GEOTECHNICAL INPUT FOR DESIGN OF POST-TENSIONED SLAB FOUNDATIONS ON EXPANSIVE SOILS USING THE NEW INTERNATIONAL BUILDING CODE

GE 441

Advanced Engineering Geology and Geotechnics

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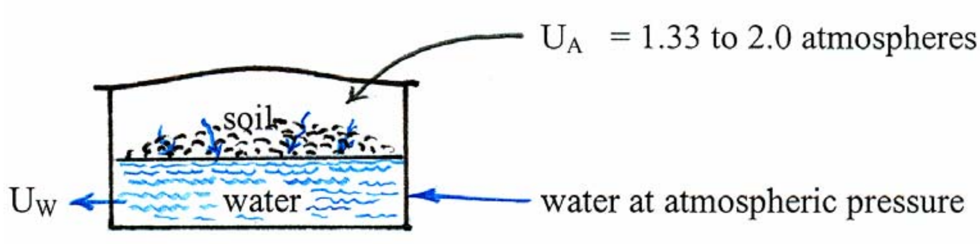
EVOLUTION OF UBC/IBC STANDARDS FOR DESIGN OF SLABS-ON-GRADE ON EXPANSIVE SOILS

- 1964-1986 Soil Conservation Service (SCS) produced Investigation Reports Nos. 1 thru 30 out of the SCS Laboratory in Lincoln, NE.

- The SCS determined Coefficients of Linear Extensibility for various kinds of expansive soils. Matric suction of different clay mixtures was determined in the lab using the following set-up



$U_A - U_W$ = matric suction $\log_{10}$ [(suction) in cm] = pF

- 1976-78 Post-Tensioning Institute (PTI) funds soil mechanics research at Texas A & M (Prof. Robert Lytton)

- 1980 Post-tension Institute issues "Design and Construction of Post-tensioned Slabs-on-Ground"

- 1981 US DOT issues report "Design of Pavements on Expansive Soils", by Prof. Gordon McKean at Univ. New Mexico. Soil suction presented as an optional method to predict behavior of expansive soils. McKeans' report incorporated SCS lab data.

- ASTM D-5298 adopted in 1992. It presents a simplified procedure for measuring soil suction that was developed by Lawrence D. Johnson at the Corps of Engineers Waterways Experiment Station Geotechnical Laboratory.

- 1991-97 Second PTI design procedures manual developed by Prof. Lytton at Texas A & M. Work was funded by PTI.

- 1997 UBC adopts the new PTI design procedure in Chapter 18, Division III.

- 2000 IBC adopts 1997 UBC statutes, minus the appendices.

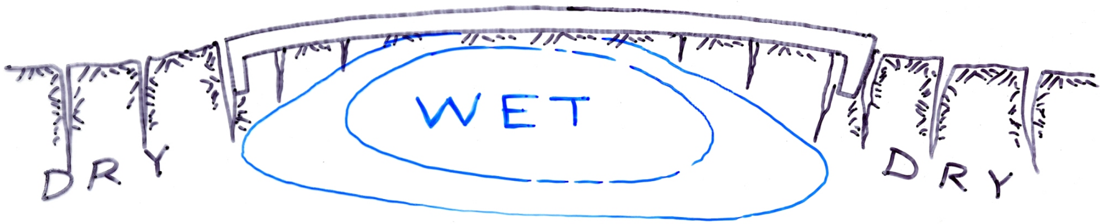
- 2001 Federal government encourages all 50 states to adopt the 2000 IBC by 2003 and its subsequent versions, to be issued every three years.

- In January 2003 the International Conference of Building Officials was integrated with the Building Officials and Code Administrators International (BOCA) and the Southern Building Code Congress International (SBCCI) into the International Code Council (ICC). This conglomeration forms the strongest code force in the world dedicated to ensuring the public's safety in the built environment.

