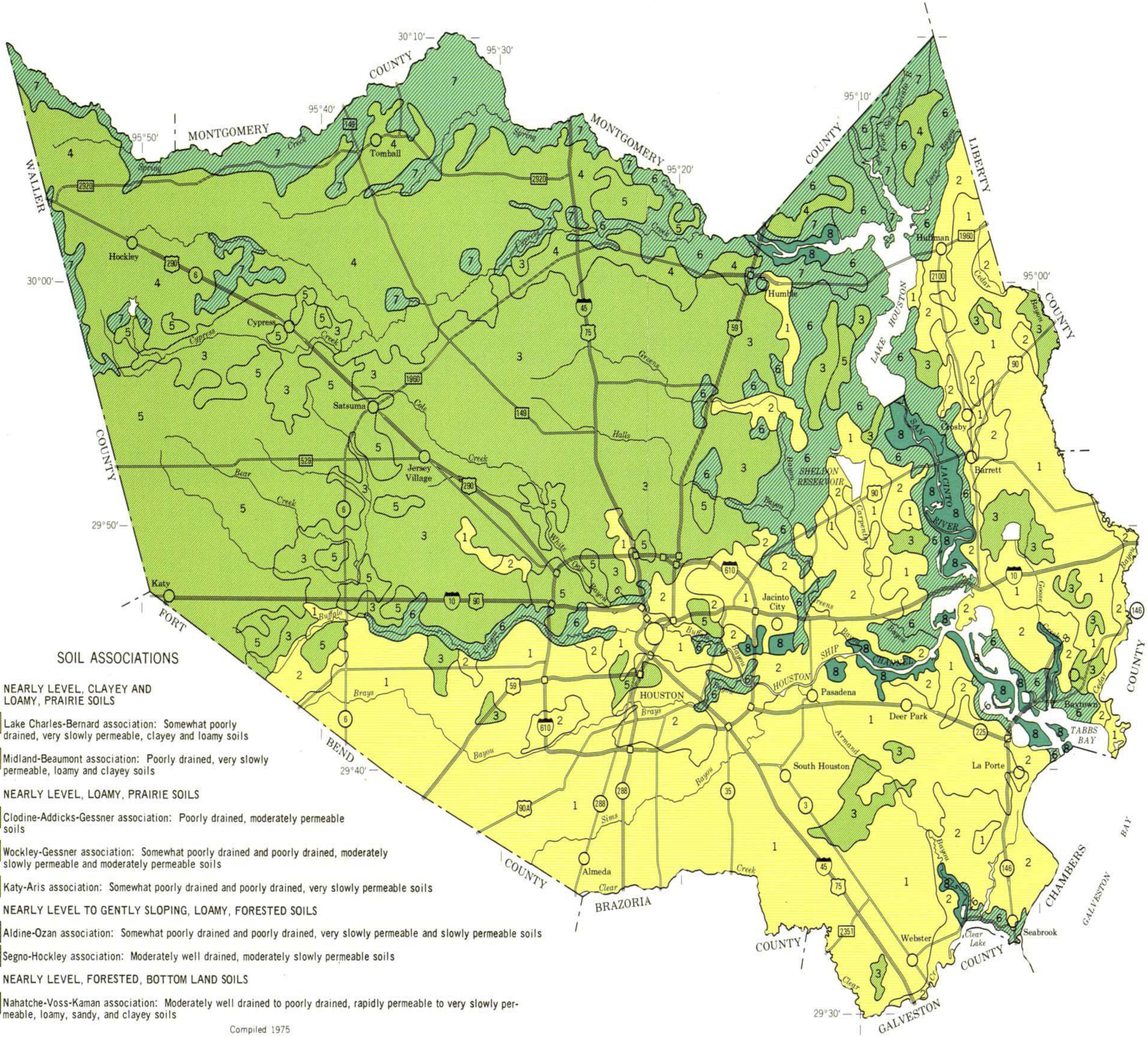
R = runoff moisture depth

DEF =deficit moisture depth

Ep = evapotranspiration

Suction Distribution with Depth





Each area outlined on this map consists of more than one kind of soil. The map is thus meant for general planning rather than a basis for decisions on the use of specific tracts.

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
TEXAS AGRICULTURAL EXPERIMENT STATION
AND
HARRIS COUNTY FLOOD CONTROL DISTRICT

GENERAL SOIL MAP
HARRIS COUNTY, TEXAS

Scale 1: 316,800

1 0 1 2 3 4 5 Miles

SOIL ASSOCIATIONS

NEARLY LEVEL, CLAYEY AND LOAMY, PRAIRIE SOILS

1 Lake Charles-Bernard association: Somewhat poorly drained, very slowly permeable, clayey and loamy soils

2 Midland-Beaumont association: Poorly drained, very slowly permeable, loamy and clayey soils

NEARLY LEVEL, LOAMY, PRAIRIE SOILS

3 Clodine-Addicks-Gessner association: Poorly drained, moderately permeable soils

4 Wockley-Gessner association: Somewhat poorly drained and poorly drained, moderately slowly permeable and moderately permeable soils

