Foundations on Expansive Clay Soil

Part 1 – The Science of Expansive Clay

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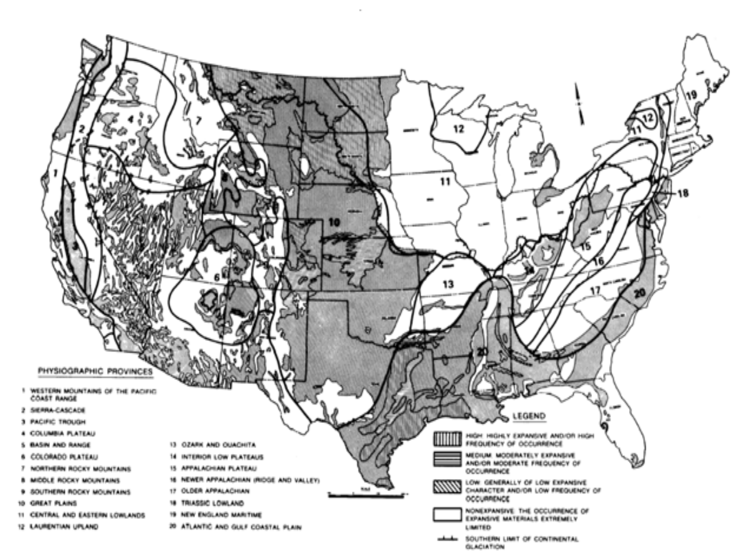
What are Expansive Clays?

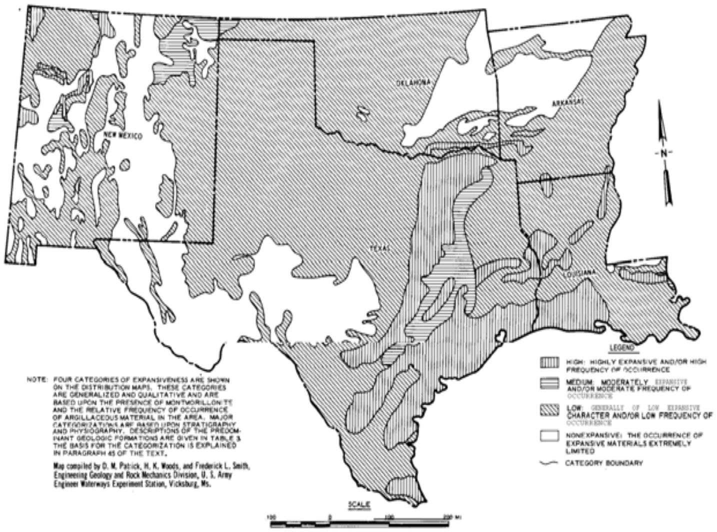
- Clay soils which expand when they gain water and shrink when they loose water (desiccation).
- Only certain clays are expansive, mainly those containing montmorillonite.
- Expansive clays are found mainly in the Great Plains and Southeast US.

Other Types of Expansive Soils

- Claystone (A sedimentary fine-grained rock consisting of compacted clay particles).
- Shale (A sedimentary rock formed from clay that is compacted together by pressure).



U. S. Army Corps of Engineers



Why Do They Do That?

- Expansive clays are made up of small, negatively charged plates.
- The clay particles attract water molecules, which are slightly polarized.
- A single pound of montmorillonite can have a surface area of 800 acres.
- This results in a potential for a massive change in volume as water is adsorbed.

Atterberg Limits

- Widely used index properties for soil.
- Plastic Limit (PL) is the moisture content (MC) at which the soil behavior changes from a semi-solid (brittle) to a plastic.
- Liquid Limit (LL) is the moisture contents at which the soil behavior changes from a plastic to a liquid.

Shrinkage Limit

- Transition from solid to semi-solid behavior.
- Defined as the water content at which a saturated clay specimen ceases to shrink when dried.
- Generally below the plastic limit.
- Commonly calculated as a function of Liquid Limit and Plasticity Index using the Casagrande Chart.

Plasticity Index

- The plasticity index (PI) is the mathematical difference between the LL and PL.
- Most soil expansion occurs as the moisture content moves from the PL to the LL.
- The higher the PI, the more water that can be adsorbed during expansion, and hence the greater the potential movement of the soil.

Identification of Expansive Clays

- Plasticity Index (PI) can be used as a reasonable surrogate to indicate soil expansivity.
  - PI > 20 considered expansive.
  - PI > 40 considered highly expansive.
- Expansion Index considers effect of clay mineral.