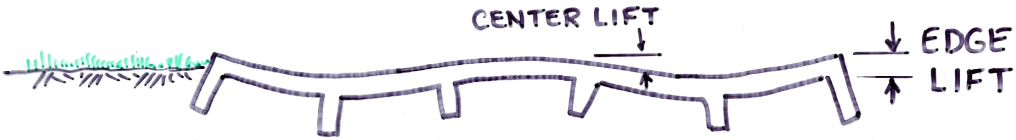
POST-TENSIONED SLAB-ON-GRADE

EARLY EDGE LIFT

DESICCATION CYCLE



LONG TERM EQUILIBRIUM



Soil differential movement y_m = center lift + edge lift

e_m e_m

SECTION 1817 — APPENDIX A (A PROCEDURE FOR ESTIMATION OF THE AMOUNT OF CLIMATE CONTROLLED DIFFERENTIAL MOVEMENT OF EXPANSIVE SOILS)

In general, the amount of differential movement to be expected in a given expansive soil should be based on recommendations supplied by a registered geotechnical engineer. The geotechnical engineer may use various soil testing procedures to provide a basis for these recommendations. A procedure developed in part through the PTI-sponsored research project at Texas A & M University that may be used by geotechnical engineers (in conjunction with accumulated experience with local soils conditions) as an aid for estimation of expected differential movements of expansive soils is presented in this appendix. This procedure is applicable only in those cases where site conditions have been corrected so that soil moisture conditions are controlled by the climate alone.

The information necessary to determine the differential movement using the procedure in this appendix is the type and amount of clay, the depth to constant or equilibrium suction, the edge moisture variation distance, the magnitude of the equilibrium suction, and the field moisture velocity. With this information either known or estimated, differential movements may be selected from Tables 18-III-A to 18-III-O for the center lift condition, or Tables 18-III-P to 18-III-DD for the edge lift condition.

Procedures for determining or estimating the necessary items of soil information are as follows:

1. Select a Thornthwaite Moisture Index from Figure 18-III-14 or 18-III-15. Alternatively, extreme annual values of the Thornthwaite Index may be calculated for a given site using Thornthwaite's procedures.

2. Obtain an estimate of the edge moisture variation distance, e_m, for both edge lift and center lift loading conditions from Figure 18-III-14.

3. Determine the percent of clay in the soil and the predominant clay mineral. The predominant type of clay can be determined by performing the following tests and calculations and by using Figure 18-III-15.

3.1 Determine the plastic limit (*PL*) and the plasticity index (*PI*) of the soil.

3.2 Determine the percentage of clay sizes in the material passing the U.S. No. 200 (75 µm) sieve (Hydrometer Test).

3.3 Calculate the activity ratio of the soil:

$$A_c = \frac{PI}{(\text{Percent passing U.S. No. 200 } [75\ \mu\text{m}] \text{ sieve} \leq 0.002\text{mm})} \qquad (1)$$

3.4 Calculate the Cation Exchange Activity. A discussion of procedures for determining Cation Exchange Capacity for use in calculating Cation Exchange Activity is presented in Appendix B.

$$CEAC = \frac{PI^{1.17}}{(\text{Percent passing U.S. No. 200 } [75\ \mu\text{m}] \text{ sieve} \leq 0.002\text{mm})} \qquad (2)$$

3.5 Enter Figure 18-III-15 with the A_c and *CEAC*. The soil type is determined by the intersection of the two entries. Note that the same mineral type is obtained from Figure 18-III-15 for a significant range of values of A_c and *CEAC*. This indicates that the determination of the mineral type is relatively insensitive to the precision by which the Atterberg Limits and other soil parameters have been determined. In the case of doubt as to the predominant mineral type, the clay may be conservatively classified as montmorillonite.

4. Depth to constant soil suction can be estimated as the depth below which the ratio of water content to plastic limit is constant. At times it will be the depth to an inert material, an unweathered shale, or to a high water table. Constant soil suction can be estimated with reasonable accuracy from Figure 18-III-16 if it is not actually determined in the laboratory; however, for most practical applications, the design soil suction value will seldom exceed a magnitude of *pF* 3.6.

5. Moisture velocity can be approximated by using a velocity equal to one half of the Thornthwaite Moisture Index [expressed in inches/year (mm/year)] for the construction site, converted to inches/month. To allow for extreme local variations in moisture velocity, this value shall not be assumed to be less than 0.5 in./month (12.7 mm/month), and the maximum moisture velocity shall be 0.7 in./month (17.8 mm/month).