5 Katy-Aris association: Somewhat poorly drained and poorly drained, very slowly permeable soils

NEARLY LEVEL TO GENTLY SLOPING, LOAMY, FORESTED SOILS

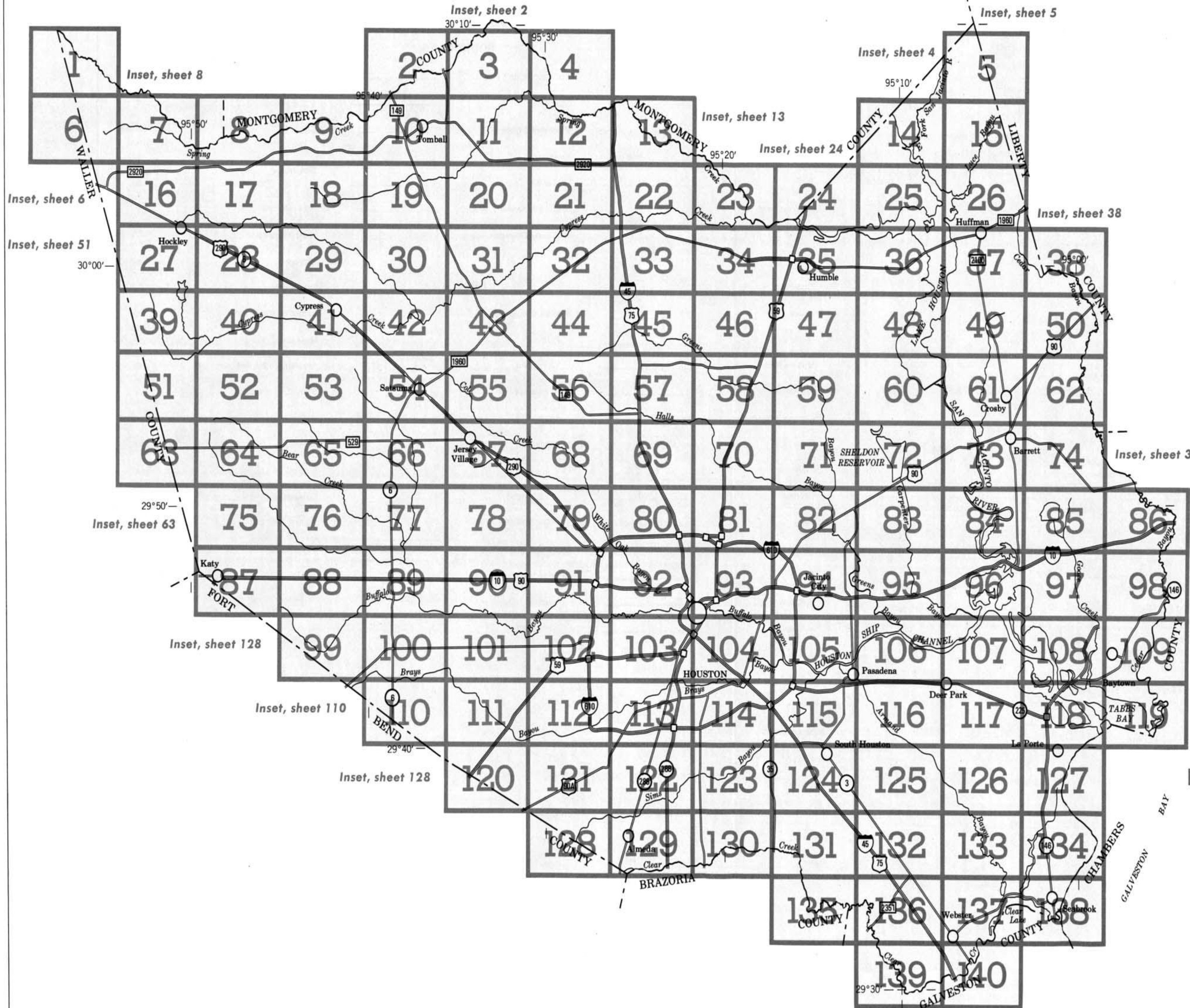
6 Aldine-Ozan association: Somewhat poorly drained and poorly drained, very slowly permeable and slowly permeable soils

7 Segno-Hockley association: Moderately well drained, moderately slowly permeable soils

NEARLY LEVEL, FORESTED, BOTTOM LAND SOILS

8 Nahatche-Voss-Kaman association: Moderately well drained to poorly drained, rapidly permeable to very slowly permeable, loamy, sandy, and clayey soils

Compiled 1975



INDEX TO MAP SHEETS

HARRIS COUNTY, TEXAS

N

Scale 1:20000

1 Mile
5000 Feet
0 ¼ ½ ¾ 1
0 1000 2000 3000 4000 5000

HARRIS COUNTY, TEXAS NO. 103

This map is compiled on 1972 aerial photography by the U.S. Department of Agriculture, Soil Conservation Service and cooperating agencies. Coordinate grid ticks and land division corners, if shown, are approximately positioned.

Soil Survey of Harris County, Texas

- Lake Charles series

B22t—50 to 65 inches; prominently mottled light gray (10YR 6/1), strong brown (7.5YR 5/6), and red (2.5YR 4/6) clay loam; few medium distinct gray (10YR 5/1) mottles; moderate coarse prismatic structure parting to moderate coarse blocky; extremely hard, very firm; few fine roots mostly between ped faces; continuous dark gray (10YR 4/1) clay films mainly on faces of blocks; fine sandy loam coatings 1 to 5 millimeters thick on prism faces; slightly acid.

The A horizon is 18 to 30 inches thick. It is slightly acid or medium acid. The Ap horizon is dark grayish brown, grayish brown, or brown. The A2 horizon is brown, pale brown, very pale brown, yellowish brown, or light yellowish brown. Mottles of yellowish brown and gray are in the A2 horizon in some places. The B2t horizon is prominently mottled gray, grayish brown or light brownish gray, yellowish brown or strong brown, and red or yellowish red. The dark red centers of some red mottles in the lower part of the B2t horizon are plinthite. The amount of plinthite ranges from 0 to about 3 percent. Some ped faces are coated with very dark gray or dark gray in most profiles. The B2t horizon is clay loam, sandy clay loam, or clay. Clay makes up 25 to 35 percent of the control section. The B2t horizon is strongly acid through neutral. Some profiles are moderately alkaline below a depth of 50 inches.

Kenney series

The Kenney series consists of deep, acid, nearly level to gently sloping, sandy soils on forested uplands. These soils have a thick sandy layer underlain by a reddish loamy layer (fig. 14). They formed in thick beds of unconsolidated sediment of loamy sand, sandy loam, and sandy clay loam.

places. The B2t horizon is fine sandy loam, sandy clay loam, or clay loam. It is very strongly acid to slightly acid. In a few places, plinthite is in the upper part of the B2t horizon and the plinthite makes up less than 4 percent of the soil.

Lake Charles series

The Lake Charles series consists of deep, neutral, nearly level to gently sloping, clayey soils on upland prairies. These soils are clayey throughout the profile and have wide deep cracks and intersecting slickensides (fig. 15). They formed in alkaline marine clay.

Undisturbed areas of these soils have gilgai microrelief, in which the microknolls are 6 to 12 inches higher than the microdepressions. When these soils are dry, deep, wide cracks form on the surface. Water enters the cracks rapidly, but when the soils are wet and the cracks are sealed, water enters very slowly. These soils are somewhat poorly drained. Surface runoff is very slow or medium. Internal drainage is very slow. Permeability is very slow, and the available water capacity is high.

These soils are used mainly for rice and pasture. Some are in urban uses.

Representative profile of Lake Charles clay, 0 to 1 percent slopes, at the center of a microdepression, in pasture, from the intersection of Cook Road and Alief Road in

Lake Charles series, cont.

Alief, 1.11 miles west along Alief Road, 1.37 miles north on Synott Road, and 75 feet west:

Ap—0 to 22 inches; black (10YR 2/1) clay, very dark gray (10YR 3/1) dry; moderate fine blocky structure; very hard, very firm, very sticky and plastic; many fine roots; few fine iron-manganese concretions; shiny pressure faces; neutral; diffuse wavy boundary.

A12—22 to 36 inches; very dark gray (10YR 3/1) clay, dark gray (10YR 4/1) dry; moderate fine blocky and subangular blocky structure in upper 12 inches and breaking to moderate fine and medium blocky in the lower part; the lower part contains common large wedge-shaped peds having long axes tilted 10 to 60 degrees from the horizontal and bordered by intersecting slickensides; extremely hard, very firm, very sticky and plastic; aggregates have shiny pressure faces; few fine iron-manganese and calcium carbonate concretions; mildly alkaline; diffuse wavy boundary.

AC1g—36 to 52 inches; dark gray (10YR 4/1) clay, gray (10YR 5/1) dry; common fine and medium distinct mottles of olive (5Y 4/3) and few fine distinct mottles of yellowish brown (10YR 5/4); common large wedge-shaped peds having long axes tilted 10 to 60 degrees from the horizontal and bordered by intersecting slickensides, peds break to moderate medium and coarse blocky structure; extremely hard, very firm, very sticky and plastic; few fine roots; aggregates have shiny pressure faces; few fine iron-manganese concretions; few calcium carbonate concretions as much as 1 centimeter in diameter; mildly alkaline; diffuse wavy boundary.

