COMMENTS REGARDING PTI SOIL DESIGN PARAMETERS

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PREPARED
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it's influence on estimating the design differential movement, y_m, from the tables in Appendix A.3. Two case studies are also presented illustrating observed failure modes and differential movement.

Familiarity of the reader with the PTI design procedure, and specifically, Appendix A.3, is necessary to follow the general discussion. A brief review of the procedures presented in Appendix A.3 of the PTI manual and some of the definitions in the PTI manual are presented in the following section.

REVIEW OF PTI PROCEDURE

Design of slabs-on-ground using the PTI manual requires various factors, with two of the more critical being the design movement, y_m, and the edge moisture distance, e_m. These parameters are required for both the "edge" lift and "center" lift condition. The conceptual definition of these two parameters for the "edge" lift and "center" lift condition are shown in Figure 1.

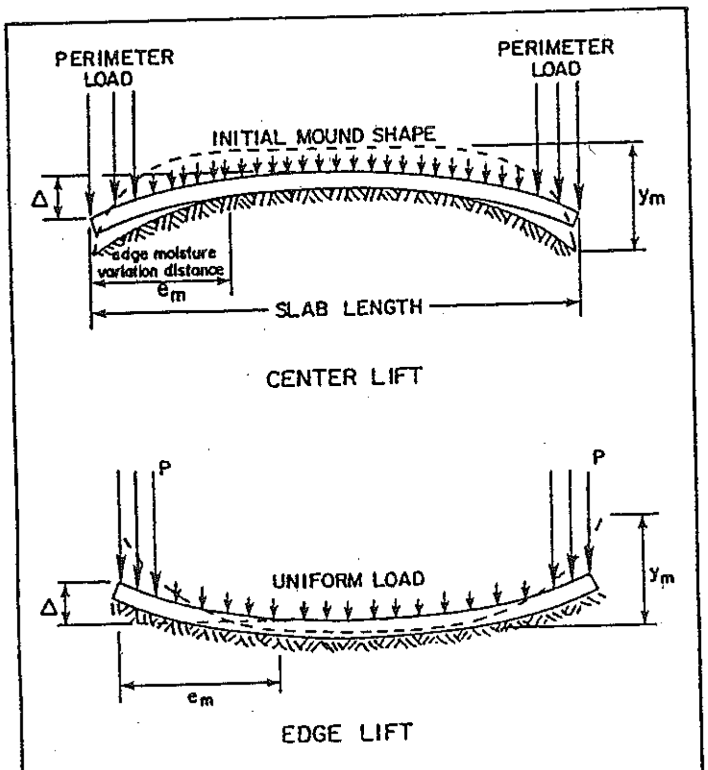


Fig. 4.2 Soil-structure interaction models (108)

Figure 1. Illustration of "Edge" and "Center" Lift Conditions.

Appendix A.3 of the manual presents a means of deriving e_m and y_m for both conditions of movement. This method has been an area of debate and many of the geotechnical engineers in the Dallas/Fort Worth area no longer provide PTI design criteria in soil reports. The method described in Appendix A.3 seems to have been embraced, however, by some structural designers. Some firms in Dallas/Fort Worth have even computerized the procedure, with the only required input from the soils engineer consisting of the city and the type and percent of clay.

Appendix A.3 contains various figures and tables for development of e_m and y_m. Required input from a soils engineer is the type and amount of clay. The structural designer can then proceed through Appendix A.3 and derive the design values. This odyssey begins with a map of Texas which plots average Thornthwaite values. This map is reproduced as Figure 2. From the average Thornthwaite value, the designer proceeds to two other figures and obtains the estimated constant suction and values for e_m for both the center lift and edge lift condition. These figures are reproduced as Figures 3 and 4. With the values obtained from Figures 3 and 4, coupled with the percent and type of clay, the designer proceeds to tables and obtains "design" values for y_m. A portion of a table from Appendix A.3 used for obtaining y_m is shown in Figure 5.