6. Using values of edge moisture distance variation, e_m, percent clay, predominant clay mineral (kaolinite, illite, or montmorillonite), depth to constant suction, soil suction, *pF*, and velocity of moisture flow determined in steps 1 through 5 above, enter the appropriate tables, Tables 18-III-A to 18-III-O for center lift and Tables 18-III-P to 18-III-DD for edge lift, and find the corresponding soil differential movements, y_m. The values of swell presented in the tables were obtained from a computer program based on the permeability of clays and the total potential of the soil water.

SECTION 1818 — APPENDIX B (SIMPLIFIED PROCEDURES FOR DETERMINING CATION EXCHANGE CAPACITY AND CATION EXCHANGE ACTIVITY)

Simplified Procedure for Determining Cation Exchange Capacity Using a Spectrophotometer

The Cation Exchange Capacity of soil samples may be determined by comparative means in the standard spectrophotometer device. This method of determining the Cation Exchange Capacity is used by the U.S. Soil Conservation Service. Data obtained by this method should be comparable with data for similar soils that have been measured by the U.S. Conservation Service. This simplified procedure is:

1. Place 10 grams of clay soil in a beaker and 100 ml of neutral 1 N ammonium acetate (NH_4AC) is added. This solution is allowed to stand overnight.

2. Filter the solution of Step 1 by washing through filter paper with 50 ml of NH_4AC.

3. Wash the material retained on the filter paper of Step 2 with two 150 ml washings of isopropyl alcohol, using suction. The isopropyl alcohol wash fluid should be added in increments of approximately 25 ml and the sample allowed to drain well between additions.

4. Transfer the soil and filter paper to a 800-ml flask. Add 50 ml M_gCI_2 solution and allow to set at least 30 minutes, but preferably 24 hours.

5. Under suction, filter the fluid resulting from Step 4.

6. Normally, the solution of M_gCI_2 must be diluted before it is placed in the spectrophotometer in Step 10. The dilution will vary from one piece of equipment to the next. The calculations given at the end of this section assume that 200 ml of distilled water have

been used to dilute 1 ml of the M_gCI_2 solution. The 200-to-1 dilution is fairly typical.

7. Prepare a standard curve by using 10 μg of nitrogen (in the NH_4 form) per ml of a standard solution in a 50 ml volumetric flask. Adjust the volume to approximately 25 ml, add 1 ml of 10 percent tartrate solution, and shake. Add 2 ml of Nessler's aliquot with rapid mixing. Add sufficient distilled water to bring the total volume to 50 ml. Allow color to develop for 30 minutes.

8. Repeat Step 7 for 1.0, 2.0, 4.0, and 8.0 ml aliquots of standard solution.

9. Insert the standard solution resulting from Steps 7 and 8 into the spectrophotometer. Record readings and plot the results to construct a standard curve. (The spectrophotometer is calibrated beforehand with distilled water.)

10. Extract 2.0 ml of sample aliquot from Step 6 and add 25 ml of distilled water in a 50 ml volumetric flask. Add 1 ml of 10 percent tartrate and shake. Add 2 ml of Nessler's aliquot with rapid mixing. Add sufficient distilled water to bring the total volume to 50 ml. Let the solution stand for 30 minutes and then insert into the spectrophotometer and record the transparency reading.

11. Typical calculations:

Weight of dry soil	=	10.64 grams
Spectrophotometer	=	81 percent
	=	24.5 μg/g from standard curve

Conversion:

$$\frac{24.5\mu g}{2\ ml/aliquot} \times \frac{200\ ml}{1\ ml} \times \frac{50\ ml}{10.64\mu g} \times \frac{1}{1{,}000\mu/mg} \times$$

$$\frac{1}{14\ mg/meq} \times 100\ g = 82.2\ meq/100g$$

Equation for Cation Exchange Capacity

A 1979 study at Texas Tech University resulted in the following proposed modifications to the Pearring and Holt equations for Clay Activity, Cation Exchange Capacity, and Cation Exchange Activity:

Clay Activity $A_c = \dfrac{PI}{\%\ Clay}$

Cation Exchange Capacity:

$CEC = (PL)^{1.17}$

Cation Exchange Activity:

$$CEAC = \frac{(PL)^{1.17}}{\%\ Clay}$$

Symbols and Notations

PI = plasticity index.