AC2g—52 to 74 inches; gray (5Y 5/1) clay, gray (5Y 6/1) dry; common fine and medium distinct mottles of light olive brown (2.5Y 5/4) and few fine distinct mottles of yellowish brown (10YR 5/6); weak fine angular blocky structure; extremely hard, very firm, very sticky and plastic; few fine iron-manganese concretions; few intersecting slickensides; few irregularly shaped pitted calcium carbonate concretions generally less than 3 centimeters in size; mildly alkaline.

In undisturbed areas, gilgai microknolls are 6 to 12 inches higher than microdepressions. The center of the microknolls is about 4 to 16 feet from the center of the microdepressions. When the soils are dry, cracks 1 to 2 inches wide form on the surface and extend into the ACg horizon. Intersecting slickensides begin at a depth of about 20 to 30 inches. The A horizon is black or very dark gray. It ranges from slightly acid through mildly alkaline. The ACg horizon is very dark gray, dark gray, or gray. Mottles in the ACg horizon are olive, yellowish brown, light olive brown, strong brown, yellow, or red. The ACg horizon is clay or silty clay. It ranges from neutral through moderately alkaline. In some places it is calcareous in the lower part.

Soil Survey of Harris County, Texas

- Engineering properties and classifications

TABLE 16.--ENGINEERING PROPERTIES AND CLASSIFICATIONS--Continued

Soil name and map symbol	Depth	USDA texture	Classification		Percentage passing sieve number--				Liquid limit	Plas-ticity index
			Unified	AASHTO	4	10	40	200		
Lake Charles:										
LcA, LcB----------	0-22	Clay------------	CH	A-7	100	99-100	80-100	75-100	64-80	40-55
	22-74	Clay------------	CH	A-7	98-100	98-100	80-100	75-100	54-90	37-60
[1]Lu:										
Lake Charles part	0-22	Clay------------	CH	A-7	100	99-100	80-100	75-100	64-80	40-55
	22-74	Clay------------	CH	A-7	98-100	98-100	80-100	75-100	54-90	37-60

Soil Survey of Harris County, Texas

- Engineering test data

TABLE 19.--ENGINEERING TEST DATA--Continued

Soil name and location	Depth from surface	Shrinkage: Linear	Shrinkage: Limit[2]	Shrinkage: Ratio	Shrinkage: Volumetric	Mechanical analysis[1] Percentage passing sieve-- No. 4	No. 10	No. 40	No. 200	Percentage smaller than-- 0.05 mm	0.02 mm	0.005 mm	0.002 mm	Liquid limit[2]	Plasticity index	Classification: AASHTO[3]	Classification: Unified[4]
	Depth																
Kenney loamy fine sand: From Spring, 3.75 miles west on Spring-Stuebner Road to Rothwood Road, 1.8 miles north on Rothwood Road and 40 feet west in timber (modal). Texas report no. 1271L-347, 348.	9-56	1.7	18.3	1.83	5.2		100	99	21	4	1	0	0	21	7	A-2-4(0)	SM-SC
	56-80	3.5	18.6	1.71	10.4			100	34	24	15	12	12	25	9	A-2-4(0)	SC
Lake Charles clay: From Alief, 1.11 miles west on Alief Road to Synott Road, then 1.37 miles north on Synott Road and 75 feet west in pasture (modal). Texas report no. 1271L-198, 199, 200.	0-22	26.2	12.5	2.02	60.0			100	96	67	64	57	56	87	60	A-7-6(20)	CH
	36-52	29.9	6.0	2.23	65.7	99	99	98	92	86	79	61	56	92	66	A-7-6(20)	CH
	52-74	29.0	6.3	2.14	64.6	95	94	93	90	87	84	71	66	91	64	A-7-6(20)	CH