Factors Affecting Shrink-Swell Potential

- Clay mineral type.
- Amount of clay.
- Surcharge pressure.
- Soil structure and fabric.
- Depth of active zone.
- Potential for change in moisture content.

Control of Shrink-Swell Behavior

- For a given structure, there are five ways to control shrink-swell:
  - Surcharge (controls only heave)
  - Replace expansive soil with non-expansive soil (select fill).
  - Control change in moisture content.
  - Isolate the structure from the soil.
  - Chemical soil treatment

Control of Soil Movement

- For a given clay soil, the amount of movement is driven by the magnitude of change in soil moisture.
- Moisture changes are primarily a result of evaporation, transpiration (water removed by vegetation), rainfall, irrigation and drainage.

Equilibrium Moisture Content

All clay soils have an equilibrium moisture content (EMC). EMC is a function of:

- Temperature
- Humidity
- Water table
- Vegetation
- Irrigation & precipitation
- Drainage

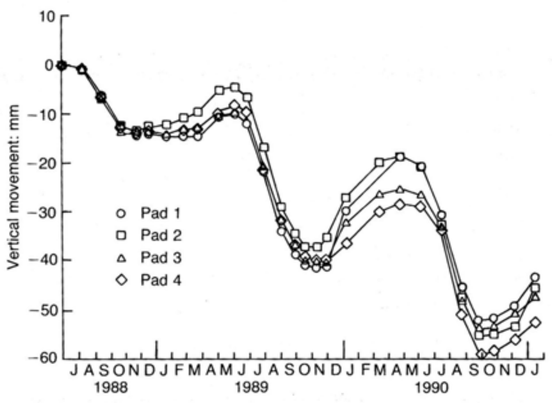
Equilibrium Moisture Content

- EMC changes constantly.
- Soil will gain moisture if MC is below the EMC.
- Soil will lose moisture if MC is above the EMC.
- Movement of MC toward the EMC can be stopped only by sealing the soil with an impermeable membrane.

Seasonal Shrink-Swell Cycle

- Because EMC changes with time, clay soils will experience seasonal shrink-swell behavior.
- Soil will swell in cool, wet weather as the soil gains moisture.
- Soil will shrink in hot, dry weather as the soils loses moisture.

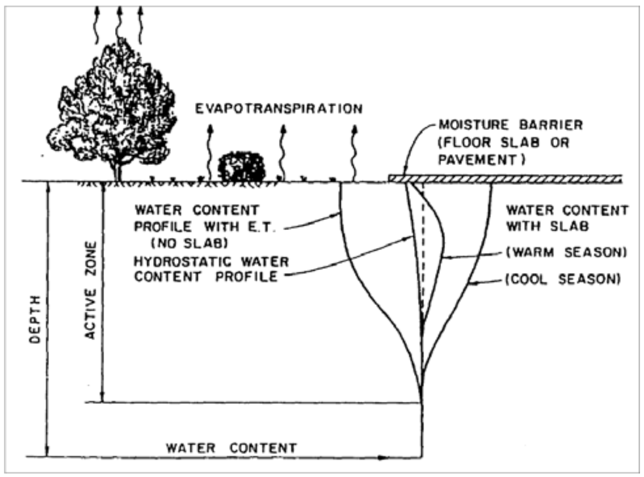
Example of Seasonal Shrink-Swell Cycle



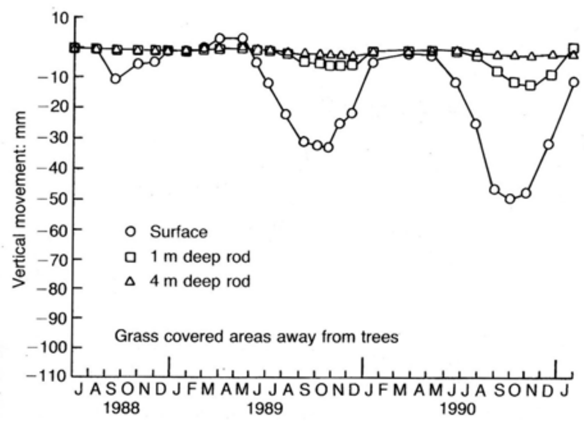
Active Zone

- The active zone is the portion of the soil that experiences seasonal changes in moisture content.
- Depth varies geographically. In Houston, typically 6 to 12 feet.
- The depth of the active zone is influenced by vegetation, water table, drainage and climate.