PL = plastic limit.

% Clay = % Passing U.S. No. 200 sieve (75 μm) ≤ 0.002 mm.

Comparison of Methods of Determining Cation Exchange Capacity in Predominant Clay Mineral

A comparison of values of Cation Exchange Capacity using atomic absorption and spectrophotometer techniques is presented in Table 18-III-EE.

Comparison of clay mineral determination between atomic absorption of the correlation equations presented above is presented in Table 18-III-FF and Figure 18-III-17.

SECTION 1819 — DESIGN OF POSTTENSIONED SLABS ON COMPRESSIBLE SOILS (BASED ON DESIGN SPECIFICATIONS OF THE POSTTENSIONING INSTITUTE)

1819.1 General. The design procedure for foundations on compressible soils is similar to the structural design procedure in Section 1816.4, except that different equations are used and the primary bending deformation is usually similar to the edge lift loading case.

1819.2 List of Symbols and Notations.

M_{cs} = applied service moment in slab on compressible soil, ft.-kips/ft. (kN·m/m).

M_{ns} = moment occurring in the "no swell" condition, ft.-kips/ft. (kN·m/m).

V_{cs} = maximum service load shear force in slab on compressible soil, kips/ft. (kN/m).

V_{ns} = service load shear force in the "no swell" condition, kips/ft. (kN/m).

Δ_{cs} = differential deflection in a slab on compressible soil, in. (mm).

Δ_{ns} = differential deflection in the "no swell" condition, in. (mm).

δ = expected settlement, reported by the geotechnical engineer occurring in compressible soil due to the total load expressed as a uniform load, in. (mm).

1819.3 Slabs-on-ground Constructed on Compressible Soils. Design of slabs constructed on compressible soils can be done in a manner similar to that of the edge lift condition for slabs on expansive soils. Compressible soils are normally assumed to have allowable values of soil-bearing capacity, q_{allow}, equal to or less than 1,500 pounds per square foot (71.9 kN/m²). Special design equations are necessary for this problem due to the expected in situ elastic property differences between compressible soils and the stiffer expansive soils. These formulas are:

1. **Moment.**

1.1 Long direction:

$$M_{cs_L} = \left(\frac{\delta}{\Delta_{ns_L}}\right)^{0.5} M_{ns_L} \qquad (19\text{-}1)$$

1.2 Short direction:

$$M_{cs_S} = \left(\frac{970 - h}{880}\right) M_{cs_L} \qquad (19\text{-}2)$$

For SI: $M_{cs_S} = \left(\dfrac{24\,638 - h}{22\,352}\right) M_{cs_L}$

WHERE:

$$M_{ns_L} = \frac{(h)^{1.35}(S)^{0.36}}{80(L)^{0.12}(P)^{0.10}} \qquad (19\text{-}3)$$

For SI: $1\ \dfrac{ft.\cdot kip}{ft.} = 4\,448\,031\ \dfrac{kN\cdot m}{m}$

$$\Delta_{ns_L} = \frac{(L)^{1.28}(S)^{0.80}}{133(h)^{0.28}(P)^{0.62}} \qquad (19\text{-}4)$$

For SI: 1 inch = 25.4 mm.

