THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH

5-6048-03-P2

MATERIALS FOR PVR SHORT COURSE AND TRAINING

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TxDOT Project 5-6048-03: Implementation of Centrifuge Technology for Pavement Design on Expansive Clays

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Performed in cooperation with the Texas Department of Transportation and the Federal Highway Administration.	

Guide to the Materials Prepared for the PVE Short Course and Training

The materials for the Project 5-6048-03 short course and training include a presentation that goes over the basics of the Potential Vertical Rise (PVR) method (**Appendix A**). The presentation is based on the work compiled over the course of 5-6048-03. Notes are included in the presentation for the instructors based on the recommendations from the research team, providing guidance on the aspects that should be emphasized.

Appendix B includes a guidance manual outlining the typical steps for calculation of the PVR.

Finally, **Appendix C** includes the main changes to current standard, Tex-124-E, outlining the revised steps used to calculate PVR as well as notes on recommendations by the research team.

Appendix A: TxDOT Training Materials (PowerPoint Presentation)

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Training Material: PVR Methodology

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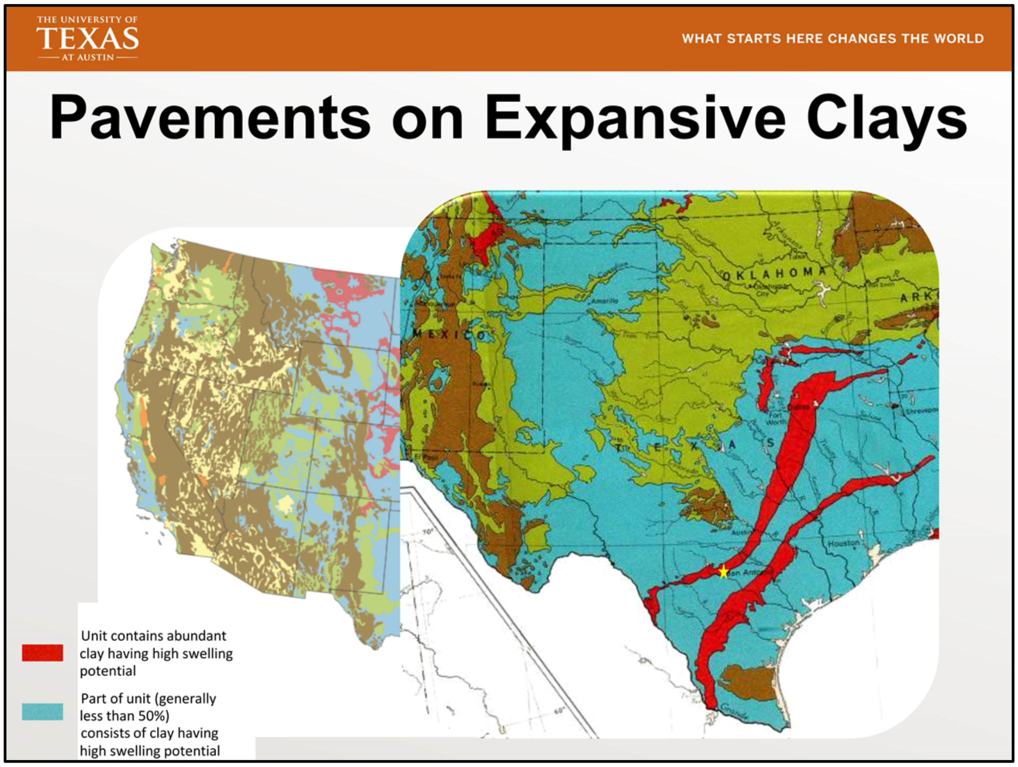
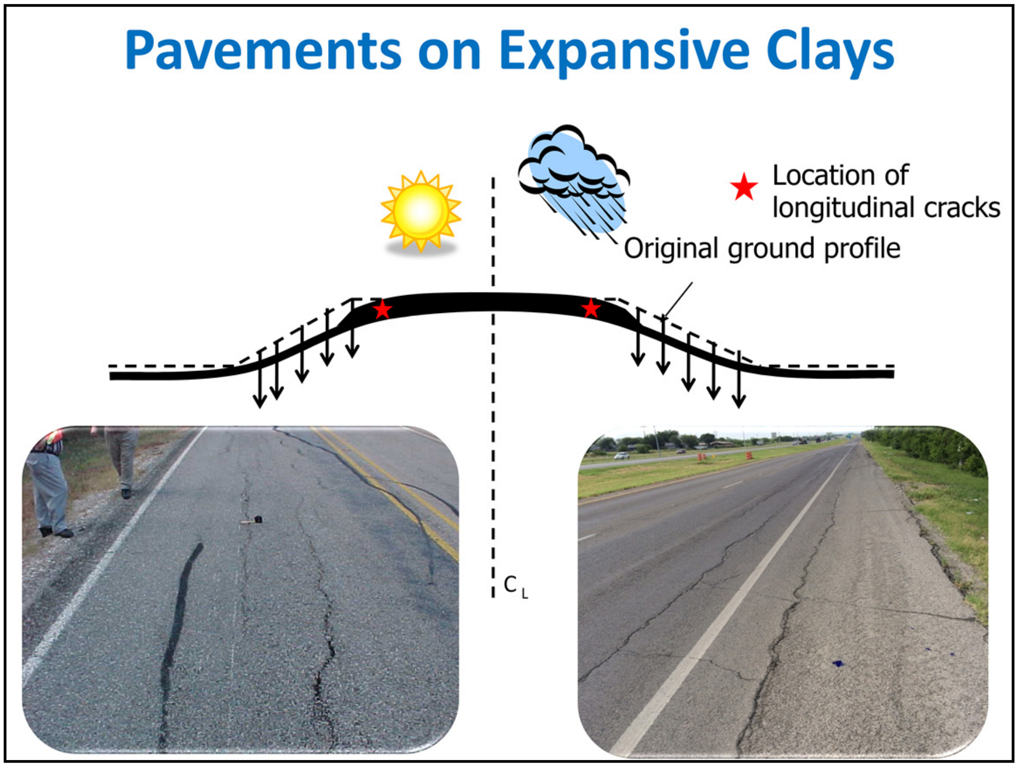
Texas Department of Transportation

The Swelling Clay Problem



Swelling clays are a problem that are an issue throughout the country, but unfortunately for Texas, the I-35 corridor from Dallas to San Antonio is built upon clays that have a very high swelling potential.



The longitudinal cracks typically happen during the drying season as the ground settles. Since the shoulders see less cover, thus more moisture fluctuations, the soil will settle in these areas creating the cracking events.

Expansive Soils Visualization

A visualization of how the expansive soils will heave under low vertical pressure structures. Note that the entire sublayer does not need to be an expansive clay in order to see significant amount of swelling.

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Existing Methodologies to Quantify Expansive Soils

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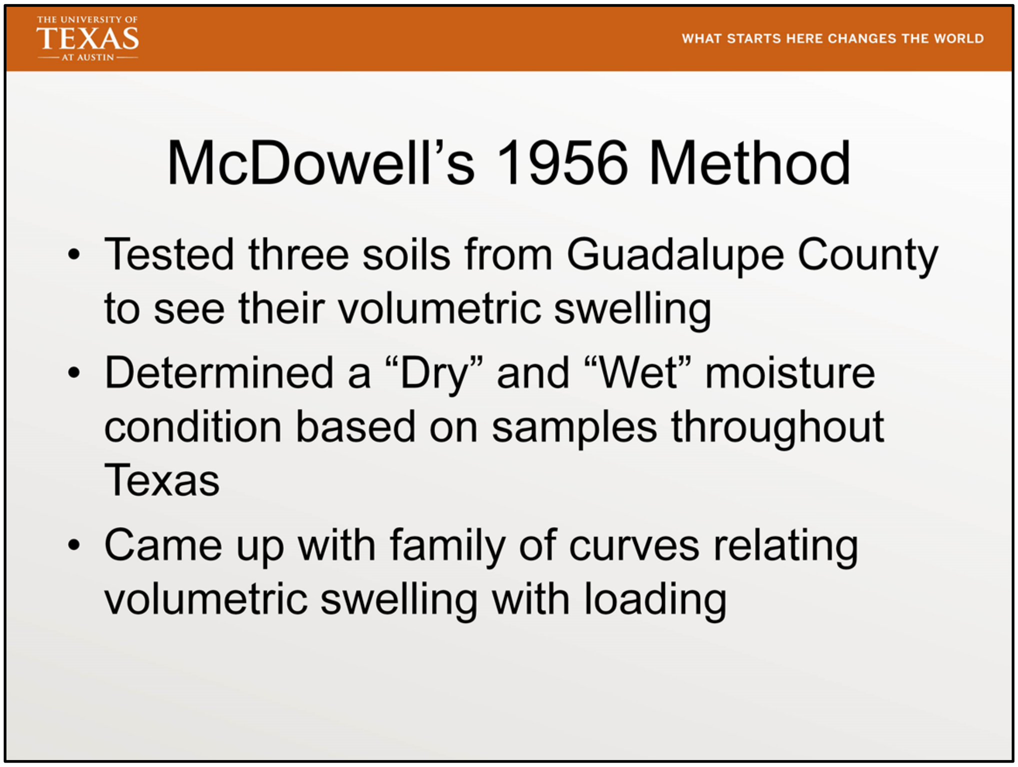
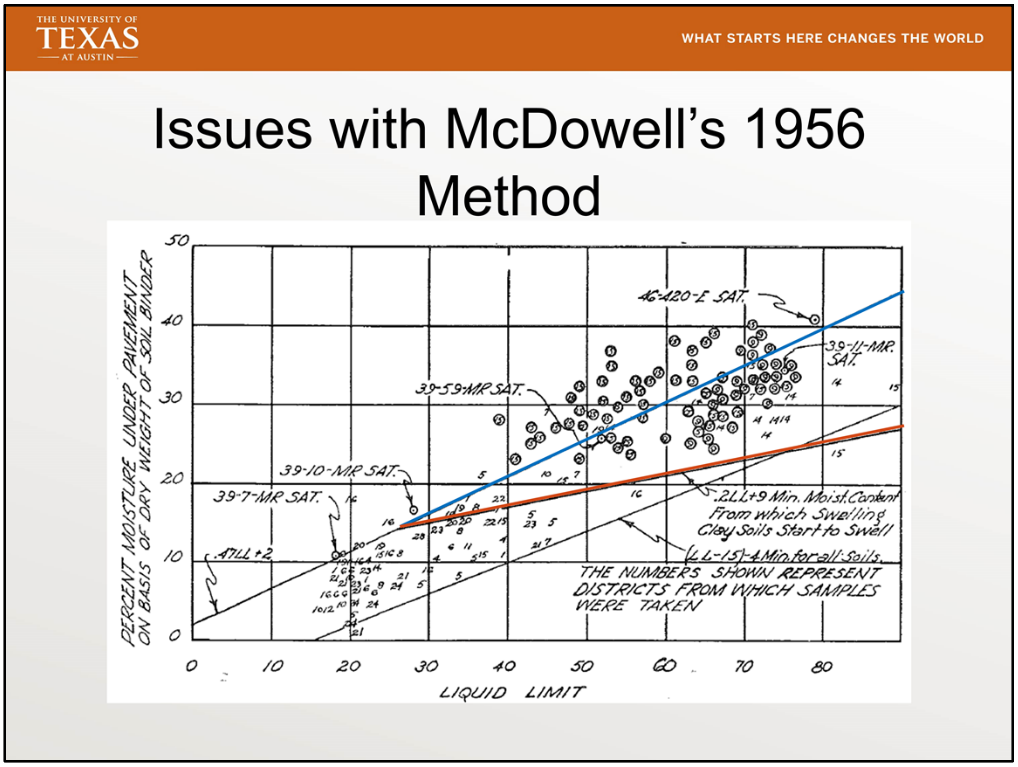
Existing Methodologies

- Predictive Relationships
  - Typically done to Liquid Limit (LL) or Plasticity Index (PI)
  - McDowell's (1956) method to calculated Potential Vertical Rise (PVR)
    - Basis for current TxDOT Method of Tex-124-E
- Direct Measurements of Soil
  - Conventional Swell Testing
    - ASTM D4546
    - Either Reconstituted or Undisturbed Specimens
  - Tri-axial Swelling Test
    - More on a research basis

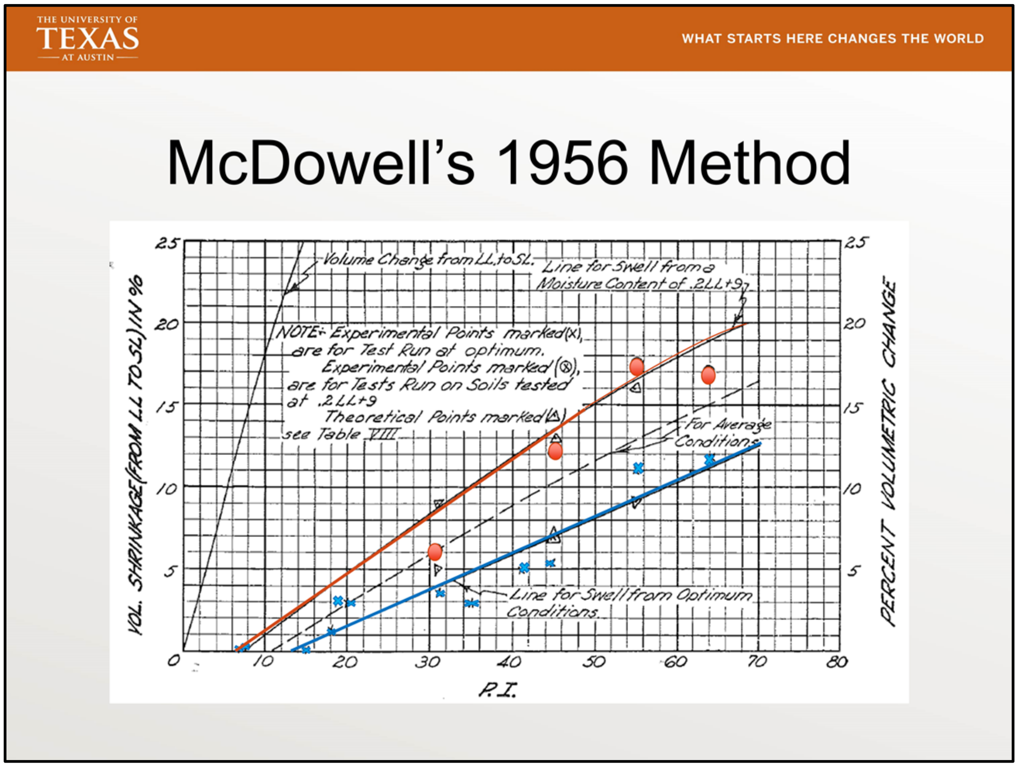
A few existing methodologies to measure the expansivity of the soil. Predictive methods involve taking index properties of the soil, namely the Atterberg Limits, to correlate how expansive a soil will be. You can also take direct measurements of the volumetric changes within the soil from conventional ASTM D4546 testing, to be followed upon, or if you are only interested in the vertical swelling, tri-axial swelling test. Note that the last method is based mainly in research as the experiment is costly and not practical to be used in industry. Therefore, most methods involve reducing the volumetric swelling by a third or a half to get an approximated vertical swelling. Also note that shrinkage test are typically not done, despite the fact this method is how cracking typically occurs, due to issues quantifying the cracks that will occur within the specimen that can not be measured unless by extremely expensive methods. Therefore, expansive soils are typically quantified by their ability to swell and not shrink.