Soil Survey of Harris County, Texas

- Profile of Lake Charles clay

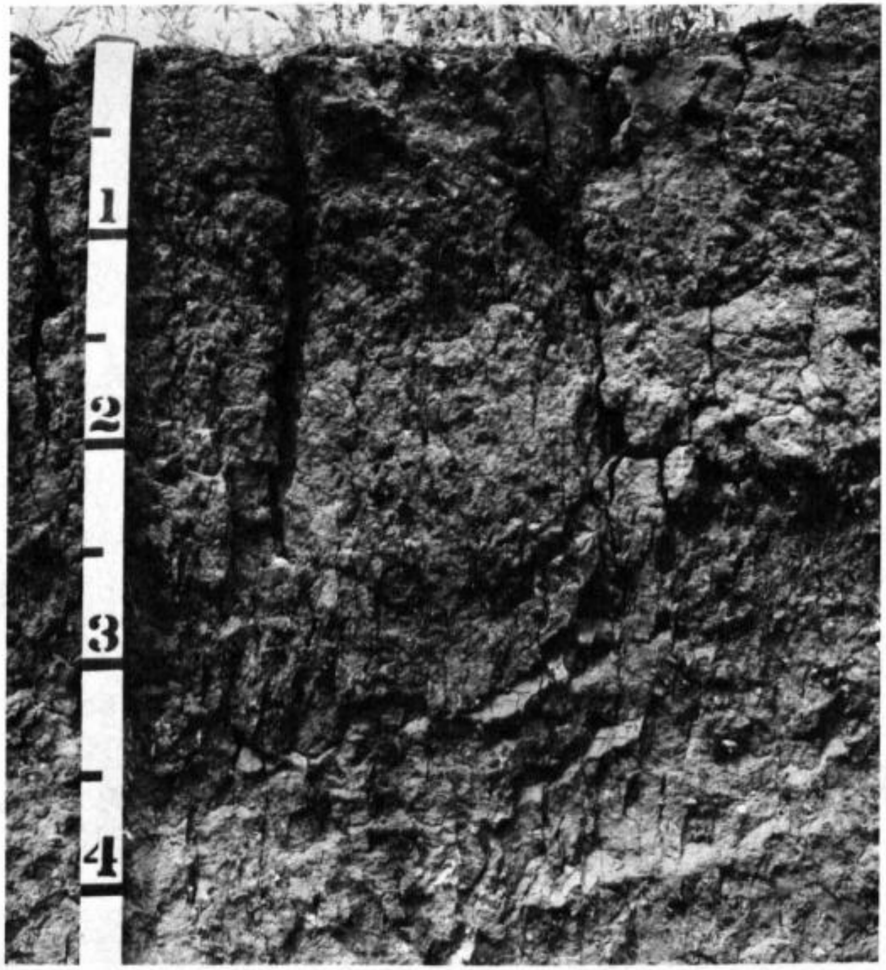


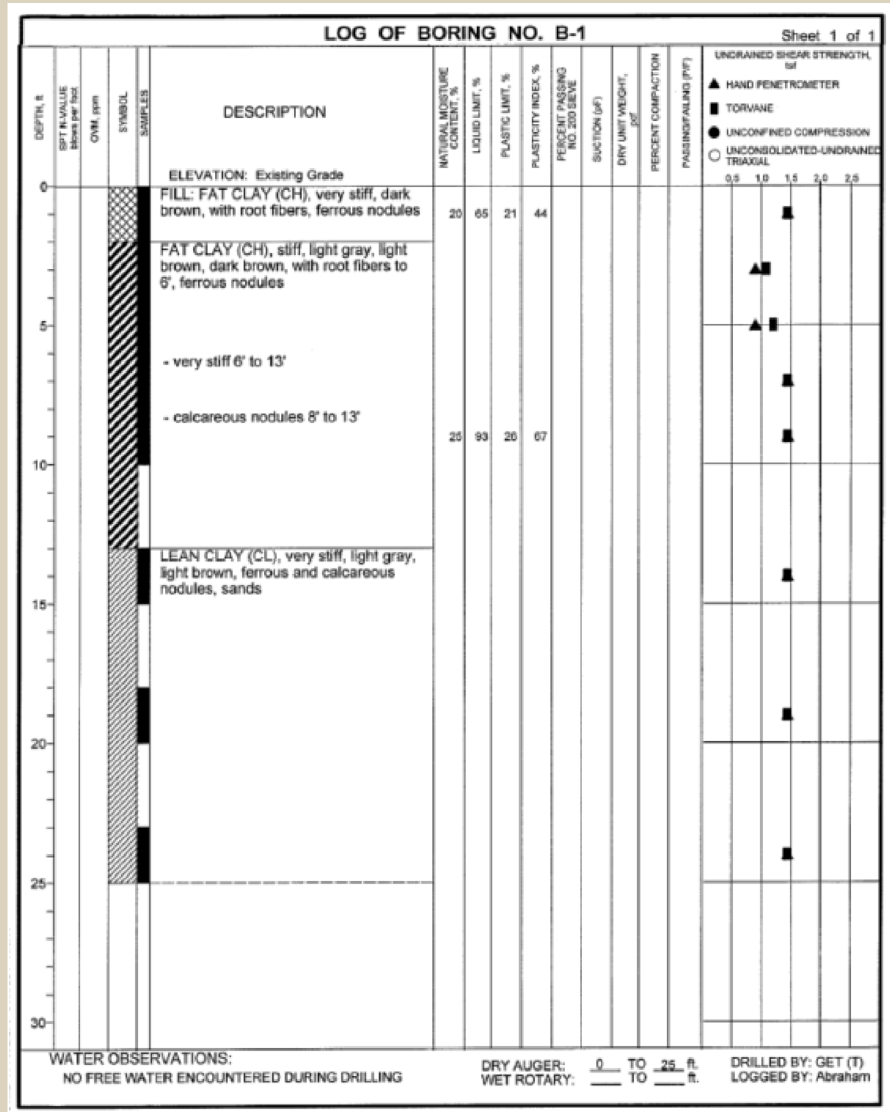
Figure 15. —Profile of Lake Charles clay, 0 to 1 percent slopes. Wide, deep cracks are in the upper layers, and intersecting slickensides are in the lower layers.

Geotechnical Study Report No. 11-700E

- Plan of Borings

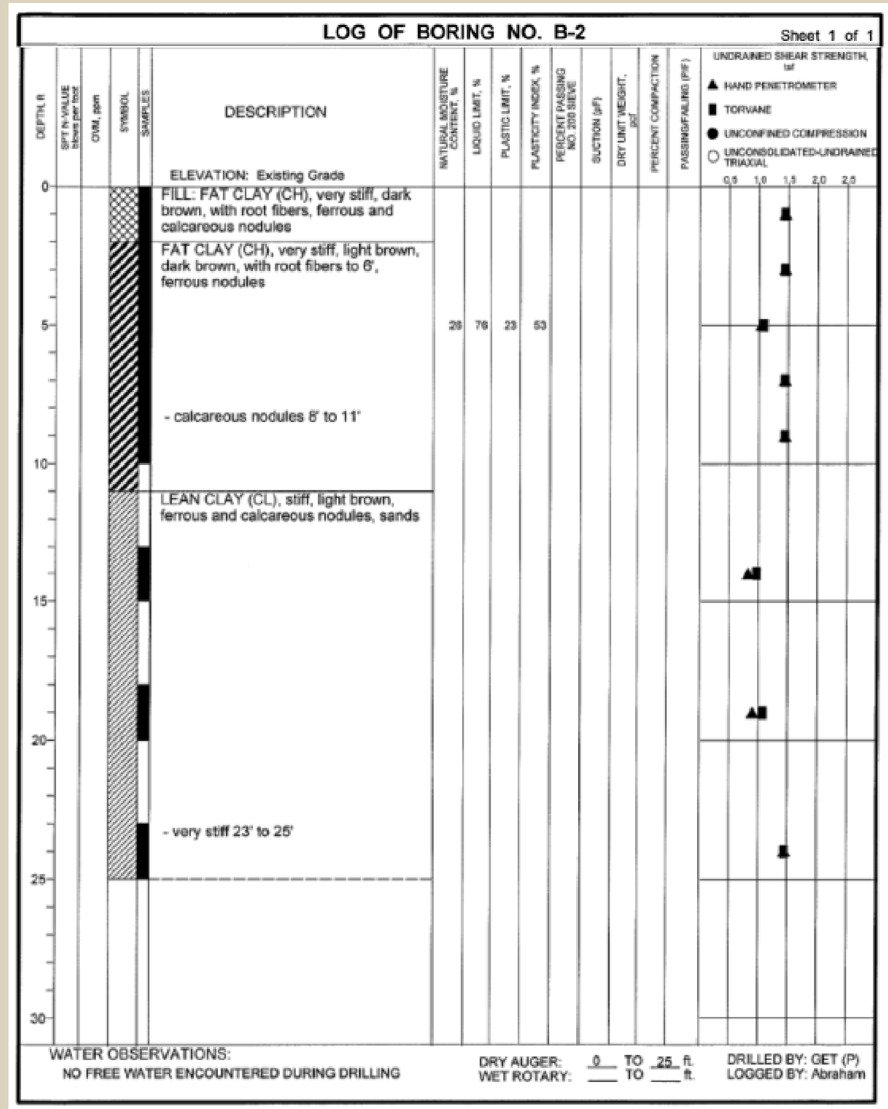
Geotechnical Study Report No. 11-700E

- Log of Boring No. B-1



Geotechnical Study Report No. 11-700E

- Log of Boring No. B-2



Steps in Design Calculations

- Strength and suction
- Depth of the movement active zone
- Depth of the anchor zone
- Size of the bell
  - Short term loading
  - Long term loading
- Reinforcing steel and size of shaft

Strength and Suction

- Input (in movement active and anchor zones)
  - Atterberg limits
  - Water content
  - Dry unit weight
  - Unconfined compressive strength in psi, tsf, or psf
  - Skin friction stress coefficient

- Output (in movement active and anchor zones)
  - Effective friction angle
  - Volumetric water content
  - Total unit weight
  - Present matric suction
  - Future matric suction
  - Skin friction stress

Design Parameters for Drilled Piers in Clay

-Design Parameters for Drilled Piers in Clay

Parameter (1)	Design category A.1 (2)	A.2 (3)	B.1 (4)	B.2 (5)	C (6)	D (7)
α_{avg}	0.5	0.3[a]	0.3	0.15[c]	0	0
Limit on side shear, in tons per square foot	0.9	0.4[b]	0.4	0.25[d]	0	0
N_c	9	9	9	9	9	9

[a] May be increased to Category A.1 value for segments of pier drilled dry.
[b] Limiting side shear is 0.9 tsf for segments of pier drilled dry.
[c] May be increased to Category B.1 value for segments of pier drilled dry.
[d] Limiting side shear is 0.4 tsf for segments of pier drilled dry.
Note: 1 tsf = 95.8 kN/m².

$$(Q_S)_{ult} = \alpha_{avg} s_u A_S$$

$$(Q_B)_{ult} = N_c c A_B$$

$$(Q_T)_{design} = (Q_S)_{ult} + \frac{(Q_B)_{ult}}{3} \leq (Q_T)_{ult}/2$$

Category A.—Straight-sided shafts in either homogeneous or layered soil with no soil of exceptional stiffness below the base.