Active Zone



Active Zone



Effect of Climate

- Areas with predominately arid or wet climates do not generally see as much seasonal movement as areas with semi-arid climates.
- Soil in wet areas tend to stay wet.
- Soils in dry areas tend to stay dry.
- Soils in semi-arid areas are more likely to experience significant swings in moisture content.

Effect of Climate

- In wet areas, problems are most likely in periods of extreme drought.
- In arid areas, problems are most likely a result unusual periods of rainfall or irrigation (intentional or accidental).

Thornthwaite Moisture Index

- The Thornthwaite Moisture Index (TMI) is used by some design methods to predict the potential for soil moisture change and hence the magnitude of potential vertical movement.
- The TMI measures the soil moisture balance between evapotranspiration (usage) and precipitation (supply).

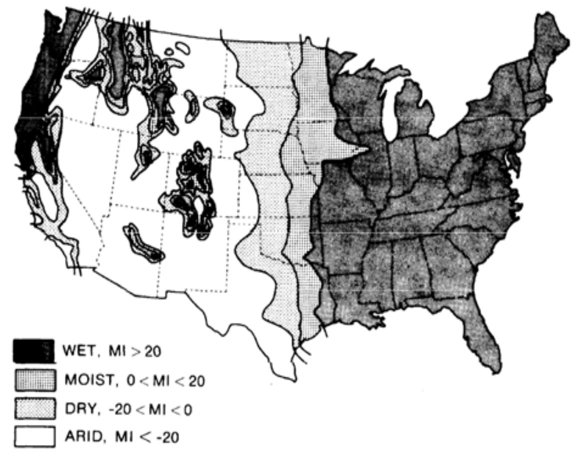
Thornthwaite Moisture Index

- Evapotranspiration is the total soil moisture lost from evaporation and vegetation.
- TMI = Rainfall – Evapotranspiration
- Reported TMI is based on <u>average</u> rainfall, <u>average</u> temperature and <u>average</u> vegetation.

Thornthwaite Moisture Index

- The TMI can be altered by vegetation, irrigation and climate.
- Excessive vegetation can decrease the TMI (increase transpiration).
- Irrigation can increase TMI (increase supply).
- Actual TMI value ranges widely from year to year.

Thornthwaite Moisture Index



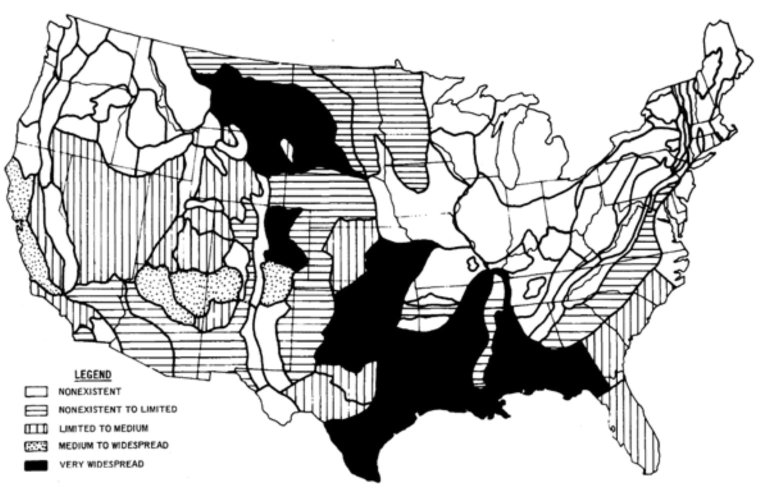


Figure 3. Estimated final adjusted frequency of occurrence rating of high volume change soils, by physiographic unit (from Witczak9)

Thornthwaite Moisture Index

Fig. A.3.2 Thornthwaite moisture index distribution in the United States (88)

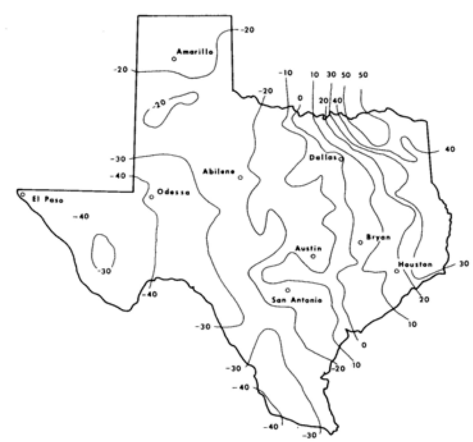


Fig. A.3.3.a. Thornthwaite Index for Texas (20 year average, 1955-1974) (108)

Effect of Vegetation

- Trees can remove large amounts of water from the soil (dessication), and can increase the depth to constant soil moisture.
- Effect of trees increases with age of tree and drought.
- Removal of existing trees can result in re-wetting and heave of soil.