2. **Differential deflection:**

$$\Delta_{cs} = \delta e_n^{[1.78 - 0.103(h) - 1.65x10^{-3}(P) + 3.95x10^{-7}(P)^2]} \qquad (19\text{-}5)$$

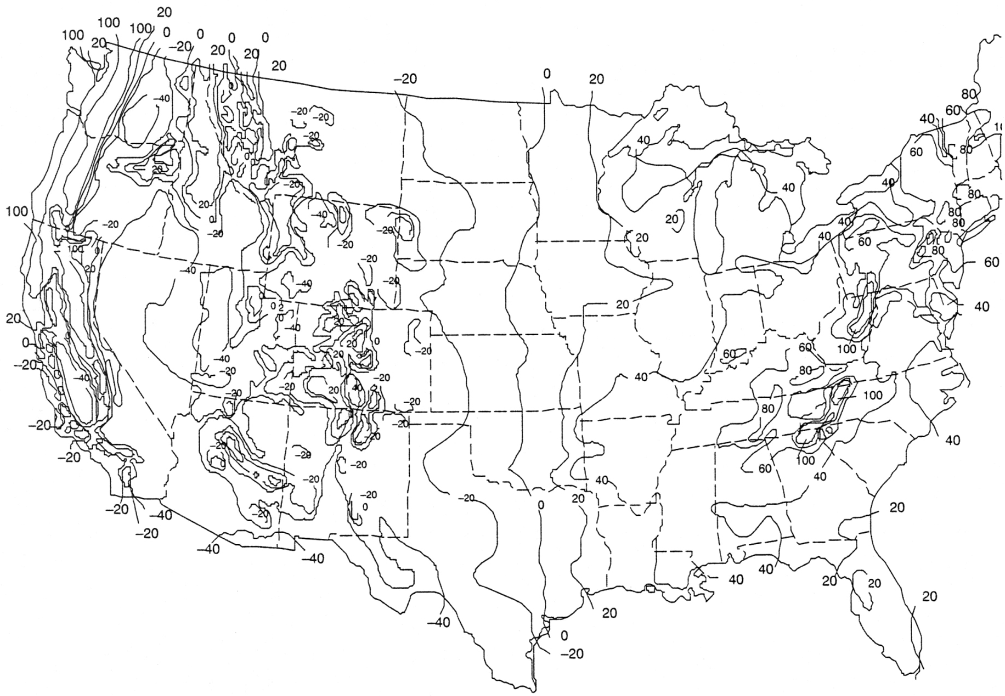
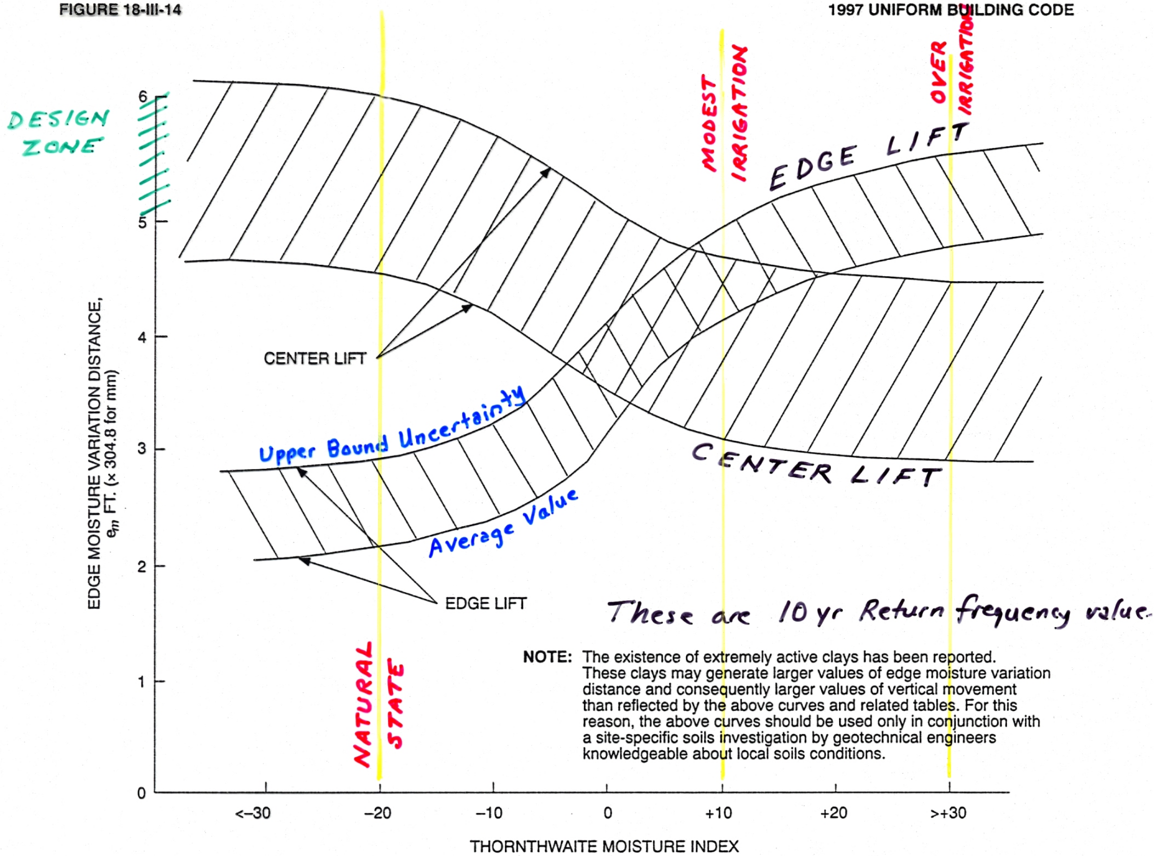