Category A.1.—Piers in Category A installed dry or by advancing the borehole with light weight drilling slurry and displacing the slurry directly with fluid concrete.

Category A.2.—Piers in Category A installed with drilling mud along some portion of the hole such that the entrapment of drilling mud between the sides of the pier and the natural soil is possible.

Category B.—Belled piers in either homogeneous or layered clays with no soil of exceptional stiffness below the base.

Category B.1.—Piers in Category B installed dry.

Category B.2.—Piers in Category B installed with drilling mud along some portion of the hole such that the entrapment of drilling mud between the sides of the pier and the natural soil is possible.

Category C.—Straight-sided piers with base resting on soil significantly stiffer than the soil around the stem.

Category D.—Belled piers with base resting on soils significantly stiffer than the soil around the stem.

	Design Category			
Parameter	A.1	A.2	B.1	B.2
α	0.5	0.3	0.3	0.15
Side Shear limit, tsf	0.9	0.4	0.4	0.25
A: straight-sided shafts				
B: belled piers				
* From Reese, Touma, and O'Neill				

Correlation between ϕ' and PI

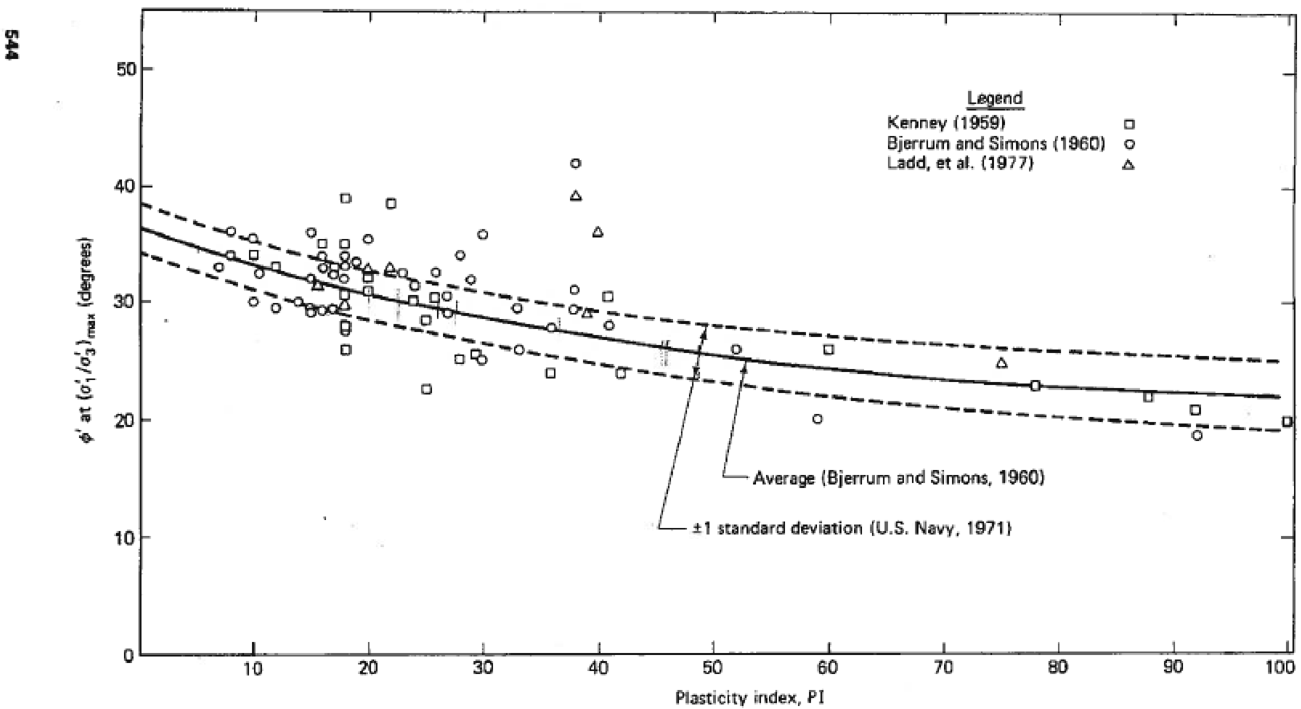


Fig. ~~11.27~~ 4.1 Empirical correlation between ϕ' and PI from triaxial compression tests on normally consolidated undisturbed clays (after U.S. Navy, 1971, and Ladd, et al., 1977).

from pg. 544, Robert D. Holtz and William D. Kovacs, An Introduction to Geotechnical Engineering, Prentice-Hall, © 1981
ISBN 0-13-484394-0

DW

Effective Friction Angle, ϕ'

$$\phi' = 0.0016(PI,\%)^2 - 0.3021(PI,\%) + 36.208$$

Total Unit Weight, lb/ft^3

$$\gamma_t = dry\ unit\ weight\ \times (1 + w)$$

Volumetric Water Content

$$\theta = w \times \frac{dry\ unit\ weight, lb/ft^3}{unit\ weight\ of\ water\ (62.4\ lb/ft^3)}$$

Matric Suction, stress units

$$Matric\ suction \cong -\frac{\begin{matrix} unconfined \\ compressive \\ strength \end{matrix}}{2} \cdot \frac{1 - \sin\phi'}{f\theta \sin\phi'}$$

"Skin Friction" or Side Shear Stress

$$"Skin\ friction" = \alpha(-\theta f h_m)\frac{\sin\phi'\cos\phi'}{1-\sin\phi'}$$

(compare with limiting side shear)