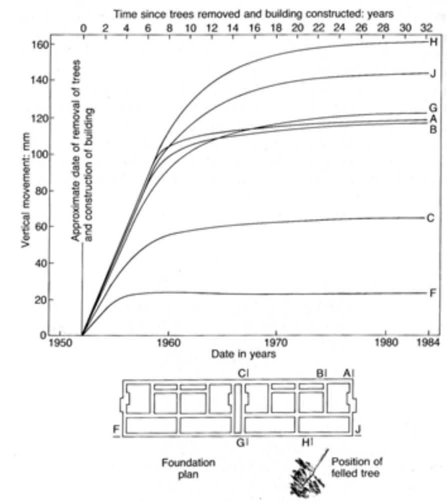
Effect of Vegetation

- Watering of flower and shrub beds can result in excessive soil moisture in these areas.
- Effect is worsened when beds are designed to hold large amounts of moisture.

Removal of Trees

- Soil near a tree will have a lower EMC relative to soil remote from the tree.
- If a tree is removed during site clearing, and a foundation is built on top of the area, heave of the foundation will occur as the soil returns to a higher EMC.
- This effect is exacerbated if construction occurs during a dry period.

Rebound After Tree Removal



Permeability

- Clay soils are extremely resistant to water movement. Typical permeability is 4.0E-7 in/sec (about 1 ft/year).
- Water will move faster through fissured soil. Exposure to water and subsequent swell tends to close fissures.
- Sand and silt seams can also increase effective permeability.

Soil Suction

- Suction testing measures the free energy content of soil water (pore pressure of the soil).
- Suction is an exact measure of the soils affinity for water (state of swell).
- Suction is reported as the Log_{10} of the pressure head (cm).

Suction (pF)	Water Ht (ft)	Description
0	0.003	Pure water
1	0.3	Soil at Liquid Limit
2	3.3	Soil at wettest natural state
2.5	10.4	
3	32.8	
3.5	103	Soil at plastic limit
4	328	
4.5	1,037	Soil at driest natural state (wilting of plants)
7.0	328,000	Oven dried soil

Applications of Soil Suction

- Prediction of potential vertical heave.
- Indication of state of swell.
- Estimation of depth of active zone (depth of constant suction).

Swell Test

- Oedometer (Consolidometer) test.
- Sample is saturated with water at start of test.
- Free Swell - Measures the amount of swell that will occur without surcharge.
- Swell Pressure – Measures surcharge required to prevent swell.
- Swell Index – UBC Free Swell test run at specified moisture content.

Oedometer (Consolidometer)

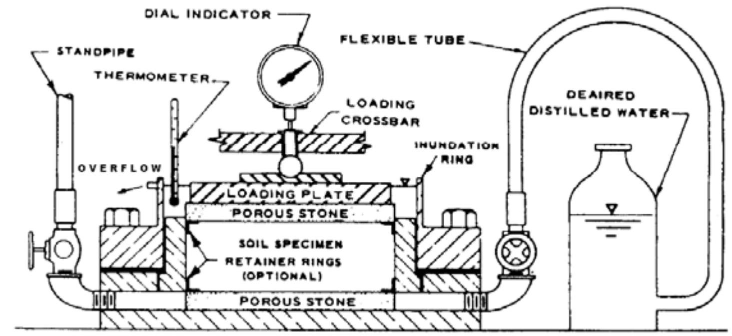
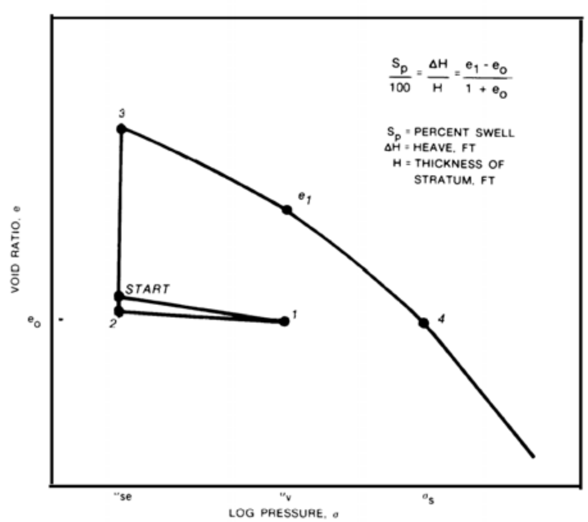


Figure 1. Typical consolidometer



Typical Swell Test

Swell Test

- Swell tests are normally run at the in-situ moisture content.
- MC at time of construction may vary from MC at time of soil recovery.
- Most severe test results will be obtained if soil sample is recovered at the end of the dry season.