FIGURE 18-III-12—THORNTHWAITE MOISTURE INDEX DISTRIBUTION IN THE UNITED STATES

The Thornthwaite Moisture Index (TMI) is an estimation of the average soil moisture loss due to evapotranspiration. A value of -20 indicates a net moisture loss of 20" annually. A value of +20 indicates 20"/year of water in excess of the maximum loss due to evapotranspiration. If people irrigate around structures, the TMI can easily shift, from -20 to +40.



NOTE: The existence of extremely active clays has been reported. These clays may generate larger values of edge moisture variation distance and consequently larger values of vertical movement than reflected by the above curves and related tables. For this reason, the above curves should be used only in conjunction with a site-specific soils investigation by geotechnical engineers knowledgeable about local soils conditions.

FIGURE 18-III-14—APPROXIMATE RELATIONSHIP BETWEEN THORNTHWAITE INDEX AND MOISTURE VARIATION DISTANCE

This chart was developed from back analysis of slabs-on-grade in the Austin, San Antonio and Houston metro areas.
They used slabs that had performed successfully, more than 10 yrs old; on FLAT sites with NO TREES. TREES cause greater drying of soil because extracting more pore water than would normally be lost through surficial desiccation. Converse can be true if constant irrigation of nearby garden areas.

50 yr swings could be expected to be much greater.