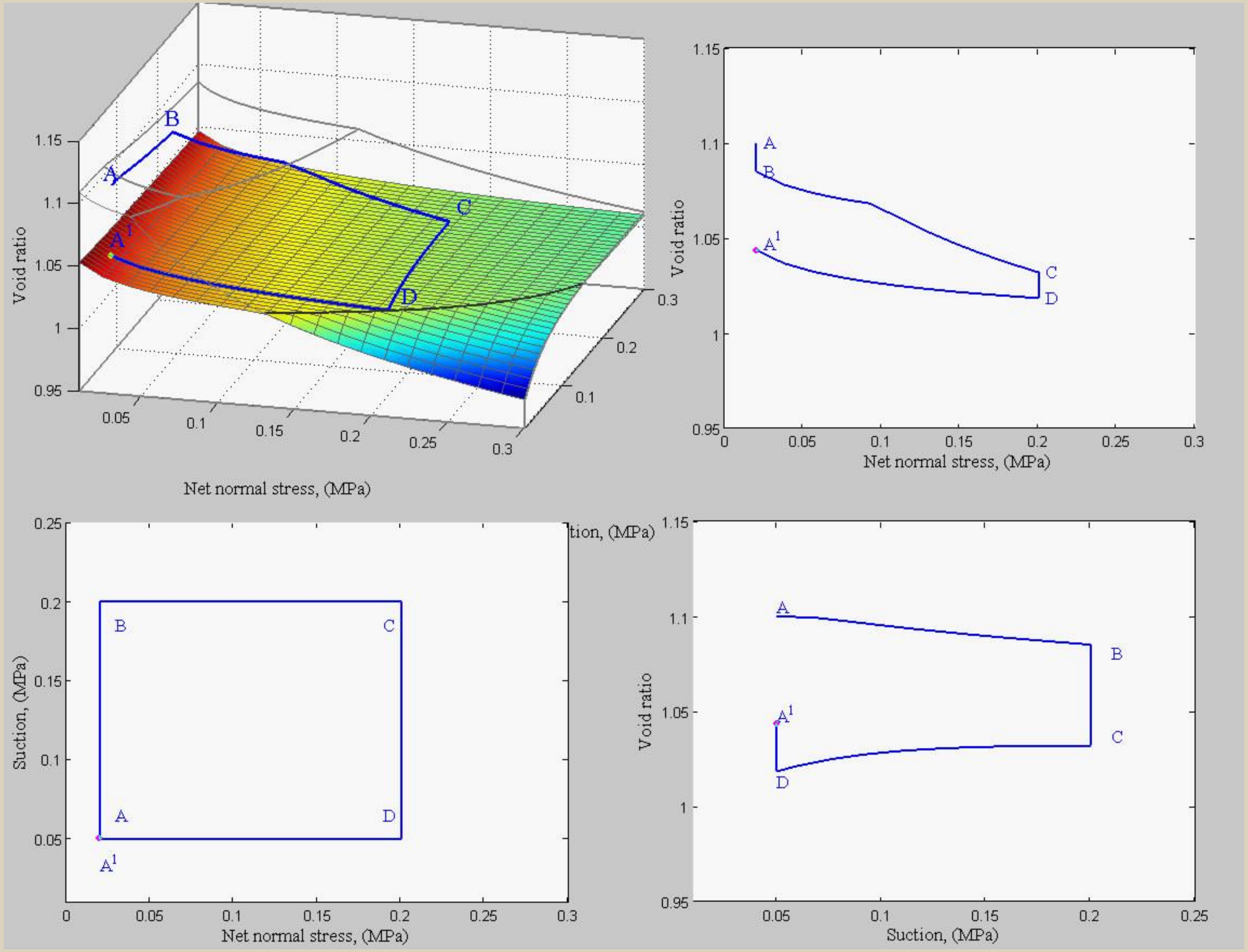
Calculation – Strength and Suction

Depth of the Movement Active Zone

- Input
  - Initial pF
  - Total unit weight (from “strength and suction” tab)
  - Final suction (from Thornthwaite Moisture Index)
  - Estimated percent fine clay (USDA NRCS county soil map)
- Output
  - Depth of movement active zone

Calculation – Depth of the Movement Active Zone

Formation of Suction vs. Pressure vs. Volume Surface

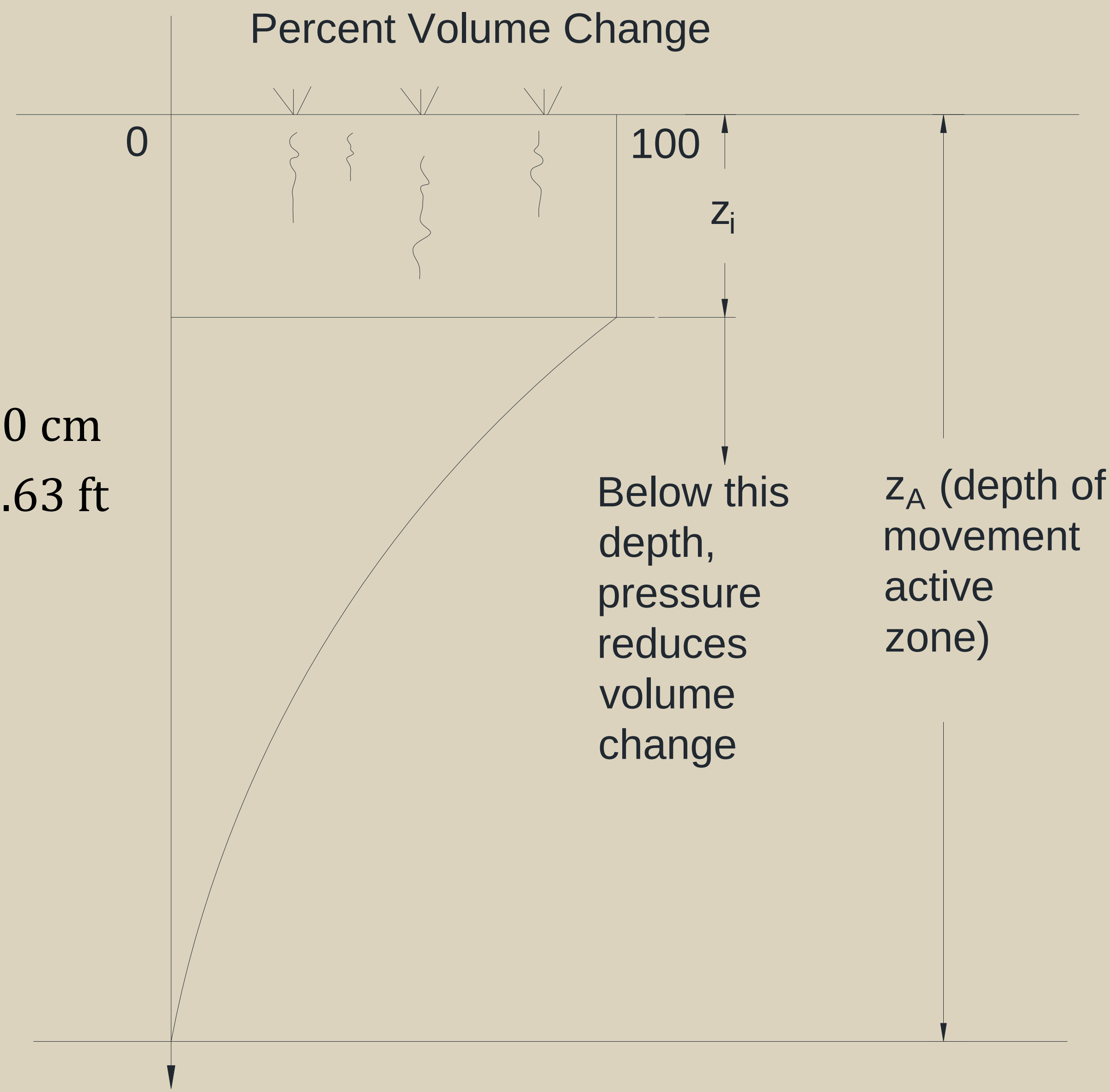


Equation of a Horizontal Path on the Surface

$$\frac{\Delta V}{V} = -\gamma_h log\left(\frac{h_f}{h_i}\right) - \gamma_\sigma \log\left(\frac{\sigma_f}{\sigma_i}\right)$$