Swelling Pressure

- Swelling pressure from expansive clays can exceed 30,000 psf (F.H. Chen, 2000).
- More typical values of swell pressure are 2000 to 4000 psf.
- Swell pressure is important if the structure is to be designed to resist uplift due to heave.

Movement Prediction

- Predicting movement is important to:
  - Investigating suitability of site for development.
  - Selecting the appropriate foundation system.
  - Investigating the effect of select fill.
- Potential heave is commonly referred to as Potential Vertical Rise (PVR)

Movement Prediction

- Three general methods exist for predicting movement:
  - Empirical
  - Semi-empirical
  - Analytical
- Most established techniques are only used to predict potential vertical heave (PVR), and potential vertical settlement (PVS) is not predicted.

Predicting Movement

- Most methods assume some change in soil moisture content, generally from the in-situ MC to an assumed final MC (such as saturation).
- If the actual MC at the time construction starts differs from the assumed MC, the actual PVR may be greater than predicted.

Empirical Methods

Heave prediction can be conducted in ways to imply various degrees of accuracy. Earlier methods predicted heave in terms of “low,” “medium,” “high,” and “very high.” Perhaps this should be retained because it does not imply accuracies that are impossible to achieve *(Nelson & Miller)*.

Empirical Methods US Army Corp of Engineers

Table 4-1. WES Classification of Potential Swell

Classification of potential swell	Potential swell S_p percent	Liquid limit LL percent	Plasticity index PI percent	Natural soil suction τ^{o}_{nat} tsf
Low	<0.5	<50	<25	<1.5
Marginal	0.5-1.5	50-60	25-35	1.5-4.0
High	>1.5	>60	>35	>4.0

Empirical Methods US Bureau of Reclamation

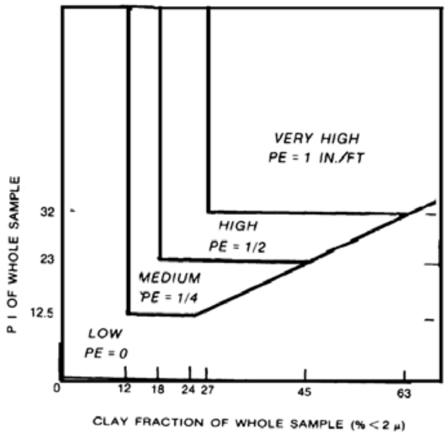
Data from index tests [1]			Probable expansion [2], percent total volume change, dry to saturated condition	Degree of expansion
Colloid content, percent minus 0.001 mm	Plasticity index, PI, %	Shrinkage limit, SL, %		
>28	>35	<11	>30	Very high
20 to 31	25 to 41	7 to 12	20 to 30	High
13 to 23	15 to 28	10 to 16	10 to 20	Medium
<15	<18	>15	<10	Low

[1] All three index tests should be considered in estimating expansive properties.
[2] Based on a vertical loading of 7 kPa (1.0 lbf/in^2)

Semi-Empirical Methods TxDOT TEX-124-E

- Based on swell test of compacted soils in Texas.
- Inputs are surcharge, LL, PI, initial moisture content and depth of active zone.
- Can easily be used to predict the effects of select fill.
- Precision and bias is unknown.

Semi-Empirical Van Der Merwe Method



Analytical Methods

- Oedometer/Consolidometer Test. Heave prediction based on stress state and changes in void ratio observed during swell and consolidation testing.
- Suction Test.
- CLOD Test.