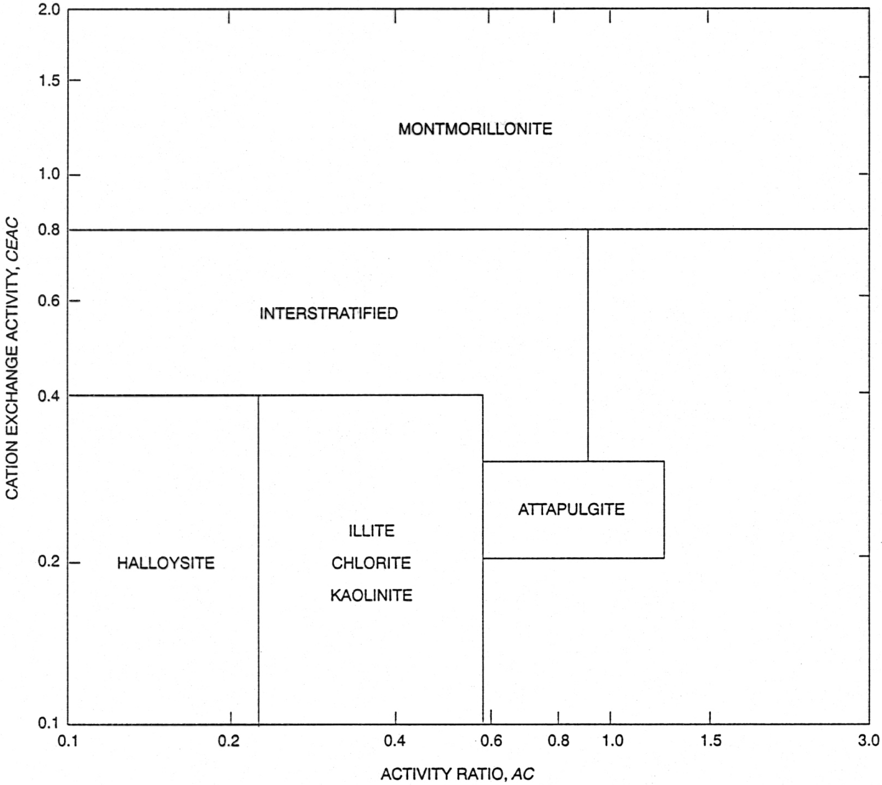


FIGURE 18-III-15—CLAY TYPE CLASSIFICATION TO CATION EXCHANGE AND CLAY ACTIVITY RATIO AFTER PEARRING AND HOLT

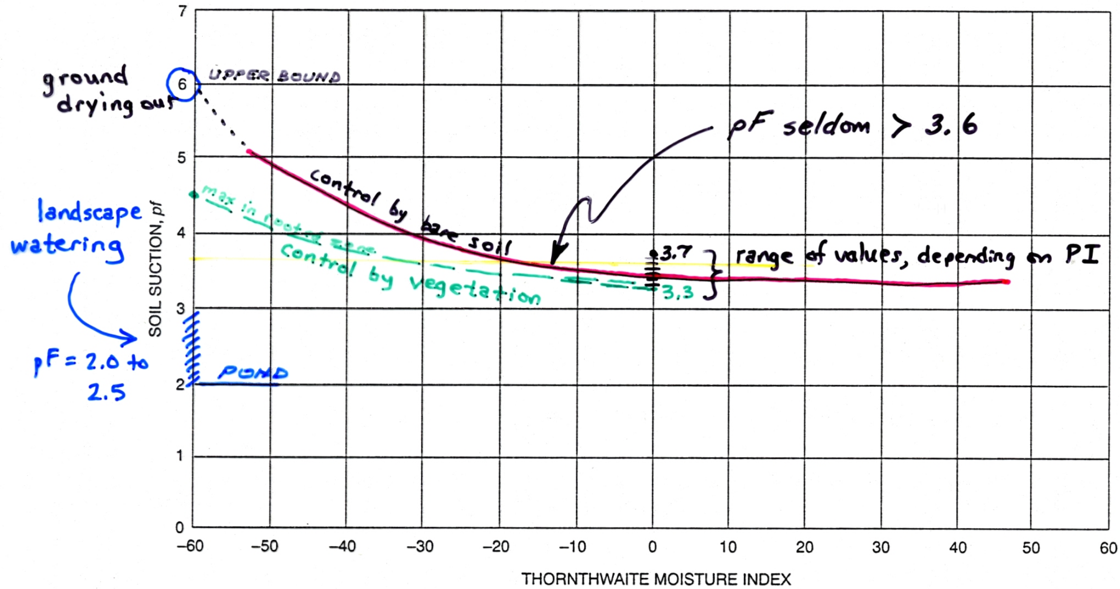


FIGURE 18-III-16—VARIATION OF CONSTANT SOIL SUCTION WITH THORNTHWAITE INDEX

$pF = \log_{10}[(\text{suction})\ cm]$ $pF \cong 3 + \log_{10}(\text{negative pressure in atmospheres})$

Soil suction is a measure of the free energy of the pore water in a soil. ~ in practical terms, it is a measure of the affinity of soil to RETAIN WATER

e.g. Change in suction WET to DRY states.