At the depth of the movement active zone

$$\frac{\Delta V}{V} = 0$$



$z_i \cong 80$ cm

$z_i \cong 2.63$ ft

Depth of the Movement Active Zone, z_A

$$z_A, ft = z_i\left(\frac{h_i}{h_f}\right)^{\left(\frac{\gamma_h}{\gamma_\sigma}\right)}$$

Ratio of Volume Change Coefficients

$$\left(\frac{\gamma_h}{\gamma_\sigma}\right) = 1 + \frac{0.4343}{Sw}$$

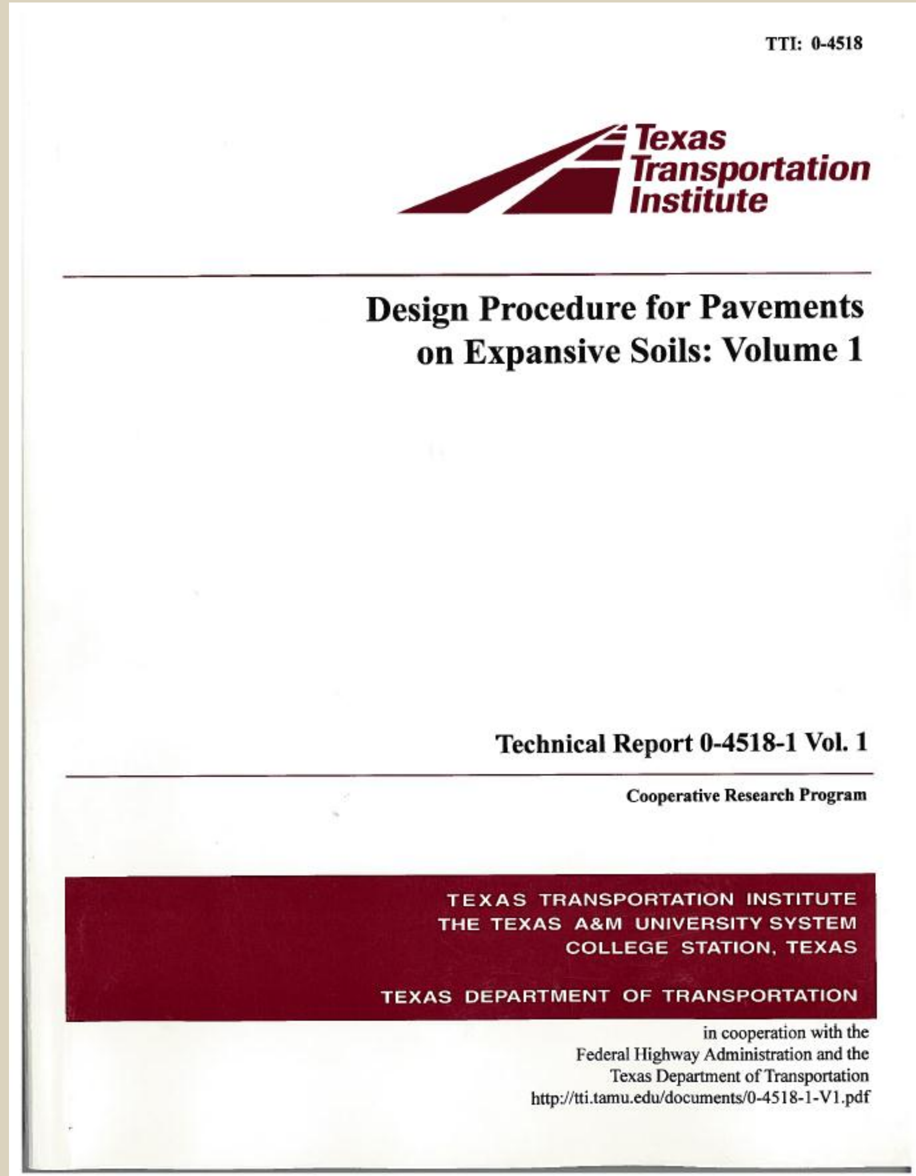
S: slope of the suction vs. water content curve

w: water content

Estimate of Sw

$$Sw = pF - 5.622 - 0.0041(\%\ fine\ clay)$$

Design Procedure for Pavements on Expansive Soils Report 0-4518-1


TTI: 0-4518

Texas Transportation Institute

Design Procedure for Pavements on Expansive Soils: Volume 1

Technical Report 0-4518-1 Vol. 1

Cooperative Research Program

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

TEXAS DEPARTMENT OF TRANSPORTATION

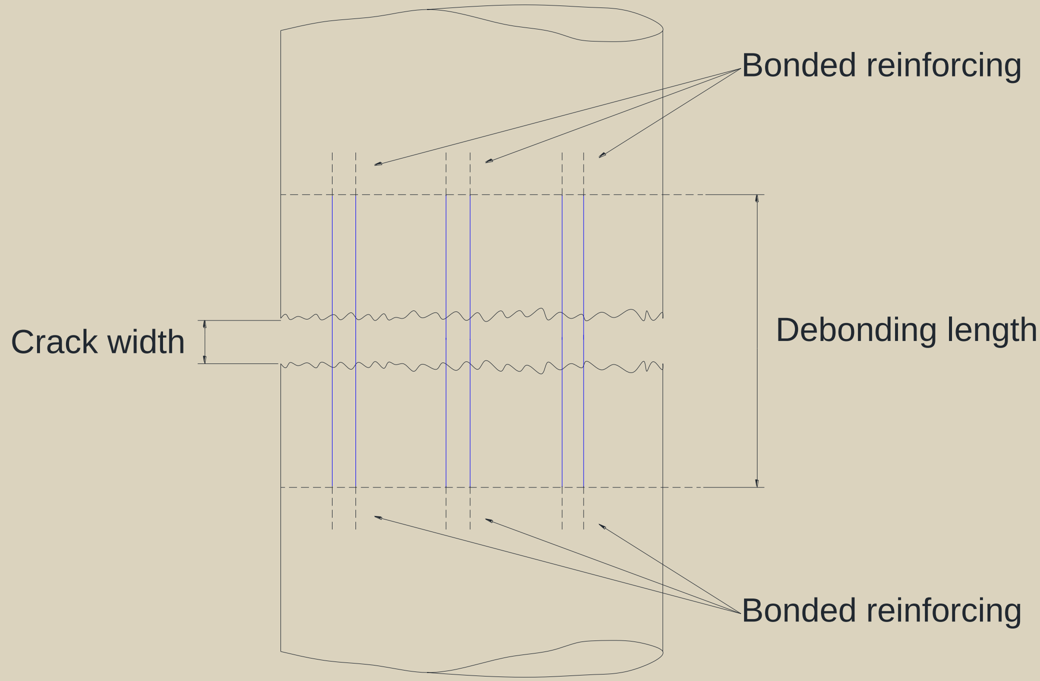
in cooperation with the
Federal Highway Administration and the
Texas Department of Transportation
http://tti.tamu.edu/documents/0-4518-1-V1.pdf

Depth of the Anchor Zone

- Input
  - Depth of the movement active zone
  - Skin friction stress (from “strength and suction” tab)
  - Trial diameter of pier shaft