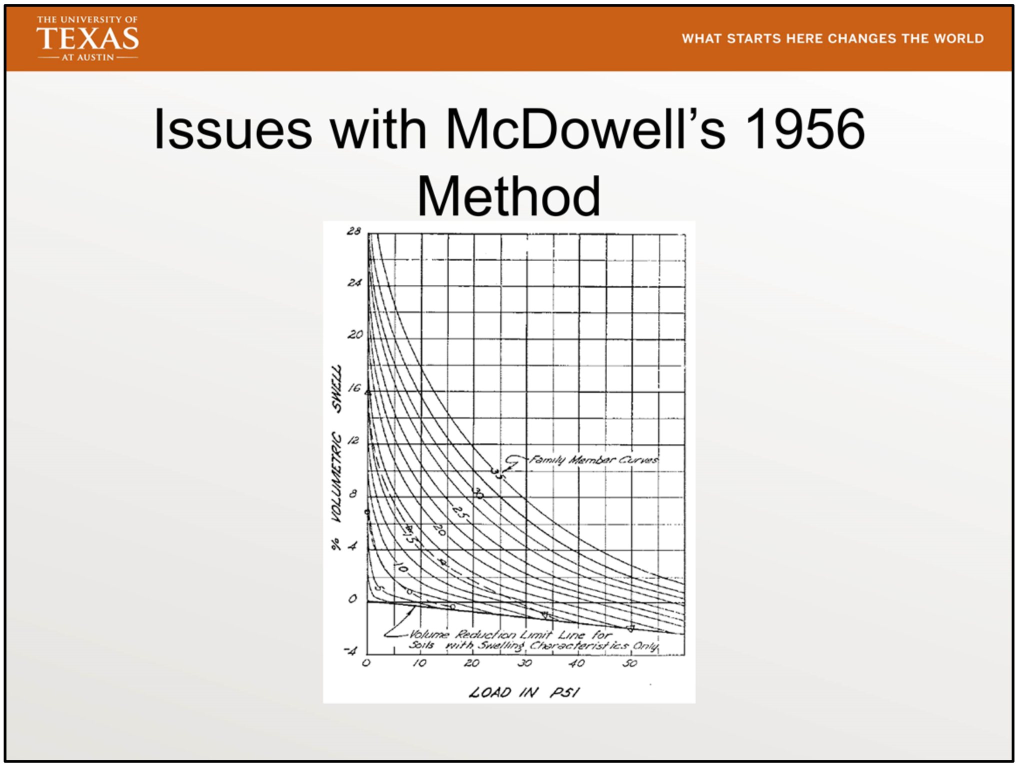
McDowell’s method is typically the one most used in TxDOT as it forms the basis for the Potential Vertical Rise method. The original method was based on using capillary swelling test on samples taken from Guadalupe County to see their volumetric swelling and then correlating that to the potential vertical rise based on three moisture conditions, “Dry,” “Average,” and “Wet.” A series of curves were determined theoretically from previous test and extrapolated. The graphs that form the method are shown below which the issues for each outlined.



The curves to create the "Wet" (Blue Line) and "Dry" moisture conditions are shown based on the liquid limit. These limits were built based upon moisture contents taken underneath roadways. Note that there is a very appreciable amount of scatter for the wet condition, and the dry condition's statement that it is the condition at which expansive soils begin to swell are very questionable.



McDowell then tested the three soils at their “Wet” (Blue x’s) and “Dry” (Red circles) conditions and plotted their volumetric change versus their PI. Note the questionable fit of the lines (Blue-wet, Red-dry) as well as the relative lack of data for the dry condition which is the dominant condition in terms of the PVR.



Finally, to relate the load in PSI to the percent volumetric swell, family curves were used based on the P.I. Note that there is very, very little data used for plotting and interpolation becomes a significant issue as no function was given.

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McDowell's 1956 Method

- Summary of Issues
  - Only three separate soils used for correlation between LL and % Volumetric Swelling
  - Does not directly measure the soil
    - McDowell originally recommended running a test on specimen using a similar method to conventional approach
  - Relationship between loading and volumetric swell is based on very limited testing

Summary of what was stated before. Note that McDowell highly recommended testing samples from the field in his original paper.

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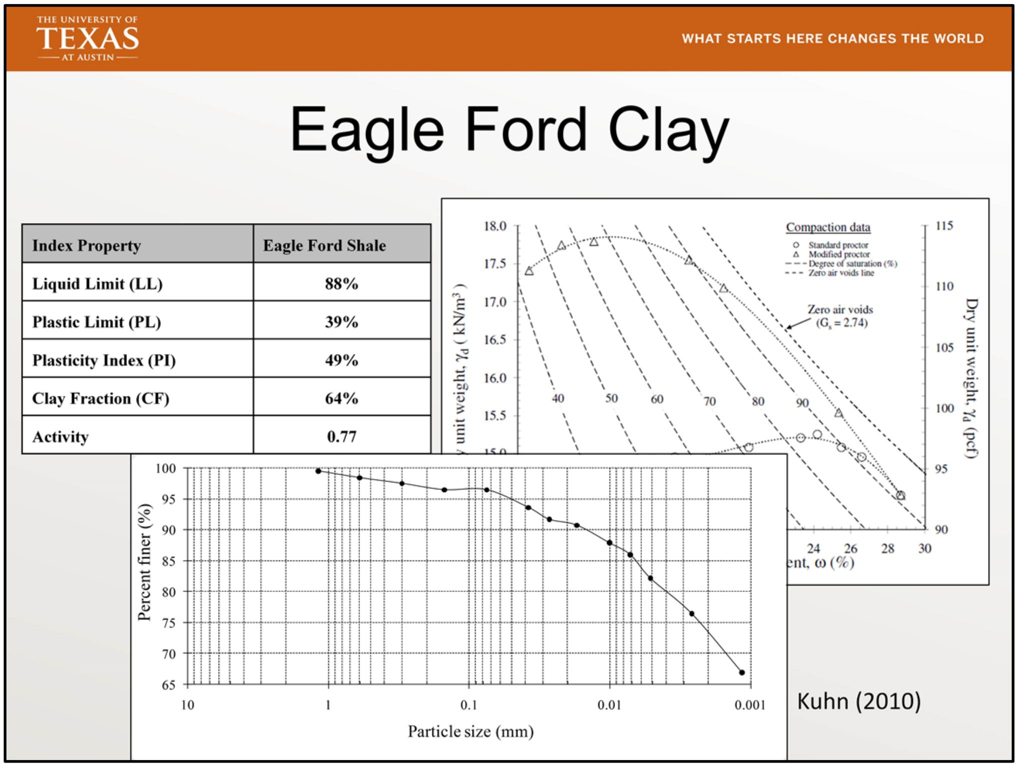
Conventional Swell Testing

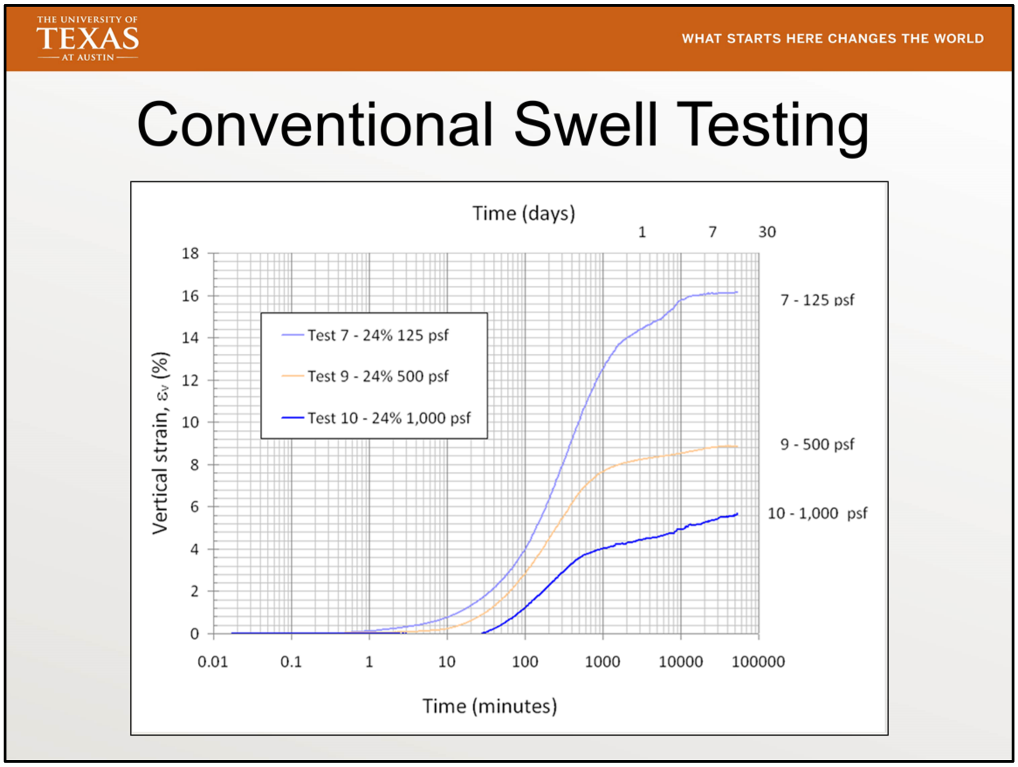
- ASTM D4546
- Performed in consolidation frames
- Samples can either be reconstituted in the cutting ring or undisturbed and trimmed
- Samples inundated with water and deflections measured over course of 48 – 72 hours
- Need to run test at multiple stresses to generate swell vs. effective stress curves

The testing that can be done currently involves the use of consolidation frames. The ASTM either has samples tested at their approximate in-situ effective stress or multiple samples run over a variety of effective stresses to determine the volumetric strain at each effective stress and the effective stress that corresponds to no volumetric strain, or the swelling pressure. These test typically take approximately 48-72 to see the changes in the stress but can last an extremely long time if one focuses on the maximum volumetric strain.

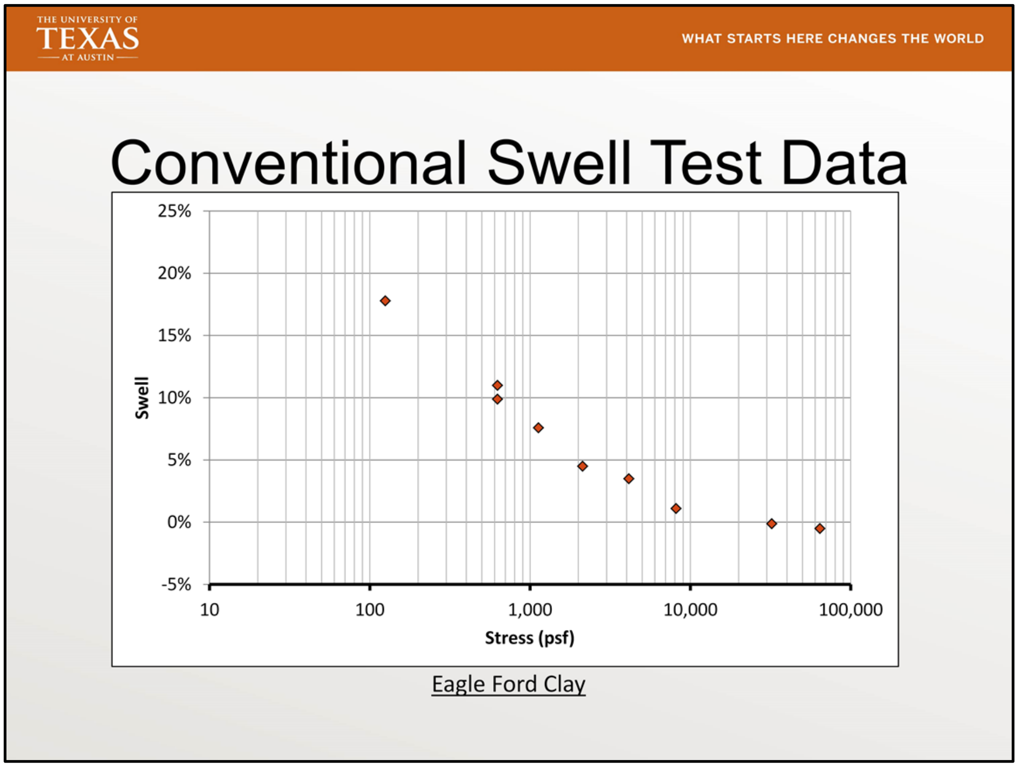


Index Property	Eagle Ford Shale
Liquid Limit (LL)	88%
Plastic Limit (PL)	39%
Plasticity Index (PI)	49%
Clay Fraction (CF)	64%
Activity	0.77

Basic soil characterization from a highly expansive soil taken from Hester's Crossing and I-35 in Round Rock, TX that will be used in following example.

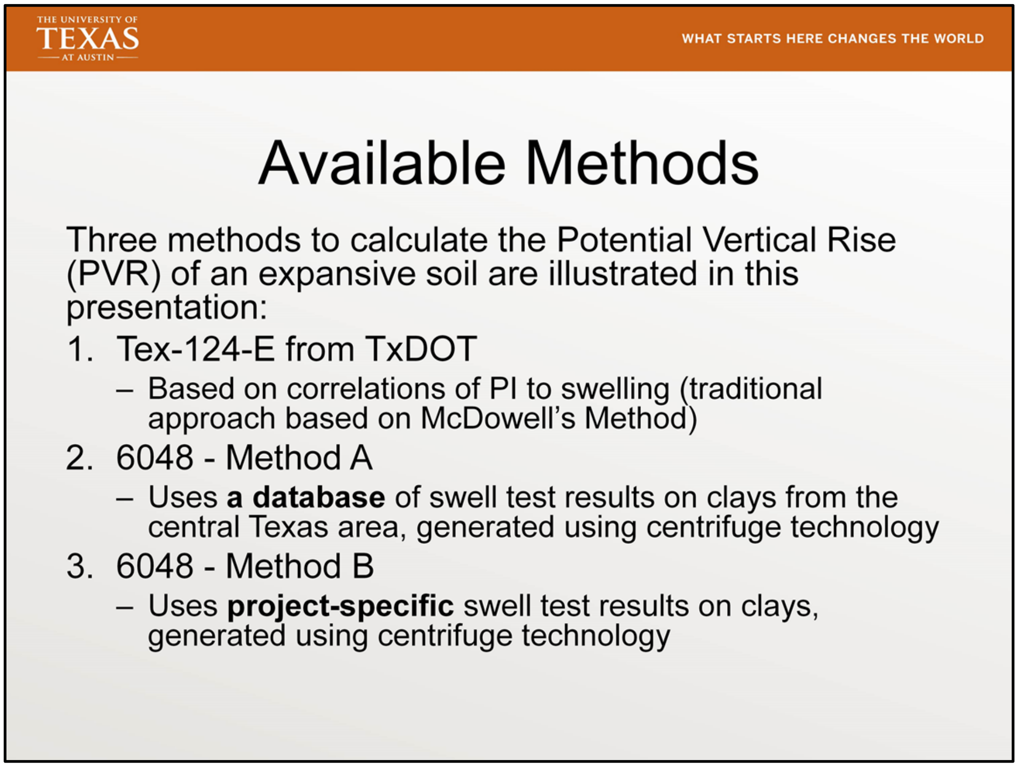


Testing takes a significant amount of time to read the end of swelling, but time to end of primary swelling isn't as significant. Still, the test can take upwards of 2 to 3 days to establish the end of primary swelling and see the secondary swelling taking place.