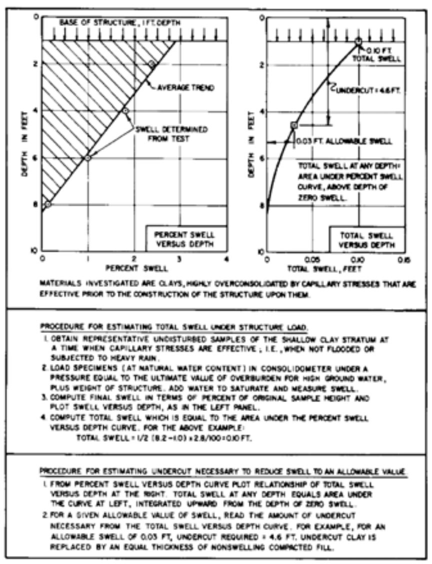


FIGURE 22
Computation of Swell of Desiccated Clays

Analytical Method - Direct Swell

Analytical Method Effective Stress State

$$\frac{\Delta H}{H} = \frac{c_s}{1 + e_o} \log \frac{\sigma_s}{\sigma'_v} \qquad (5\text{-}8)$$

where

- H = thickness of expansive soil layer, feet
- c_s = swell index, slope of the curve between points 3 and 4, figure 4-2
- σ_s = swell pressure, tons per square foot
- σ'_v = final vertical effective pressure, tons per square foot

The final effective pressure is given by

$$\sigma'_v = \sigma_v - u_w \qquad (5\text{-}9)$$

Potential Differential Heave

- Potential differential heave can vary from zero to as much as the PVR.
- Differential heave can approach the total heave for most practical cases.
- Assume potential differential heave is equal to PVR.

Potential Differential Heave PTI Method

- Most significant input to PTI design method for slabs-on-grade is Ym, the maximum differential soil movement.
- Ym was originally determined using VOLFLO program developed by Dr. Lytton using moisture diffusion theory.
- PTI recently released a refined method for calculating Ym.

State of Swell

- State of swell (SoS) refers to the current of volume relative to its fully swelled (saturated) or fully shrunken (dessicated) condition.
- Important for design and failure investigations
- SoS is generally indicated by the Suction or MC relative to the PL and LL, not to the absolute MC.

State of Swell

- The shrinkage limit can be reasonably approximated as the plastic limit (PL).
- Maximum swell occurs at some point between the plastic limit and liquid limit. This can be quantified by the Liquidity Index (LI):

$$\mathrm{LI} = \frac{w_n - \mathrm{PL}}{\mathrm{PI}}$$

State of Swell

- Maximum swell is generally considered to occurs at a LI between 20-40%.
- The LI index is an empirical indicator of SoS, so data must be evaluated for patterns rather than absolute values.

The Geotechnical Report

Skepticism is the chastity of the intellect, and it is shameful to surrender it too soon or to the first comer (George Santayana).

The Geotechnical Engineer

- Do not assume liability for the geotechnical portion of the work
- The geotechnical engineer should be an active participant in the foundation design process from start to finish.
- The involvement of the geotechnical engineer is critical for informed consent on the part of the owner.

Geotechnical Report Normal Contents

- Recommended foundation type.
- Allowable bearing pressure (piers and footings).
- Potential vertical rise (PVR).
- Depth to constant moisture (depth of active zone).

Geotechnical Report Normal Contents

- Recommendations for select fill (depth and properties).
- WRI/BRAB/PTI design parameters.
- Drainage recommendations.

What's Missing from the Geotechnical Report?

We are drowning in information and starved for knowledge (Unknown).

All Geotechnical Reports are not Created Equal

- The quality and contents of geotechnical reports varies widely.
- The structural engineer must be prepared to require the geotechnical engineer to supplement needed data that is not provided in the geotechnical report.

Commonly Missing Items

- Uplift skin friction on piers from swell.
- Down-drag force on piers due to soil settlement.
- Expansion index (IBC).
- Expected swell pressure (IBC).
- Presence of trees and effect of tree removal.
- Effect of ambient climatic conditions at time of investigation and construction.

Commonly Missing Items

- Accuracy of PVR (bounding values).
- Potential vertical settlement (PVS).
- State of swell.
- Discussion of performance expectations of various foundation options.
- Use of void boxes.
- Bathtub effect for fill.

Commonly Missing Items

- Fill as replacement vs. fill as a surcharge.
- Assumptions made in calculating design values (e.g. effect of local conditions).
- Modulus of subgrade reaction (not needed for consideration of expansive clay, but frequently MIA).

Coordination Geotechnical vs. Structural

- Who is responsible for verifying impact of pre-boring site conditions?
- Who is responsible for selection of the foundation system?
- Who is responsible for suitability of foundation for site?

Coordination Geotechnical vs. Structural

- Who is responsible for changes in site between time of borings and time of construction?
- Who is responsible for ensuring that foundation design complies with intent of geotechnical engineer?
- Who is responsible for specifying construction material testing schedule?

Coordination
Geotechnical vs. Structural

- Who is responsible for fill specifications?