- Output
  - Depth of the anchor zone
  - Depth of pier
  - Maximum tensile force in pier shaft
  - Required area of reinforcing steel

Reinforcing Steel

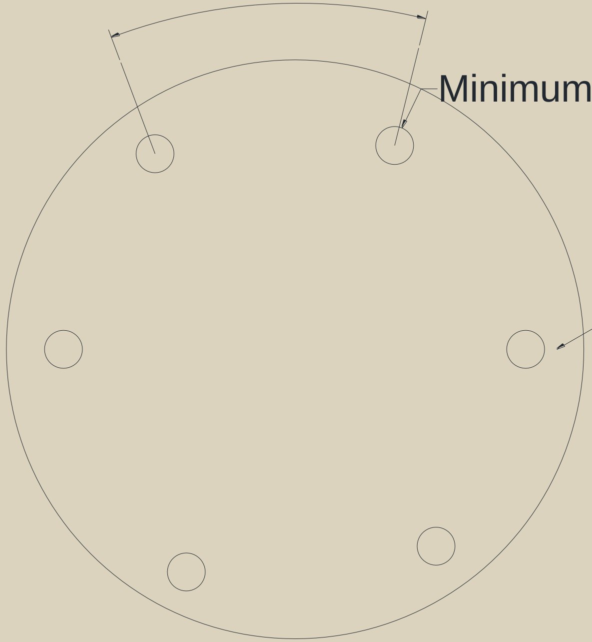


The smaller the bars

The smaller the debonding length

The smaller the crack width

Minimum size of pier shaft



Required Percent Steel

$$P(\%\, steel) = \left(\frac{4}{d}\frac{{s_u}^M}{f_y} - \frac{\gamma_c}{f_y}\right) - \frac{P}{Af_y}$$

d = diameter of shaft, in

${s_u}^M$ = side shear in the movement active zone, lb/in^2

f_y = yield strength of the reinforcing steel, ksi

A = cross sectional area of the shaft, in^2

P = minimum load at the top of the pier, kips

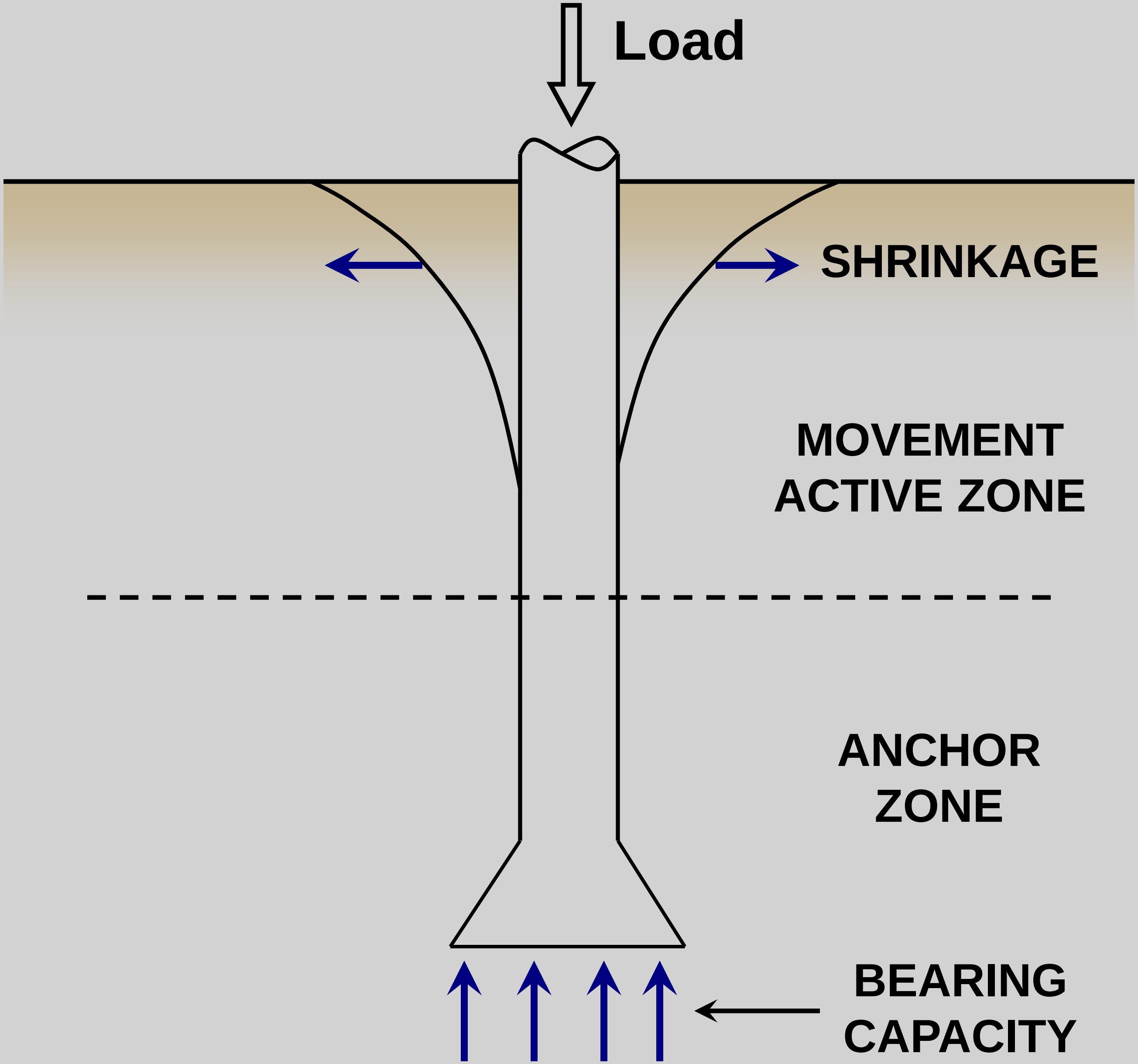
Reinforcing Steel

- Input
  - Required area of steel
  - Steel cover
  - Steel spacing
- Select
  - Reinforcing bar size
- Output
  - Number of reinforcing bars
  - Minimum pier shaft diameter

Calculation – Reinforcing Steel

Size of the Bell

- Input
  - Maximum load on pier
  - Depth of movement active zone
  - Depth of anchor zone
  - Skin fiction stress in the anchor zone
  - Long term bearing capacity factor of safety
  - Short term bearing capacity factor of safety
- Output
  - Diameter of bell
    - Short term loading
    - Long term loading
  - Minimum diameter of pier shaft


Load
SHRINKAGE
MOVEMENT
ACTIVE ZONE
ANCHOR
ZONE
BEARING
CAPACITY

Calculation – Size of the Bell

Steps in Design Calculations

- Strength and suction
- Depth of the movement active zone
- Depth of the anchor zone
- Size of the bell
  - Short term loading
  - Long term loading
- Reinforcing steel and size of shaft

TEXAS A&M ENGINEERING

Design of Drilled Shafts in Expansive Soils

Robert L. Lytton

Professor, Fred J. Benson Endowed Chair
Zachry Department of Civil Engineering
Texas A&M University

Foundation Performance Association
Houston, Texas
December 14, 2011