After multiple samples are run, a Swell vs. Effective Stress curve can be generate. Note that the swelling pressure for this soil is approximately 32,000 psf, a very significant amount that pavements won't be able to reach to prevent swelling.

Before we begin, note that the PVR is an indicator and not necessarily the exact potential vertical rise felt in the field. There are many, many components that go into expansion and shrinking of a soil from the initial moisture content and density to suction to fissures within the surface that designing for an expected rise should be based on a relative number in relation to others i.e. whether you are going to have an issue at this particular site or not.



Three methods can be used to calculate the PVR. The first method is predictive based on the Tex-124-E methodology. The second and third are based on using a centrifuge in lieu of traditional testing to accelerate the testing process. The first of these centrifuge methods involve taking reconstituted specimens from the major expansive soils in the Austin area, the Houston Black clay, the Branyon Clay, the Tan Taylor, the Behrig Clay, the Eagle Ford Clay, and the Cook Mountain clay, and testing them to generate a database of stress vs. swell curves. The second involves retrieving site-specific soils and testing them based on their in-situ effective stress at the in-situ moisture content and a moisture conditioned state to see a worse case scenario.

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Example Problem

Problem Statement:

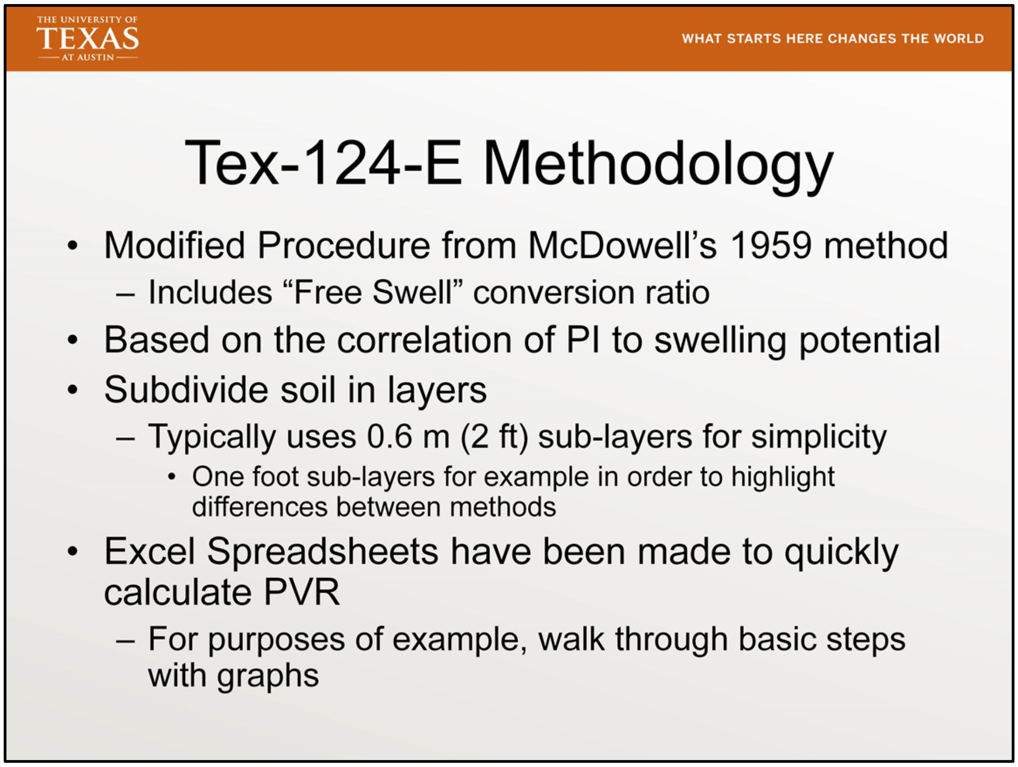
Consider a subgrade with a 2 ft stratum of Houston Black Clay underlain by an 6 ft stratum of Eagle Ford Shale

Soil / Property	Houston Black	Eagle Ford
ω (%)	21%	21-27%
γ (pcf)	105-110	110-120
LL (%)	62%	88%
PI (%)	35%	49%
%< No. 40	80%	93%

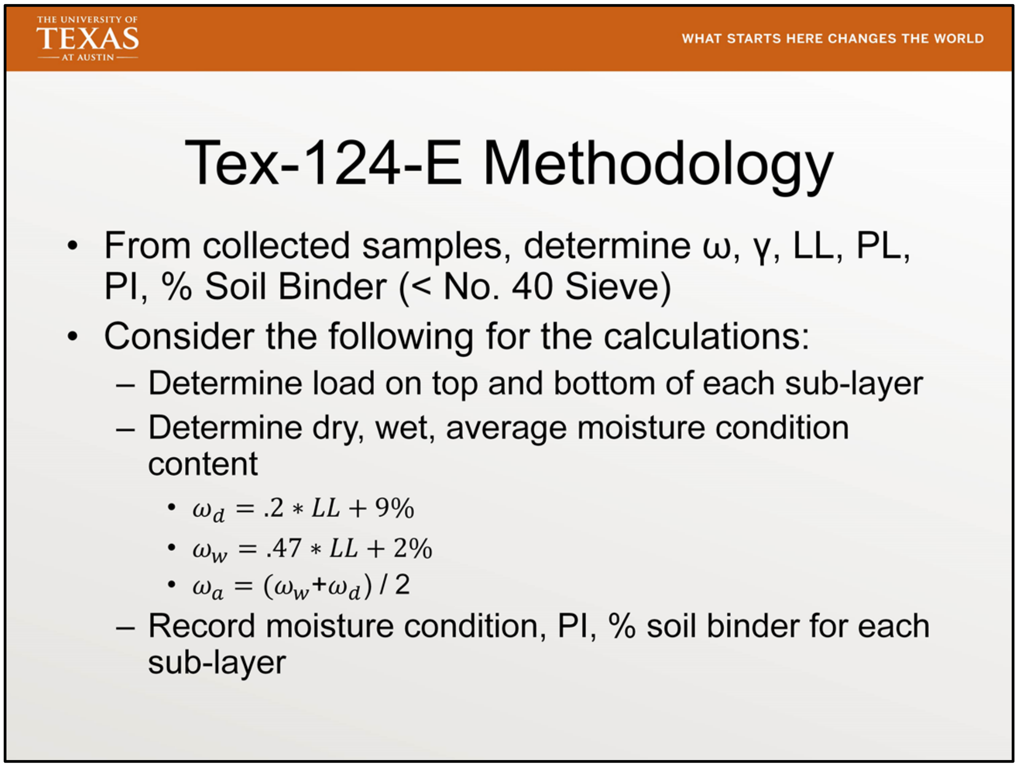
Objective:

Calculate PVR using the three proposed methods. For Method 6048(A) use the available database of swell test results on Eagle Ford Clay. For Method 6048(B) use project-specific data from three centrifuge tests conducted using on-site.

In order to see the difference in these methods, an example problem is to be followed. Note that the depth only goes down only around 8 ft, something that is important as the active zone, or the zone of moisture fluctuation, extends typically to only a depth of 10 ft in clays.



The Tex-124-E method is based on the McDowell method covered earlier. It relates the LL and PI of a soil to the PVR based on the previous graphs and two foot sub-layers are used for simplicity. A few TxDOT districts have developed their own Excel Spreadsheets for the calculations, though this presentation will be walking through it manually for a sub-layer to explaint eh steps.



The method is predicated on having the data for a certain location. If the data is unavailable, previous reports should be used to get an idea or sense of the data. The most important things for each of the locations is the determination of the geologic layering within the system, and the atterberg limits, moisture contents (typically a range of seasonal data would be best, but can be approximated), the unit weight of the sublayer, and the percent binder, i.e. the percent of the sublayer that passes the number 40 sieve. From there, you determine the moisture content condition, dry, wet, or average, based on a correlation to the liquid limit.

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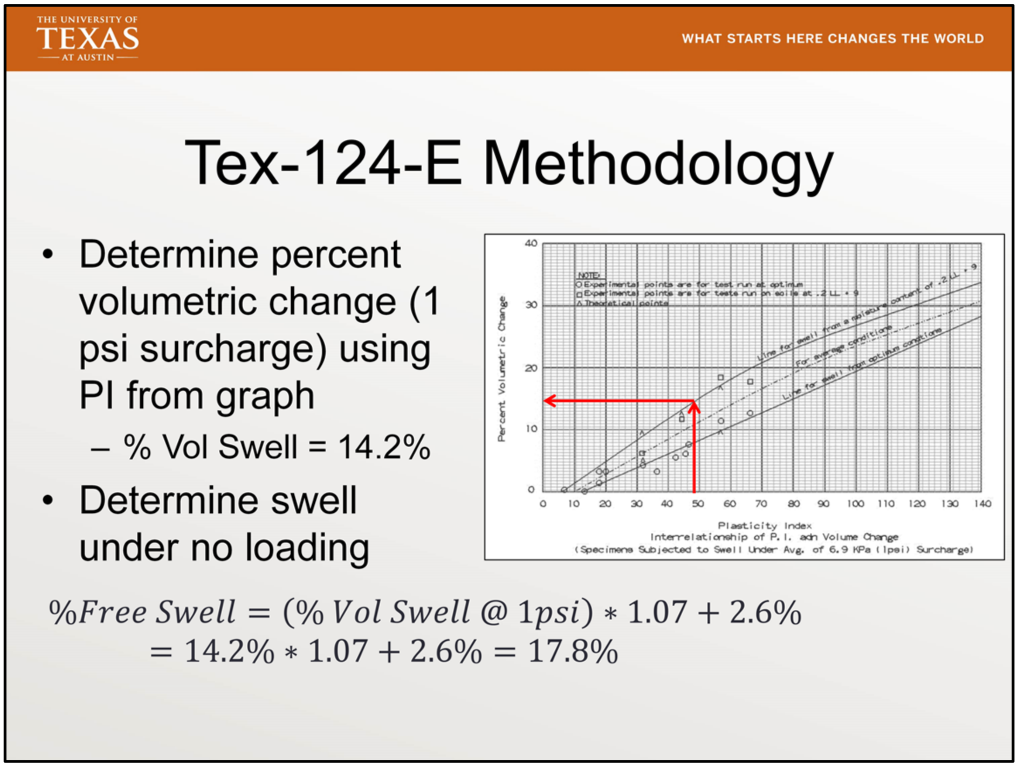
Introduction to Example

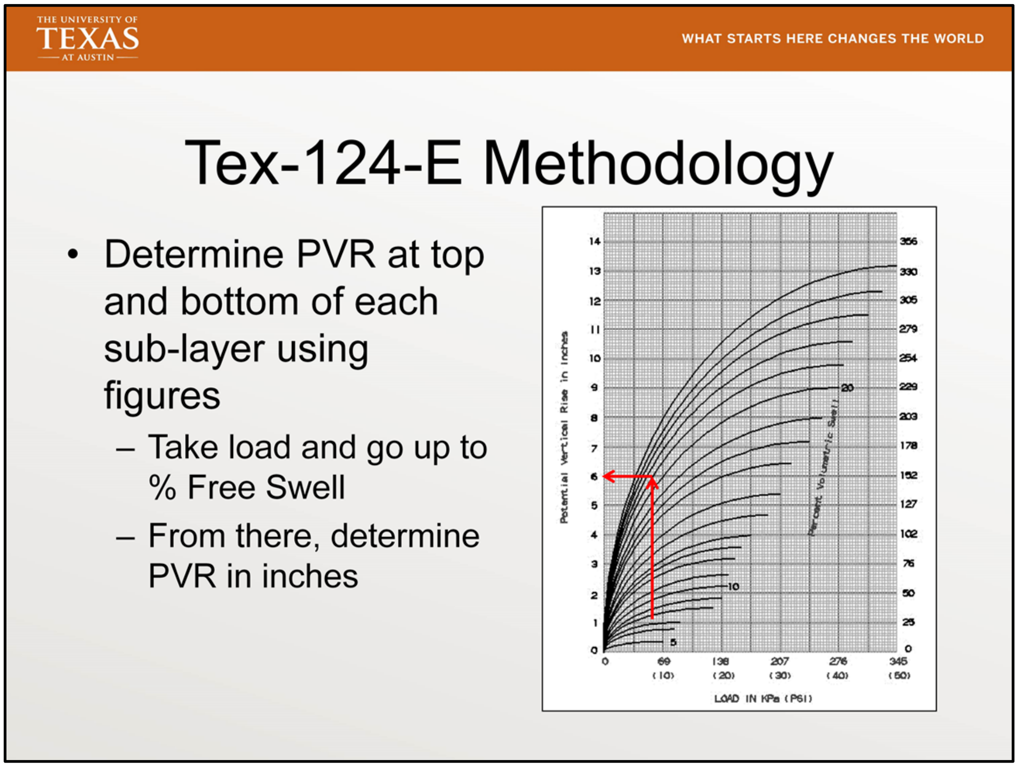
Information from the sub-layers considered in the calculation:

Depth to Bottom of Layer [ft]	Soil (USCS)	Average Load [psi]	Liquid Limit (LL)	Dry (0.2LL+9) (%)	Wet (0.47LL+2) (%)	Percent Moisture	Dry Avg Wet	Percent -No.40	Unit Weight (pcf)	Plasticity Index (PI)
1.0	HB (CH)	0.4	62	21.4	31.1	21.0	Dry	80.0	105	35
2.0	HB (CH)	0.7	62	21.4	31.1	21.0	Dry	80.0	110	35
3.0	EF (CH)	1.1	88	26.6	43.4	21.0	Dry	93.0	110	49
4.0	EF (CH)	1.5	88	26.6	43.4	21.0	Dry	93.0	110	49
5.0	EF (CH)	1.9	88	26.6	43.4	24.0	Dry	93.0	115	49
6.0	EF (CH)	2.3	88	26.6	43.4	24.0	Dry	93.0	115	49
7.0	EF (CH)	2.7	88	26.6	43.4	24.0	Dry	93.0	115	49
8.0	EF (CH)	3.1	88	26.6	43.4	27.0	Dry	93.0	120	49

Overview of data for the example. Note that the average load is taken at the center of each layer



Once the data for each sublayer is determined, one goes to the graph in Tex-124-E to relate the Plasticity Index to the Percent Volumetric Change. This Percent Volumetric Change is then converted to a "Free Swell" condition via an equation from Tex-124-E shown above.