$u_A = 15000$ cm wet $pF = 4.18$

$u_A = 316$ cm dry $pF = 2.5$

∴ max. change in suction: $4.18 - 2.50 = 1.7 = \Delta pF$

$$\frac{\left(\frac{\Delta V}{V}\right)}{\Delta pF} = \gamma_h = \text{suction compression index}$$

US DOT Work @ Univ New Mexico Airport Runways

$$3\sqrt{\frac{\Delta V}{V}} = \text{SCS Coefficient of Linear Extensibility}$$

Example Input for Design of Post-Tensioned Slabs-on-Grade

The 2000 International Building Code (IBC) includes special provisions for the design of post-tensioned floor slabs on expansive soils. These specifications are included Chapter 18, Division III, Section 1816 titled: Design of Posttensioned Slab-on-Ground (Based on Design Specification of the Posttension Institute). The IBC states that post-tensioned slab foundations are acceptable for structures located on relatively level building pads with the foundations setback at least 10 feet from any descending slope steeper than 5:1 (horizontal to vertical). The setback is increased to 20 feet if the slopes are 2:1.

For purposes of design, one begins with an assumption of the soil expansion potential, based on either the Atterberg Limits or the IBC Soil Expansion Test. For the purposes of illustration, we are assuming moderately high expansion potential, with an average Plasticity Index (PI) of 25. Bulk samples of these materials should be screened using the Soil Plasticity Indices test battery (ASTM D-4318), to ascertain if the Plasticity Index is equal to or less than the assumed value of 25. If PI of greater than 25 is encountered, then additional testing will be required. Such tests will include: Soil Expansion Potential (ASTM D-4829/UBC Standard 18-2); Percent Clay Fraction (ASTM D-1140) (to calculate the cation exchange capacity, in accord with UBC Section 1818); and Soil Potential/Suction Tests (ASTM D-5298).

After the completion of the rough grading, building pads should be periodically watered to reduce desiccation and promote hydro-expansion of the fill pads prior to foundation construction. When foundation construction is ready to proceed, the subgrade in the areas to receive foundations should be moisture-conditioned to at least 2 percent above optimum moisture.

If some of the lots are situated on bedrock cut, these should be covered with a two feet thick cushion of compacted fill. The soil cushion placed on these lots should be screened using the Soil Plasticity Indices Test procedures (ASTM D-4318), to ascertain if the materials have Plasticity Indices of less than 25. If the PI values are less than or equal to 25, no additional grading recommendations are required for these lots prior to foundation construction, short of watering to reduce post-construction soil heave.

Due to variable conditions, it has been assumed that moderately high expansion potential soils may be present at the foundation level on all lots containing fill from the subject parcel. The following parameters were used in developing appropriate foundation recommendations for post-tensioned slab foundations at this site in accordance with the Post-Tensioning Institute (PTI) and Chapter 18 of the 2000 IBC:

Plasticity Index (from laboratory tests) = 25%

Clay Fraction (assumed worst case) = 30% illite and kaolinite

Depth to Constant Soil Suction (from soil moisture profiles on boring logs) = 7 feet

Thornthwaite Moisture Index (per UBC/PTI) = 40

Using these values, an edge moisture variation distance of 3 to 4.5 feet should be used for center lift (controlled by drought or unirrigated conditions), while an edge moisture variation distance of 5 to 6 feet should be used for the slab perimeter (controlled by rainfall or irrigated conditions).

Constant soil suction (pF) has been taken as 3.4 for a Thornthwaite Moisture Index of 40. The resulting values for differential movement are 0.077 inches for center lift and 0.078 inches for edge lift.

The slab foundations should be designed for a soil bearing capacity of 1000 pounds per square foot (psf) for dead loads, 1200 psf for dead plus live loads, and 1500 psf for all loads, including wind and seismic. A friction coefficient of about 0.35 should be used for the portions of the slab in direct contact with the subgrade.

The slab foundations should have a minimum edge thickness of at least 12 inches and a minimum center thickness of at least 8 inches. The slabs should bear on a prepared subgrade of firmly compacted material at least 6 inches below the lowest adjacent finished grade.

To reduce the likelihood of moisture infiltration through the slab, a heavy plastic vapor barrier consisting of 10mil Visqueen (or an approved equivalent) should be placed directly on the prepared subgrade. The plastic should be protected during construction by a layer of at least 2 inches of clean sand. The sand should be thoroughly moistened prior to concrete placement.

All appropriate requirements of the latest edition of the IBC and the Post-Tensioning Institute should be followed in the design and construction of post-tensioned slab foundations at any site.