After determining the % Free Swell, one goes to the load at the top and bottom in the sublayer in PSI and finds the PVR in inches at the top and bottom of each sublayer based on the % Free Swell at which the curves are spaced. If the load is past the extents of the curves, the PVR for the layer is taken to be 0.

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Tex-124-E Methodology

- Correction for Soil binder
  - Assumes that it is all passing No. 40
  - $C_{SB} = \frac{\%\ less\ than\ 25\ \mu m}{100\%} = \frac{80\%}{100\%} = .8$
- Correction for Total Unit Weight
  - Assumes a Total Unit Weight of 125 pcf
  - $C_{\gamma} = \frac{125\ pcf}{\gamma_a} = \frac{125\ pcf}{110\ pcf} = 1.14$
- Difference in PVR between top and bottom of sub-layer is the PVR of the sub-layer
- Multiply this by correction factors to get corrected PVR

The PVR determined from the previous slide needs to be corrected for the percent of the soil that is considered to be apart of the binder, i.e. the portion of the soil that passes the No. 40 sieve, and the correction for the total unit weight of the soil, taken to be 125 pcf generally. Note that this correction will be used frequently as the typical total unit weight of expansive clays lies between 90 to 115 pcf.

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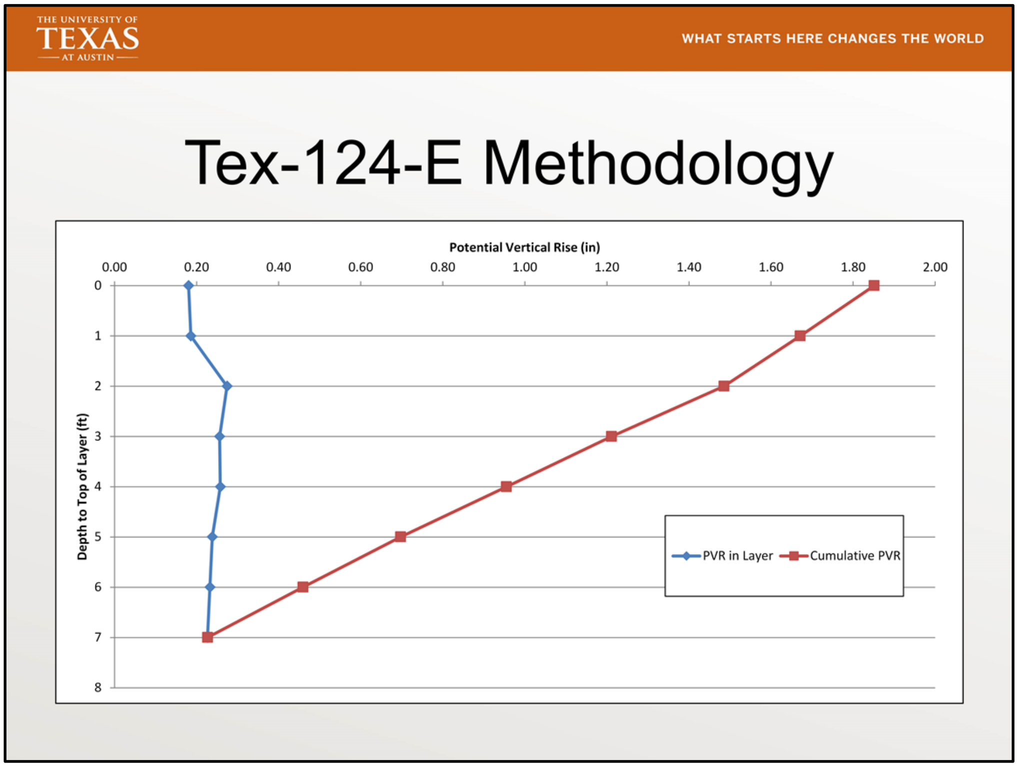
Tex-124-E Methodology

Tex-124-E Calculations based on TxDOT Excel Spreadsheet for each sub-layer:

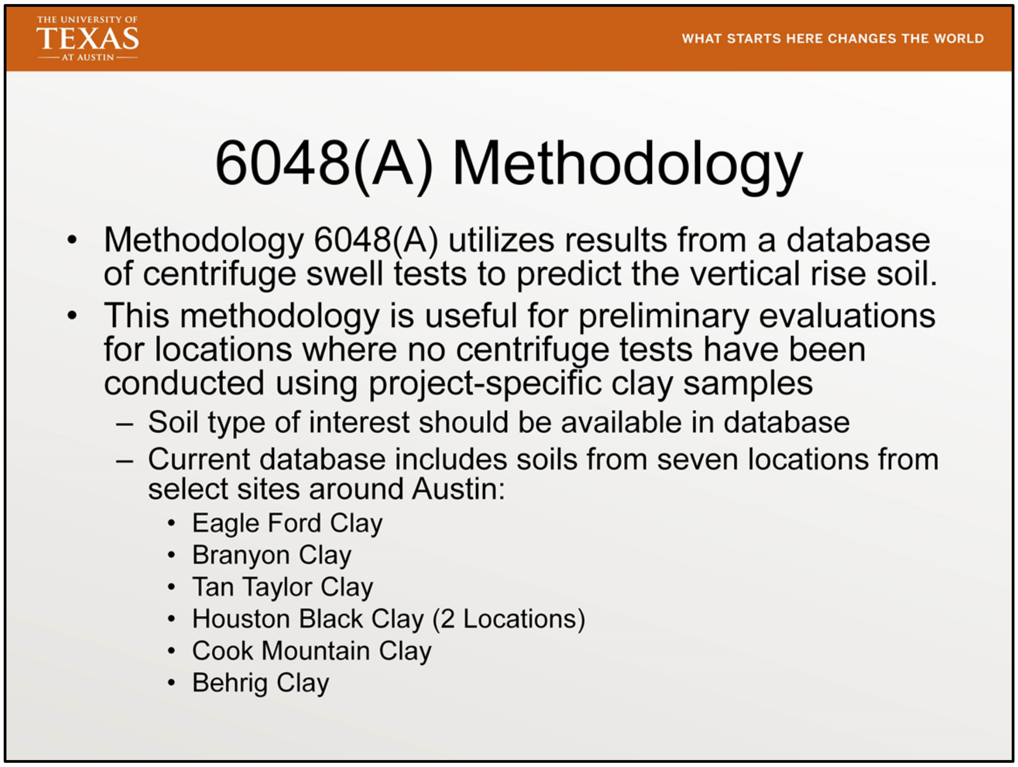
Depth to Bottom of Layer [ft]	Soil (USCS)	Percent Volume Swell	Percent Free Swell	PVR [in] Top of Layer	PVR [in] Bottom of Layer	Differential Swell [in]	Modified -No.40 Factor	Modified Density Factor	PVR in Layers [in]	Total PVR [in]
0.0		-	-	-	-	-	-	-	-	1.85
1.0	HB (CH)	9.6	12.9	0.00	0.19	0.19	0.80	1.19	0.18	1.67
2.0	HB (CH)	9.6	12.9	0.19	0.39	0.20	0.80	1.14	0.19	1.49
3.0	EF (CH)	14.2	17.8	0.53	0.79	0.26	0.93	1.14	0.27	1.21
4.0	EF (CH)	14.2	17.8	0.79	1.03	0.24	0.93	1.14	0.26	0.95
5.0	EF (CH)	14.2	17.8	1.03	1.29	0.26	0.93	1.09	0.26	0.70
6.0	EF (CH)	14.2	17.8	1.29	1.52	0.24	0.93	1.09	0.24	0.46
7.0	EF (CH)	14.2	17.8	1.52	1.75	0.23	0.93	1.09	0.23	0.23
8.0	EF (CH)	14.2	17.8	1.75	1.99	0.23	0.93	1.04	0.23	0.00

Calculated PVR using Tex-124-E Methodology: **1.85 inches**

When combining all of the previous steps together for all the sub-layers, get a PVR of 1.85 inches.



A look at the cumulative PVR and the PVR in each sublayer. Note that there is a decreasing amount of PVR as the depth increases.



The reconstituted centrifuge approach, based on a database of values, is shown here. The methodology gives insight into how a site could possibly perform if undisturbed samples are unavailable or for preliminary analysis of locations. The soils currently in the database are shown here.

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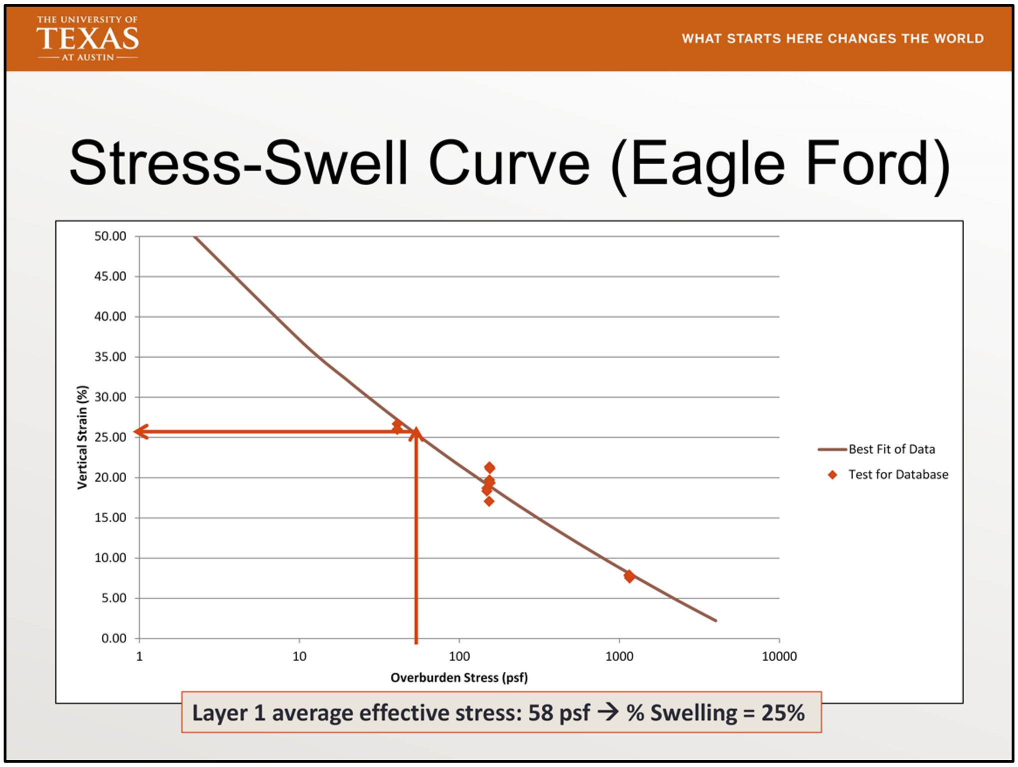
6048(A) Methodology

Procedure:

1. Information should be obtained (e.g. available boring logs) or inferred on water content, void ratio, and soil type with depth.
    - Can also get index properties, grain size distributions, etc.
2. Divide soil profile into sub-layers, two foot layers are typical.
3. Determine the effective stress at the top and bottom of each layer
4. From the matching curve in the database, obtain the average percent vertical strain for the range of stresses in each layer. The average percent vertical strain (% Swelling) may be taken:
    - as the % Swelling corresponding to the effective stress at the center of the layer (less accurate)
    - as the % Swelling corresponding to the log-average of the effective stress at the top and bottom of the layer
    - by calculating the average of the Swell-Stress curve across the range of stresses in the layer (most accurate, requires integration)

Note that the preferred method would be integration, but taking the log-linear average stress for each sublayer will give suitable results.



By going to the stress vs swell curve, in this case for the Eagle Ford clay, you can determine the vertical strain, or swelling, at a given average pressure.

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6048(A) Methodology

5. Multiply swell by layer thickness to determine the PVR of a layer
6. Sum of PVR of each layer is the PVR of the soil

- Note that no correction for the % soil binder or total unit weight is needed

This swelling in turn can be multiplied by the thickness of the layer to determine the PVR of the layer. Note that there isn't a correction needed for the percent soil binder or total unit weight with this method as you are testing the actual soil itself.

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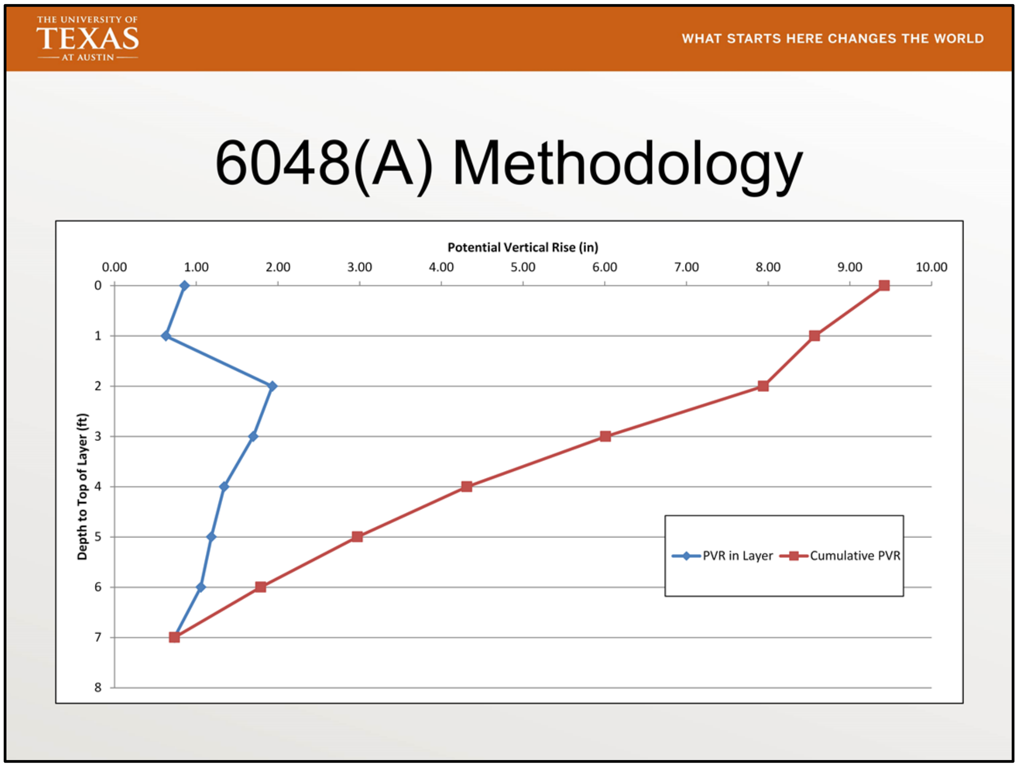
6048(A) Methodology

6048(A) Calculations for each sub-layer:

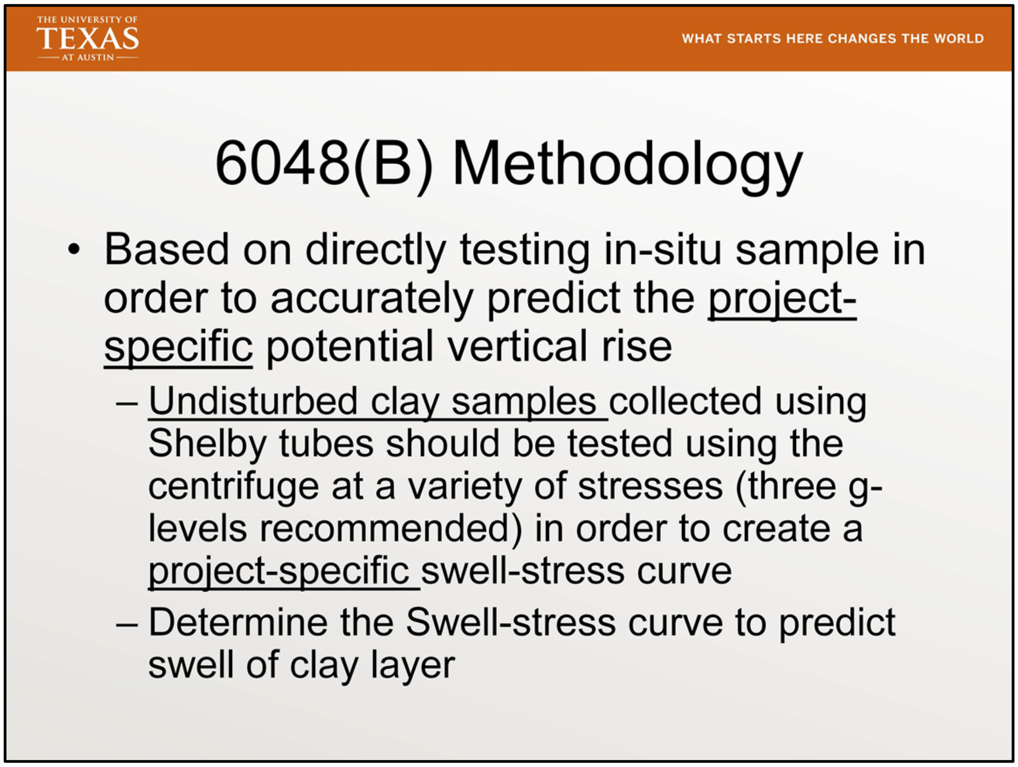
Depth to Top (ft)	Thickness (ft)	Soil	w%	Unit Weight (pcf)	Top Stress (psf)	Bot. Stress (psf)	Average Effective Stress (psf)	Swell (%)	Vertical Rise (in)	Cumulative PVR (in)
0	1	HB	21	105	0	105	10	7.14%	0.86	**9.42**
1	1	HB	21	110	105	215	150	5.22%	0.63	8.57
2	1	EF	21	110	215	325	264	16.09%	1.93	7.94
3	1	EF	21	110	325	435	376	14.14%	1.70	6.01
4	1	EF	24	115	435	550	489	11.17%	1.34	4.31
5	1	EF	24	115	550	665	605	9.87%	1.18	2.97
6	1	EF	24	115	665	780	720	8.80%	1.06	1.79
7	1	EF	27	120	780	900	838	6.11%	0.73	0.73

Calculated PVR using proposed 6048(A) Methodology: **9.42 inches**

Going back to the example and calculating the average effective stress in a log-linear space, then the swelling from the swell-stress curves, the PVR can be determined.



This examines the change in the PVR in each of the layers, namely showing that the cumulative PVR shows two distinct sublayers in respect to the TxDOT method.



The second centrifuge methedology involves taking undisturbed specimens and testing them to create a project-specific swell-stress curve. Note that the samples can be tested at their in-situ condition or a drier condition at which the sample may reach in the field to generate these swell-stress curves.

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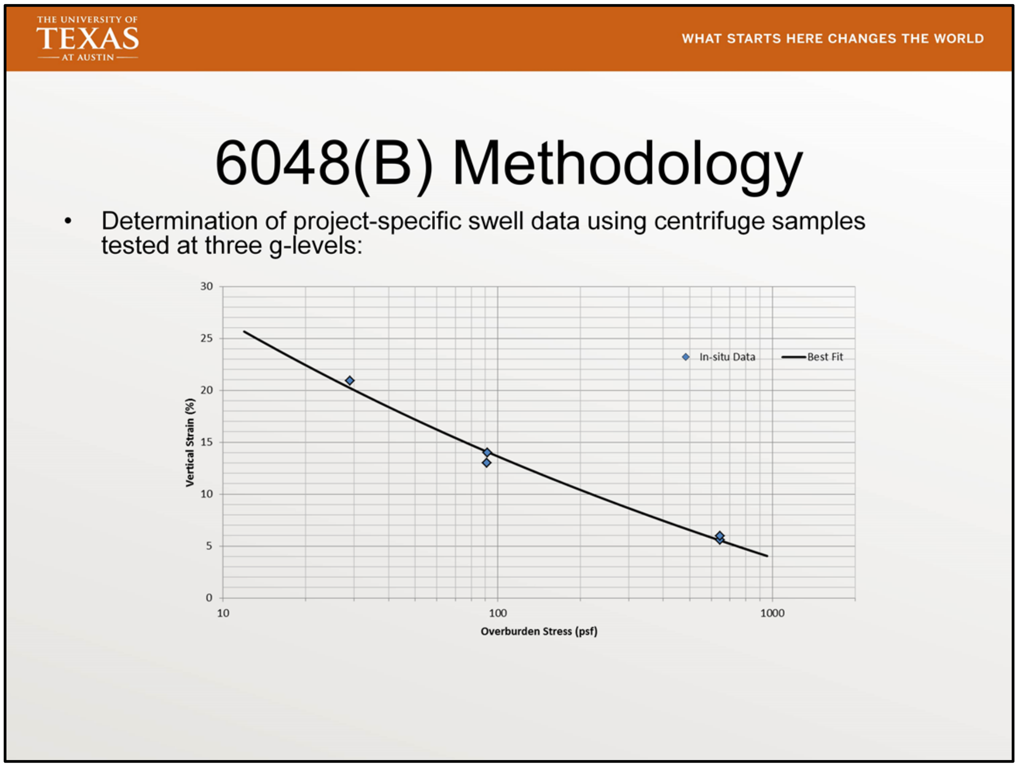
6048(B) Methodology

- Run centrifuge test at three different effective stresses (5g, 25g, 100g)
  - Determine effective stresses at top and bottom of sample
  - Determine water content and unit weight for each divided layer
- Generate Swell vs. Effective Stress from centrifuge test results in order to calculate swell for each layer
- Multiply by height to determine PVR of each layer
- Sum of PVR for each layer is total PVR

Note on the Example used in this presentation: Undisturbed In-situ Eagle Ford or Houston Black samples were not available at this stage in the implementation project. Instead, a set of results from remolded clay samples were used for illustration purposes.

Similar steps to that from the previous methodology. Note that there aren't undisturbed specimens for these sites, so reconstituted samples were tested.



Test are run to generate the swell versus stress curves. Note that this swell-stress curve is NOT the curve for the given site, but taken from Eagle Ford reconstituted specimens only to illustrate how a site would be run. In the case of multiple sublayers and geologic strata, there would be disconnects at certain overburden stresses from the change in soil classification.

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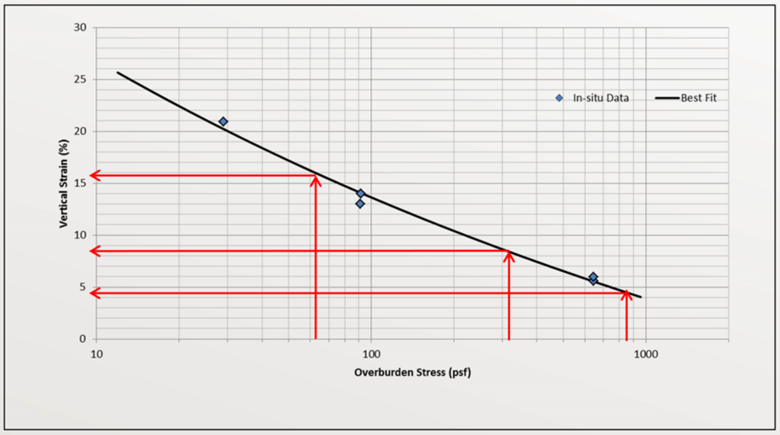
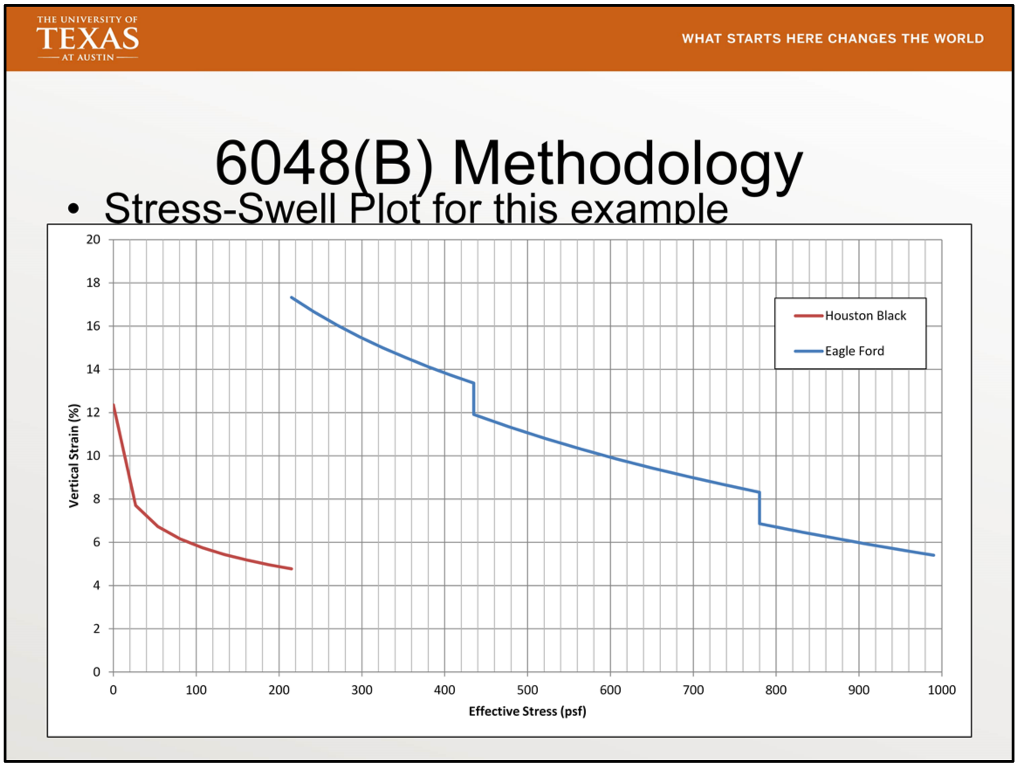
6048(B) Methodology

- Determination of swell for each sub-layer



At each sub-layer, you determine the swelling that will occur.



Notice the jumps between the changes in the moisture contents

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6048(B) Methodology

6048(B) Calculations for each sub-layer:

Depth to Top of Layer(ft)	Thickness (ft)	ω (%)	Unit Weight (pcf)	Average Effective Stress (psf)	Swell (%)	PVR (in)	Cumulative PVR (in)
0	1	21	105	10	10.50%	1.26	**9.95**
1	1	21	110	150	5.40%	0.65	8.69
2	1	21	110	264	16.20%	1.94	8.05
3	1	21	110	376	14.25%	1.71	6.10
4	1	24	115	489	11.40%	1.37	4.39
5	1	24	115	605	9.99%	1.20	3.02
6	1	24	115	720	8.85%	1.06	1.83
7	1	27	120	838	6.36%	0.76	0.76

Calculated PVR using proposed 6048(B) Methodology: **9.95 inches**

Based on this visualization for 6048 B using data from the reconstituted specimens, you get a PVR of 3.32 inches

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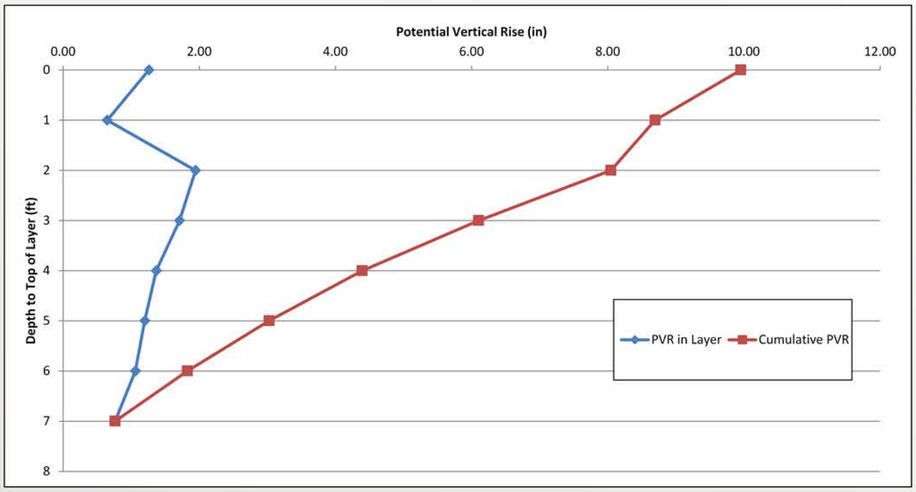
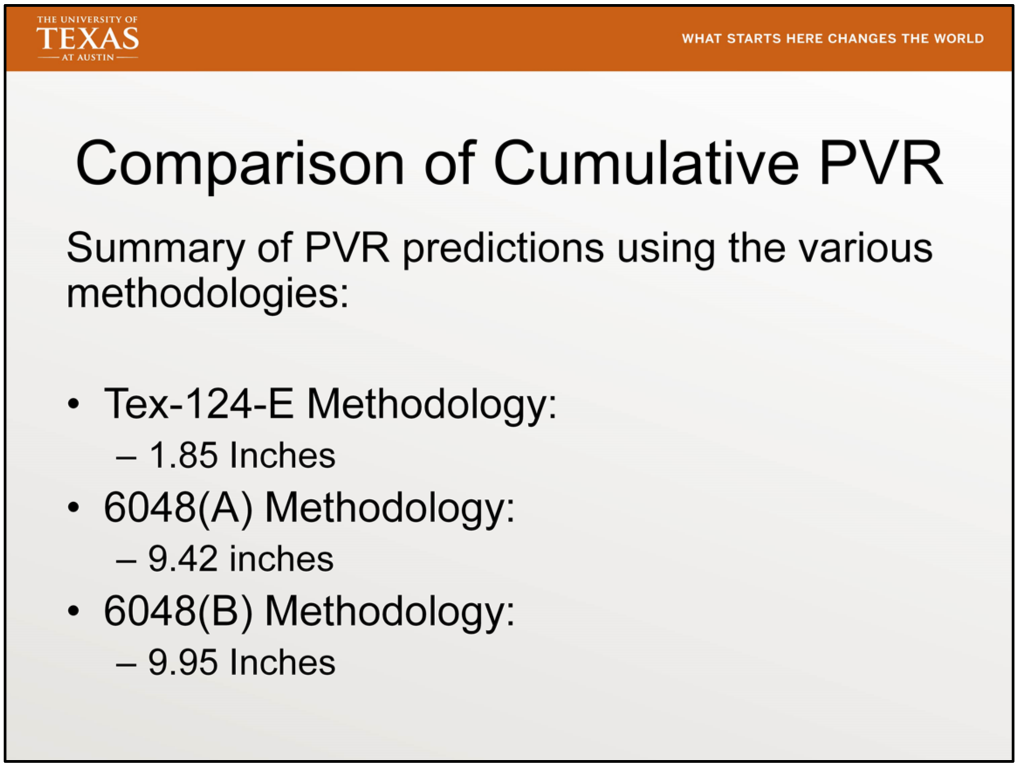
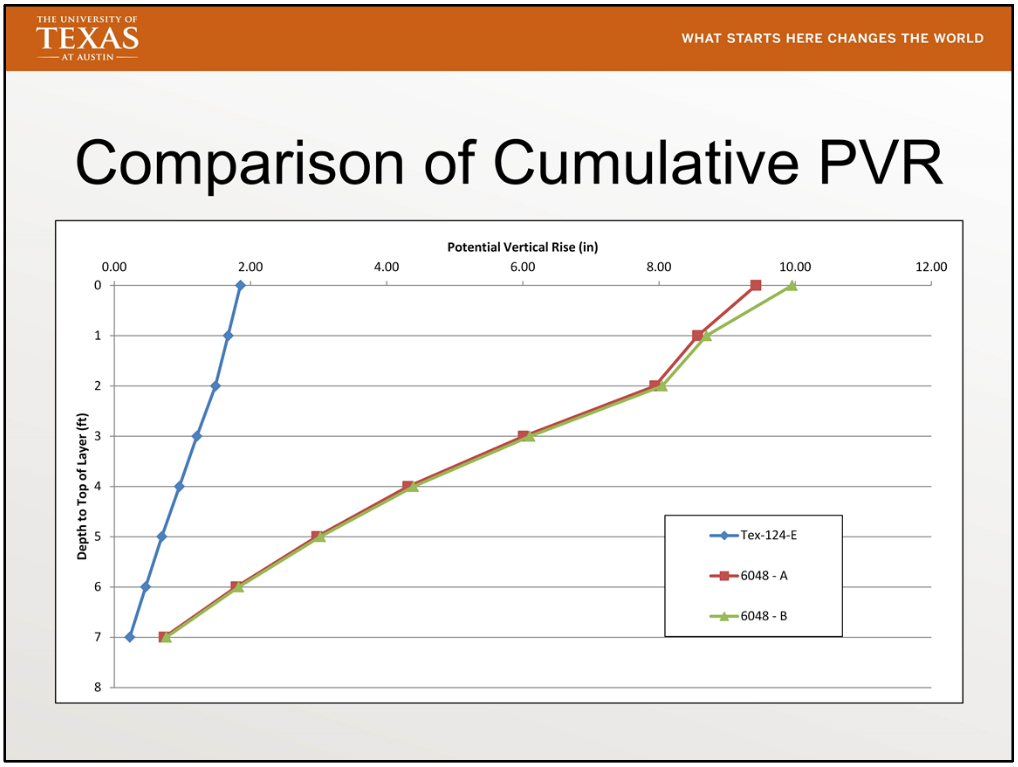
6048(B) Methodology





Note not to generalize whether the PVR from each method will be conservative in relation to the others as things may change based on how the soils actually perform in each location.



Based on this, the centrifuge testing data is able to give a different PVR that illustrates a much more distinct boundary between two sublayers.

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Final Remarks

- The use of Methodology 6048(A) is preferable to Tex-124-E as it leads to a soil-specific prediction of vertical rise.
- The use of Methodology 6048(B) is recommended when project soil data is available. This approach leads to a project-specific prediction of vertical rise.
- The use of a database (Methodology 6048(A)) is suitable for preliminary predictions of PVR.
- Methodology 6048(B) is recommended for prediction of PVR for final design or critical projects

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Texas Department of Transportation

Thank You

Appendix B: Manual for PVR Calculations using Centrifuge Technique

1. Introduction

The purpose of this manual is to walk through the current steps for calculating the potential vertical rise (PVR) of a given subgrade based on the Tex-124-E method as well as centrifuge testing of reconstituted (6048–A) or undisturbed (6048–B) specimens. Spreadsheets currently exist for the Tex-124-E method from the TxDOT Austin District, but calculations will be done for a specific layer in order to illustrate the methodology behind the work that Excel does. The centrifuge-based methods are taken from testing data previously created at The University of Texas at Austin based on Zornberg et al. (2013) and Armstrong (2014). For any clarification on these steps, do not hesitate to contact either Dr. Jorge Zornberg (zornberg@mail.utexas.edu) or Christian Armstrong (christian.armstrong@utexas.edu). Note that the following example problem is the same problem from the "Training Material: PVR Methodology" presentation (Appendix A of this document).

2. Example Parameters

For this example, two soils that are relevant subgrades in Austin—the Houston Black clay that is a part of the Taylor-Navarro Formation and the Eagle Ford clay from the Eagle Ford shale—are combined as a subgrade at a given location. Both are classified as fat clays (designated "CH" in Tables 2 and 3), and their index and engineering properties are summarized in Table 1. Note that the "%<No. 40" figures indicate the portion of the soil that passes through the No. 40 sieve, an important parameter for the Tex-124-E method.

Table 1: Properties of Example Expansive Clays

Property \ Soil	Houston Black	Eagle Ford
ω (%)	21%	21-27%
γ (pcf)	105-110	110-120
LL (%)	62%	88%
PI (%)	35%	49%
%< No. 40	80%	93%

The subgrade for this proposed example is a 2-ft layer of the Houston Black clay underlain by 6 ft of the Eagle Ford clay. The example extends only 8 ft because the typical active zone (the zone at which moisture fluctuates seasonally) typically ranges from 6 to 10 ft in Central Texas. Both of the clays used in this example are problematic, especially the Houston Black clay, which is typical of the Taylor-Navarro formation that covers a significant amount of the region east of the I-35 corridor in Austin.

3. Tex-124-E Method

Note: These steps are to be followed for both a sublayer of the Houston Black clay and a sublayer of the Eagle Ford clay simultaneously.

1) Subdivide the subgrade into 1-ft layers and indicate the liquid limit (LL), plasticity index (PI), moisture content (ω), total unit weight (γ), and percent finer than the No. 40 sieve.
    - Tex-124-E typically indicates that 2-ft sublayers are preferred, but for this example, 1-ft layers are shown to illustrate the differences between the two clays.

2) Determine the "Dry," "Wet," and "Average" moisture condition by the following equations:
   a. $\text{"Dry" Moisture Content} = \omega_d = .2 * LL + 9\%$
   b. $\text{"Wet" Moisture Content} = \omega_w = .47 * LL + 2\%$
   c. $\text{"Average" Moisture Content} = \omega\_a = (\omega_w + \omega_d) / 2$
      i. The Houston Black clay (LL=62%) has the following moisture contents for each condition:
         - $\omega_d = 22.6\%$
         - $\omega_w = 31.1\%$
         - $\omega_a = \frac{31.1\% + 22.6\%}{2} = 26.9\%$
      ii. The Eagle Ford clay (LL=62%) has the following moisture contents for each condition:
         - $\omega_d = 28.4\%$
         - $\omega_w = 43.4\%$
         - $\omega_a = \frac{28.4\% + 43.4\%}{2} = 35.9\%$
3) Determine the average load in each of the sublayers based on the unit weight of the soil. Make sure you convert the average load in terms of psi.
   - In order to determine the average load, the average load measurement is taken at the middle of the sublayer.
   - A summary of the data from the first three steps is shown in Table 2. The moisture condition is shown by relating the moisture content of the soil to the closest moisture condition.

Table 2: Summary of Sublayers

Depth to Bottom of Layer [ft]	Soil (USCS)	Average Load [psi]	Liquid Limit (LL)	Dry Moisture Content	Wet Moisture Content	Moisture Content (%)	Dry Avg Wet	Percent <No.40	Unit Weight (pcf)	Plasticity Index (PI)
1.0	HB (CH)	0.4	62	21.4	31.1	21.0	Dry	80.0	105	35
2.0	HB (CH)	0.7	62	21.4	31.1	21.0	Dry	80.0	110	35
3.0	EF (CH)	1.1	88	26.6	43.4	21.0	Dry	93.0	110	49
4.0	EF (CH)	1.5	88	26.6	43.4	21.0	Dry	93.0	110	49
5.0	EF (CH)	1.9	88	26.6	43.4	24.0	Dry	93.0	115	49
6.0	EF (CH)	2.3	88	26.6	43.4	24.0	Dry	93.0	115	49
7.0	EF (CH)	2.7	88	26.6	43.4	24.0	Dry	93.0	115	49
8.0	EF (CH)	3.1	88	26.6	43.4	27.0	Dry	93.0	120	49

4) Using Figure 3 from Tex-124-E (Figure 1 in this example), find the percent volumetric strain under 1 psi of loading using the plasticity index and moisture condition of the soil.
   - Figure 1 shows the process of locating this percent volumetric strain for the Houston Black clay (PI=35, "Dry" moisture condition) and Eagle Ford clay (PI=49, "Dry" moisture condition).
   - For this example, the percent volumetric change for the Houston Black clay is 9.6%, with 12.9% for the Eagle Ford clay.

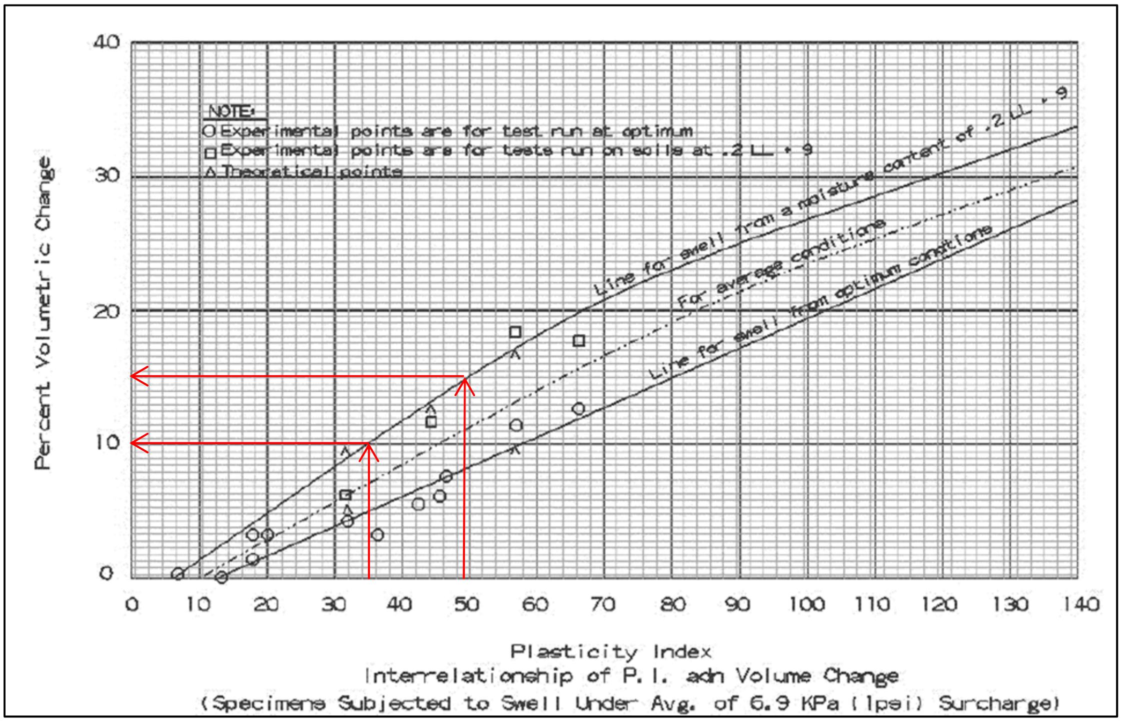

Figure 1: Relationship of % Volumetric Strain under 1 psi Surcharge and Plasticity Index

5) The percent volumetric strain under 1 psi of surcharge needs to be converted to a percent free swell, or the swelling under no loading using the following equation.
   - $\%Free\ Swell = (\%\ Vol\ Swell\ @\ 1psi) * 1.07 + 2.6\%$
   - For this example, the %Free Swell is 12.9% for the Houston Black clay and 17.8% for the Eagle Ford clay.

6) From the percent free swell and the load at the top and bottom of each layer, determine the PVR in inches from either Figure 2 or 3. (Note: The figure is Figure 1 and 2 in Tex-124-E).
   - The load at the top of the layer for the first layer is taken to be zero psi, whereas the load at the bottom of the layer is taken to be the average load calculated previously.
   - Note that an example is not shown in this step, as the loading condition is very minimal and the differences in the graph are hard to extrapolate visually. Thus, the spreadsheet's function is extremely helpful during this calculation because the loading conditions are typically low in relation to those loads in the active zone.

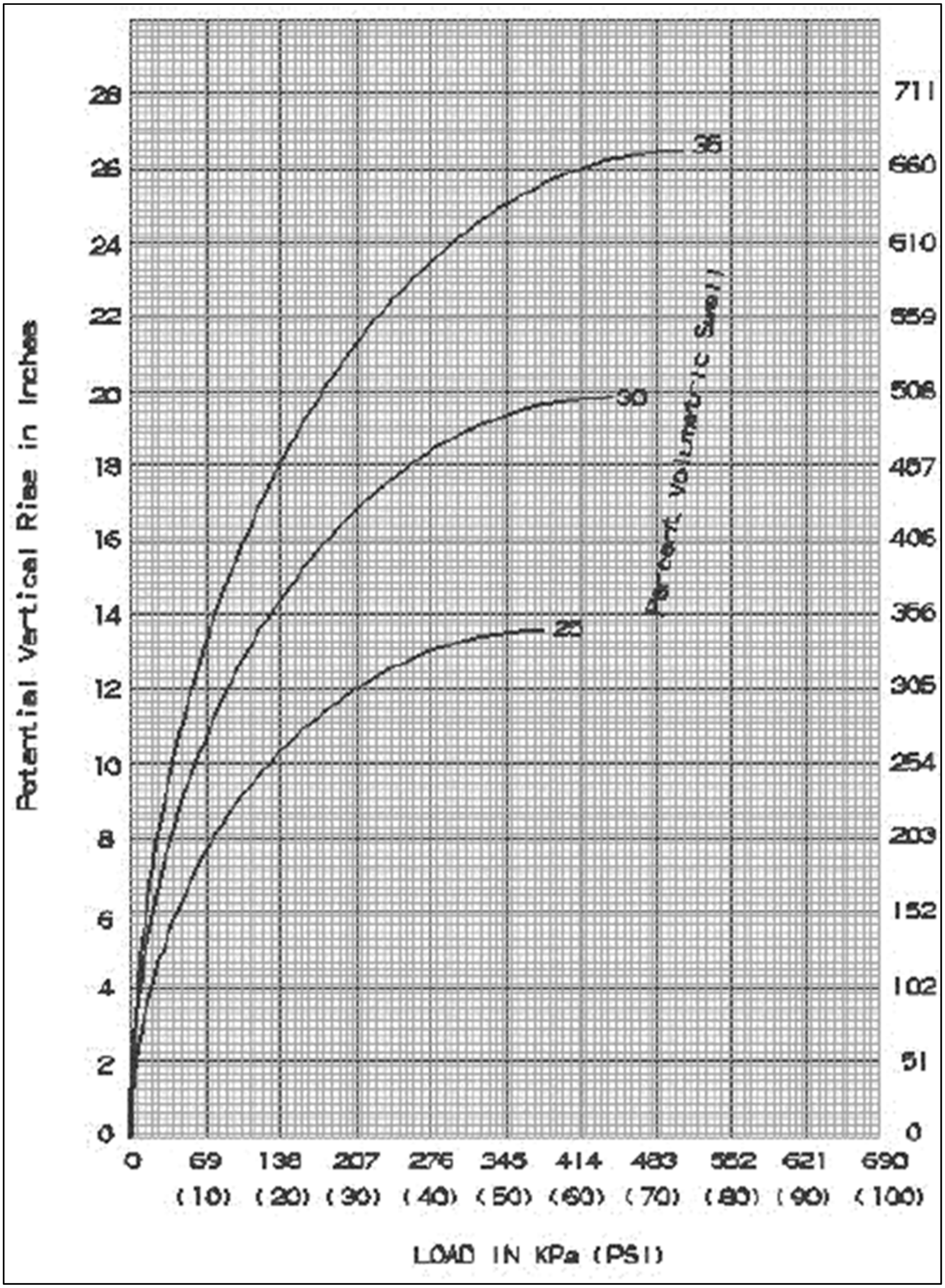

Figure 2: Relationship between Load and PVR for High Free Swelling Soils

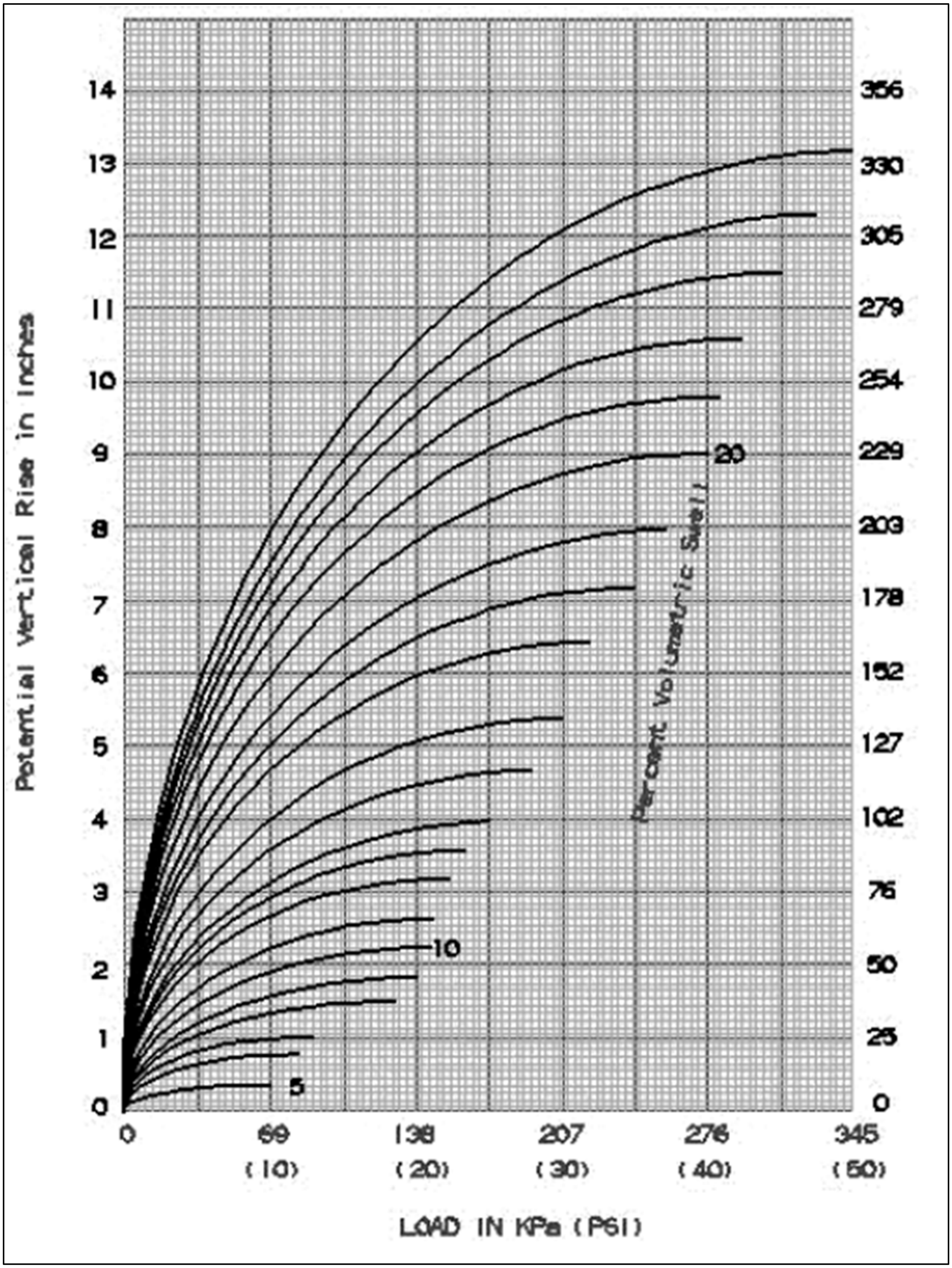

Figure 3: Relationship between Load and PVR for Expansive Soils

7) The difference in the PVR at the top and the bottom of the layer is taken to be the PVR of the layer as shown below:
   - $PVR, layer = PVR, bottom - PVR, top$
8) The PVR needs to be corrected, as the PVR calculation assumes a total unit weight of 125 pcf or that all the soil is finer than the number 40 sieve. Thus, two corrections are given as shown below and solved for the Houston Black Clay:
   - $C_{SB} = \frac{\%\ less\ than\ 25\ \mu m}{100\%} = \frac{80\%}{100\%} = .8$
   - $C_{\gamma} = \frac{125\ pcf}{\gamma_a} = \frac{125\ pcf}{110\ pcf} = 1.14$
9) These correction factors are then multiplied times the PVR calculated in Step 7 to get the actual PVR of the layer as shown below:
   - $PVR, corrected = PVR, layer * C_{SB} * C_{\gamma}$
10) The sum of the corrected PVR for each layer is taken to be the PVR of the site. The results for the given example are shown in Table 3 using the TxDOT Austin District spreadsheet.

Table 3: Summary of PVR for Tex-124-E Method

Depth to Bottom of Layer [ft]	Soil (USCS)	% Volume Swell	% Free Swell	PVR [in] Top of Layer	PVR [in] Bottom of Layer	Differential Swell [in]	Modified -No.40 Factor	Modified Density Factor	PVR in Layers [in]	Total PVR [in]
0.0	-	-	-	-	-	-	-	-	-	1.85
1.0	HB (CH)	9.6	12.9	0.00	0.19	0.19	0.80	1.19	0.18	1.67
2.0	HB (CH)	9.6	12.9	0.19	0.39	0.20	0.80	1.14	0.19	1.49
3.0	EF (CH)	14.2	17.8	0.53	0.79	0.26	0.93	1.14	0.27	1.21
4.0	EF (CH)	14.2	17.8	0.79	1.03	0.24	0.93	1.14	0.26	0.95
5.0	EF (CH)	14.2	17.8	1.03	1.29	0.26	0.93	1.09	0.26	0.70
6.0	EF (CH)	14.2	17.8	1.29	1.52	0.24	0.93	1.09	0.24	0.46
7.0	EF (CH)	14.2	17.8	1.52	1.75	0.23	0.93	1.09	0.23	0.23
8.0	EF (CH)	14.2	17.8	1.75	1.99	0.23	0.93	1.04	0.23	0.00

4. 6048 – A: Reconstituted Centrifuge Method

1) Subdivide the subgrade into sublayers and record the moisture contents and unit weights from the field or assumed subgrade.
   - Sublayers of 2 ft are typical as prescribed by Tex-124-E.
2) From the database of soil, select the stress-swell curve for the given soil at the most appropriate moisture content and unit weight.

- Note that the moisture conditions and unit weights are varied based on tests previously done at the University of Texas. Some moisture contents and unit weights are based on the optimum conditions as prescribed by the Standard Proctor compaction test and others are based on the conditions prescribed by Tex-124-E, i.e., a "Dry," "Wet", or "Average" moisture condition at a unit weight at or near 125 pcf.
- Multiple stress-swell curves may be used in case of multiple moisture contents and unit weights expected in the field. Note that the effect of the moisture content is much greater than that of the unit weight of the soil. Thus, the moisture content used for the stress-swell curve is the most important variable.

3) Determine the stress at the top and bottom of each layer in terms of psf based on the unit weights from the field.
4) Determine the average stress in the sublayer. This can be accomplished in three separate ways:
   - The easiest, but the most inaccurate, is to take the arithmetic average stress in the sublayer as prescribed by the following equation:

$$\sigma_{avg} = \frac{(\sigma_{top} + \sigma_{bottom})}{2}$$

   - Another method is to take the arithmetic mean of logarithms, or the log-average of the effective stress at the top and bottom of the sublayer, as prescribed by the following equation:

$$\sigma_{avg} = \exp\left(\frac{ln(\sigma_{top}) + ln(\sigma_{bottom})}{2}\right)$$

   - The most accurate method, but also the most time consuming, is to calculate the average of the stress-swell curve across the range of stresses. This, however, will lead to the same answer as the log-average if the assumption is that the stress vs. swell curve is log-linear over the given range of stresses in the subgrade. This assumption leads to a small amount of error but is suitable for the majority of the stresses examined in the subgrade.
5) Determine the vertical strain at the given average overburden stress from the stress-swell curve in Step 2. An example for the Eagle Ford clay at an average stress of 489 psf (i.e. the log-average stress for the sublayer between 4 and 5 ft) is shown in Figure 4.
   - Note that this vertical strain can be calculated as determined by the constants for the best-fit curve in the database for the expansive soils in the Austin district.

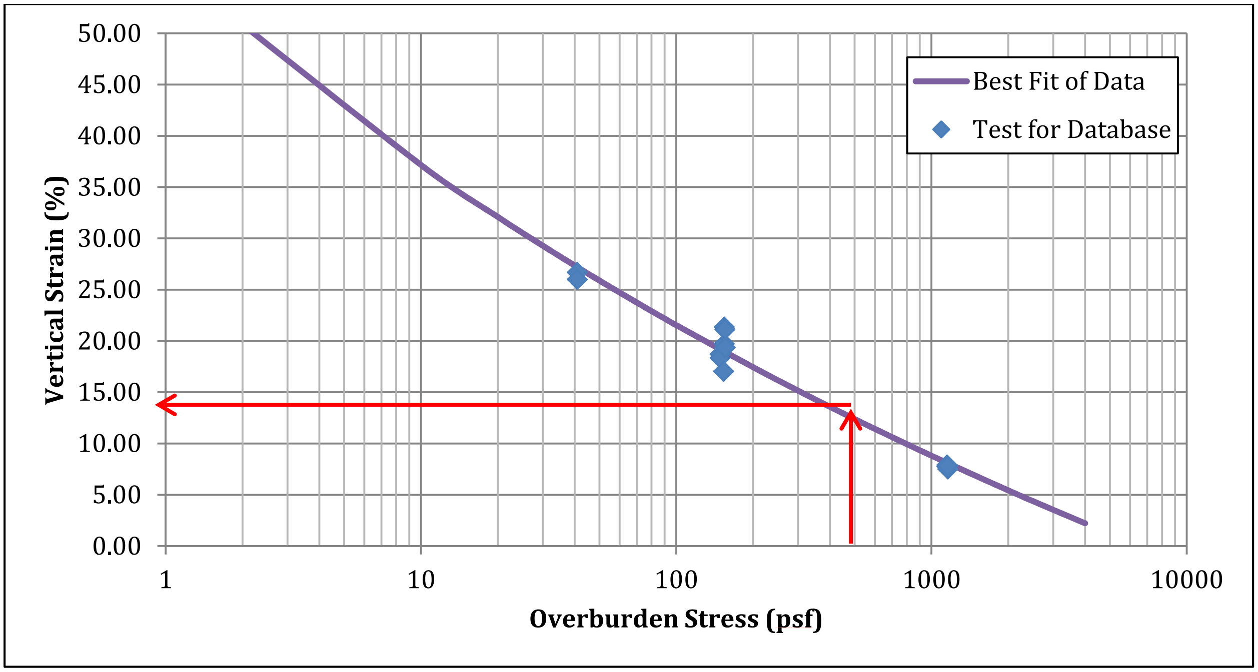

Figure 4: Stress-Swell Curve for Eagle Ford Clay

6) Multiply this vertical strain by the thickness of the layer to determine the potential vertical layer of the sublayer.
7) Sum up the PVR of each sublayer to determine the PVR of the given location. Note that no correction factor for the percent soil binder or unit weight is necessary as the test are based upon the actual tested soil. A summary of the PVR for the example based on the given data and previous stress-swell curves is presented in Table 4.

Table 4: Summary of PVR For Method 6048–A

Depth to Top (ft)	Thickness (ft)	Soil	ω (%)	Unit Weight (pcf)	Top Stress (psf)	Bot. Stress (psf)	Average Effective Stress (psf)	Swell (%)	Vertical Rise (in)	Cumulative PVR (in)
0	1	HB	21	105	0	105	10	7.14%	0.86	**9.42**
1	1	HB	21	110	105	215	150	5.22%	0.63	8.57
2	1	EF	21	110	215	325	264	16.09%	1.93	7.94
3	1	EF	21	110	325	435	376	14.14%	1.70	6.01
4	1	EF	24	115	435	550	489	11.17%	1.34	4.31
5	1	EF	24	115	550	665	605	9.87%	1.18	2.97
6	1	EF	24	115	665	780	720	8.80%	1.06	1.79
7	1	EF	27	120	780	900	838	6.11%	0.73	0.73

5. 6048 – B: Undisturbed Centrifuge Method

1) Subdivide the boring into sublayers. A maximum of a 2-ft sublayer is recommended, though smaller sections can be used.

- The samples can be moisture conditioned from their in-situ condition to a drier moisture condition. If so, the LL of the sublayer needs to be known, typically to be recommended to come from a single-point LL test using the wet method from ASTM D4318.

2) Test the sublayer specimens to generate a stress vs. swell curve plot following Armstrong (2014). A stress-swell curve for the given example using a combination of reconstituted specimens over the given ranges of stresses for each sublayer is shown in Figure 5.

    - If there are multiple geologic strata, a stress vs. swell curve needs to be generated for each strata over the corresponding stresses in the strata.

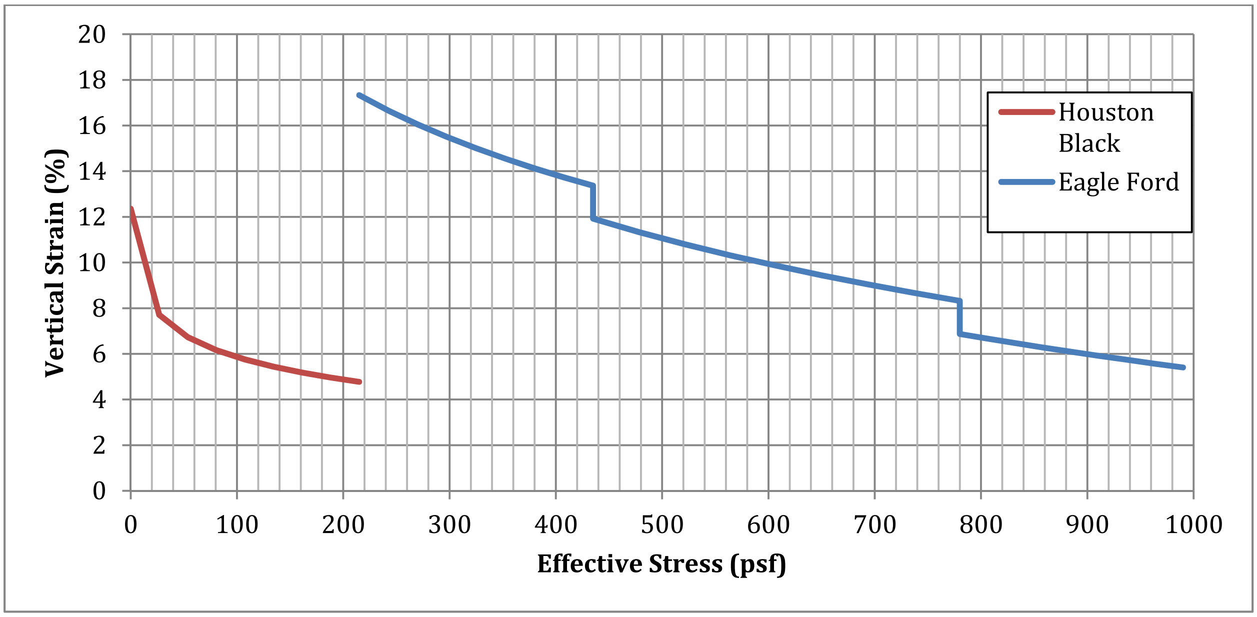

Figure 5: Stress-Swell Curve for Method 6048–B

3) Determine the stress at the top and bottom of each layer in terms of psf based on the unit weights from the field.
4) Determine the average stress in the sublayer. Using the log-linear average is the recommended
5) Determine the vertical strain at the given average overburden stress from the stress-swell curve in Step 2.
6) Multiply this vertical strain by the thickness of the layer to determine the potential vertical layer of the sublayer.
7) Sum up the PVR of each sublayer to determine the PVR of the given location. Note that no correction factor for the percent soil binder or unit weight is necessary as the test is based upon the actual tested soil. A summary of the PVR for the example—based on the given data and previous stress-swell curves in Figure 5—is presented in Table 5.

Table 5: Summary of PVR for Method 6048–B

Depth to Top of Layer (ft)	Thickness (ft)	ω (%)	Unit Weight (pcf)	Average Effective Stress (psf)	Swell (%)	PVR (in.)	Cumulative PVR (in.)
0	1	21	105	10	10.50%	1.26	**9.95**
1	1	21	110	150	5.40%	0.65	8.69
2	1	21	110	264	16.20%	1.94	8.05
3	1	21	110	376	14.25%	1.71	6.10
4	1	24	115	489	11.40%	1.37	4.39
5	1	24	115	605	9.99%	1.20	3.02
6	1	24	115	720	8.85%	1.06	1.83
7	1	27	120	838	6.36%	0.76	0.76

References

Armstrong, Christian. (2014). Effect of Fabric on the Swelling of Highly Plastic Clays. The University of Texas at Austin.

ASTM D4318. *Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils*. American Society of Testing Materials.

Tex-124-E. *Determining Potential Vertical Rise.* Texas Department of Transportation.

Zornberg, J.G., Armstrong, C.P., Plaisted, M.D., and Walker, T.M. (2013). Swelling of Highly Plastic Clays under Centrifuge Loading. Center for Transportation Research (CTR), Product Report No. 5-6048-01-P2, Austin, Texas, May, 8 p.

Appendix C: Revisions to Tex-124-E to Incorporate Centrifuge Test Approach

5. PROCEDURE

5.1 If only cuttings were taken during sampling, determine the moisture content of each layer in accordance with Tex-103-E.

5.1.1 If core samples were paraffined for moisture preservation, use those samples in this procedure.

5.1.2 It is preferable to take moisture samples for each layer at the time of sampling, regardless of whether cores or cuttings were taken.

5.2 For core sampling, select cores representative of each swelling layer.

5.2.1 Trim cores into right circular cylinders using knives or other convenient hand tools.

5.2.2 Measure the height, h, and diameter, D, and calculate the volume of the core in cubic meters (cubic feet).

5.2.3 Determine the mass of the wet core to the nearest 0.5 g.

5.2.4 Calculate the wet density by dividing the wet mass by the volume of the core and record to the nearest 0.02 kg/m^3 (0.001 lb./ft.^{3})

Note 2—If only cuttings are taken during sampling, use a wet density of 2002.5 kg/m^3 (125 lb./ft.^{3}), which is usually a reasonable value. Other accepted methods for determining density of cores, such as set forth by paraffin coatings in Tex-207-F, may be used, if desired.

5.3 In calculating the PVR, it is convenient or preferable to use 0.6 m (2 ft.) elements or layers, provided the moisture contents and the log of the hole will permit.

5.4 Once the soil has been tested using the guidelines of Texas Research Project 6048, either Method A or B, the data is used to create a stress-swell plot. An example of a stress-swell plot is shown in Figure 1 using both sets of curve fitting parameters.

Note: If the soil profile contains multiple moisture contents, a stress-swell plot must be calculated for each moisture content used over the ranges of the load in the field.

5.4.1 Determine the average load in psf for each layer.

5.4.2 In the Stress-Swell spreadsheet, input the soil fitting parameters & average load for the first layer into the designated location. Doing so will result in the calculation of a swell percentage based on the given stress level.

5.4.3 To calculate the PVR for the first layer, use the following equation:

$$PVR_{layer\ 1} = Swell\ \% * \ t_{layer\ 1}$$
$$Where:\ t_{layer\ 1} = Thickness\ of\ Layer\ 1$$

5.5 For calculation of the total PVR for the entire soil profile, Steps 5.4.2 & 5.4.3 must be completed for each layer of the soil profile.

5.5.1 To calculate the total PVR of the soil profile, use the following equation:

$$Total\ PVR = \sum_{i=1}^{n=\#\ of\ Layers} PVR_{layer\ i}$$

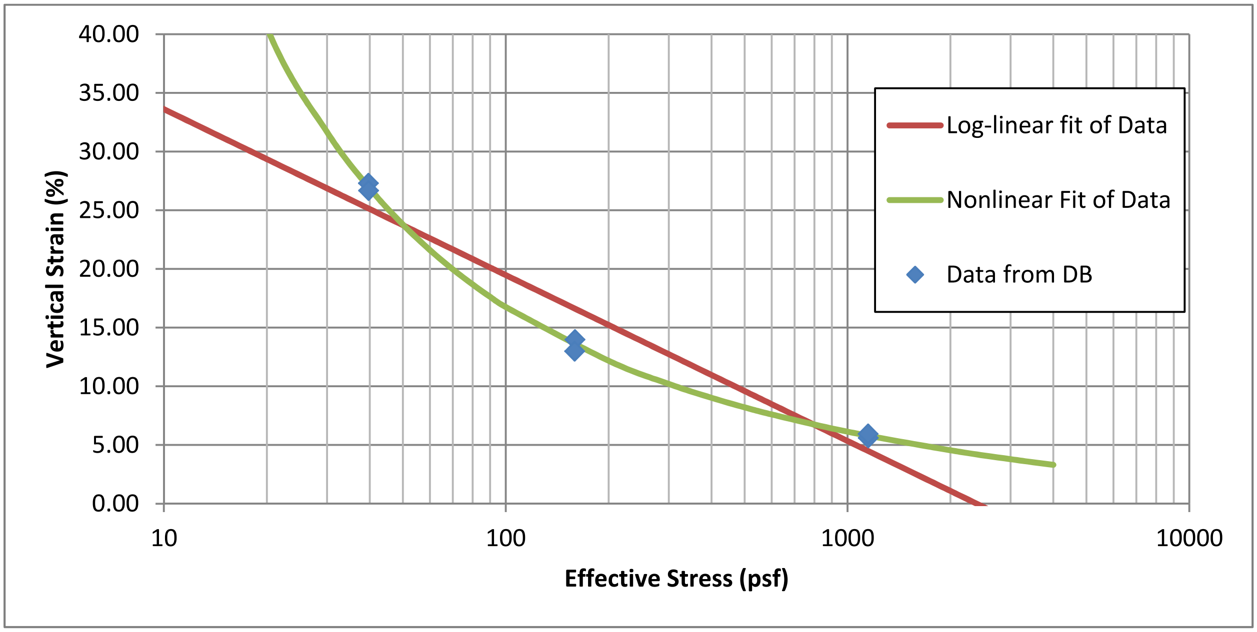

Figure 1- Example of Stress-Swell Plot for a given moisture conditions

6. TEST REPORT

6.1 To report the test results, submit a copy of the Example Calculation, with appropriate job and site identifications.

7. NOTES

7.1 Often, during design, it is necessary to estimate PVR without knowing moisture contents anticipated at time of construction. In cases of this kind, the design and planning of the job should influence the choice of moisture contents to assembly of the stress-swell curve from Figure 1.

7.1.1 If the project exists in an arid to semiarid climate and the plans and specifications do not provide for moisture-density control or preservation of moisture, use the moisture content that corresponds to the "Dry" condition based upon ω_{dry}= 0.2 LL + 9.

7.1.2 If the plans and specifications require moisture-density control and moisture preservation, use the average moisture condition.

7.1.3 In the high rainfall areas, use the average line where moisture preservation is provided for, but if moisture-density control and moisture preservation are provided for, use the moisture condition for the "Wet" condition based upon ω_{wet}=0.47 LL + 2.

7.2 The determination of PVR in deep cut sections or deep side hill cuts presents a special case of this test method.

7.2.1 In the case of these two conditions, the material is surcharged in such a manner that the movement from swell is mostly in one direction.

7.2.2 In some high rainfall areas, it could be greater than that obtained by use of these procedures.

7.3 When layers of expansive clays of less than 0.6 m (2 ft.) exist (example: 1.2 to 1.4 m [4 to 4.6 ft.]), it is preferable to enter the abscissa of the proper swell curve at 1.2 and 1.4 m (4 and 4.6 ft.), respectively, and use the difference in the respective ordinate readings as the unmodified swell in the 0.2 m (0.6 ft.) thick layer.

7.4 In order to determine the average load in the sublayer, one of three methods may be used.

7.4.1 The first method involves taking the arithmetic average load in the sublayer based on the stress at the top and bottom of the layer and the following equation:

$$\sigma_{avg} = \frac{(\sigma_{top} + \sigma_{bottom})}{2}$$

This method is the most inaccurate of the three methods as the swelling changes non-linearly.

7.4.2 The second method involves taking the log-average of the load in the sublayer based on the stress at the top and bottom of the layer and the following equation:

$$\sigma_{avg} = exp\left(\frac{ln(\sigma_{top}) + ln(\sigma_{bottom})}{2}\right)$$

This method is more accurate than the first method but has a minimal amount of error based on the log-linear assumption.

7.4.3 The third method involves numerically calculating the average of the swell-stress curve over the range of stresses. This method is the most time-consuming and, as the stresses typically vary log-linearly over a sublayer, gives a similar answer to the second method.

7.5 For 6048-Method B, a juxtaposition of stress-swell plots may be necessary over the various load ranges for each sublayer. If this is the case, one must be careful as to what the correct depths are at each location in order to verify that the range of stresses matches what is prominent and/or found in the field.

7.6 The curve fitting parameters for each soil condition vary based on two parameters: the initial moisture content and the initial dry density.

7.6.1 If the initial moisture content lies on a point between any of the conditions, a linear interpolation between experimental best fit lines may be used for the range of stresses.

7.6.2 If the initial moisture content lies above or below the tested moisture contents, an additional laboratory testing regime is recommended to get the correct values.

7.6.3 If the density varies from the densities tested in the experimental data, a correction factor may be used based on the following equation:

$$CF = \frac{Dry\ Density, In - Situ}{Dry\ Density, Tested}$$

7.7 For the curve fitting of the experimental data, two separate sets of fitting coefficients exist.

7.7.1 The first curve fitting is for a log-linear curve with the equation below. Only two coefficients are needed for this fitting; thus, this method induces more error. However, the fitting allows for an integration of the given stress-swell curve.

$$Swelling(\%) = A * \ln(Load) + B$$

7.7.2 The second curve fitting is a non-linear and non-log-linear curve with the equation below. Three coefficients are used, but the method is not integratable.

$$Swelling(\%) = \frac{A}{\ln(B * Load + 1)} + C$$