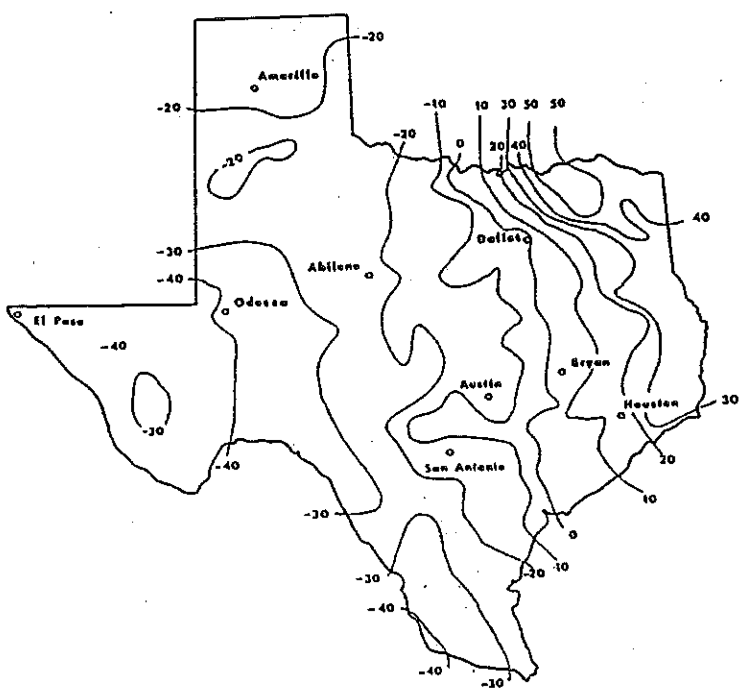


Figure 2. Average Values of the Thornthwaite Index for Texas.

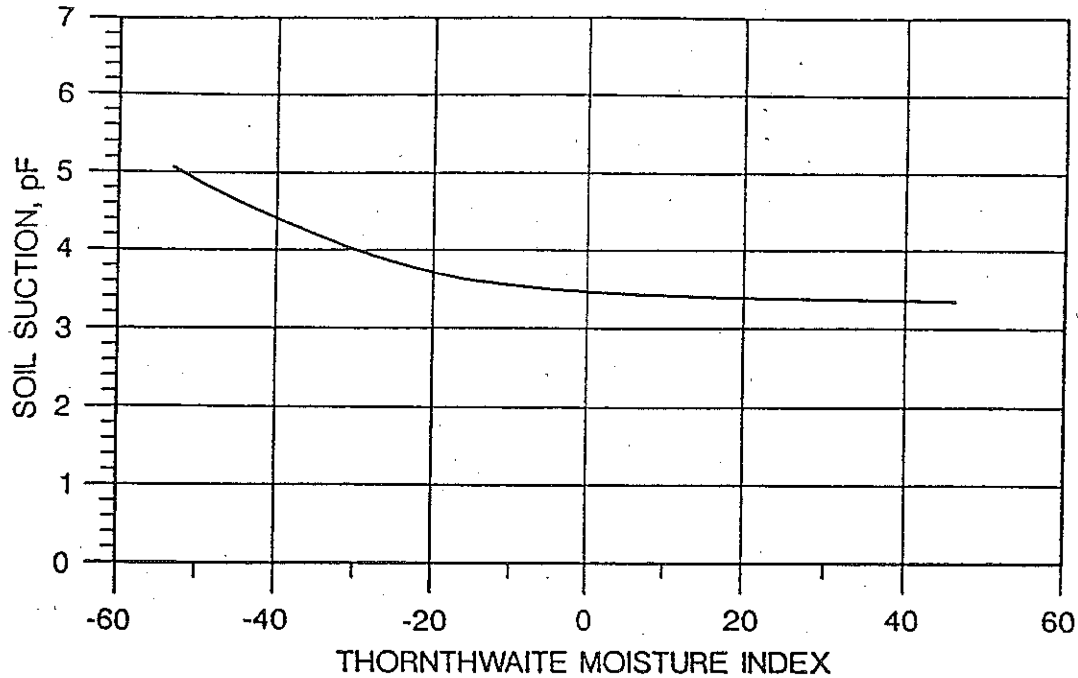


Figure 3. Values of Constant Suction.

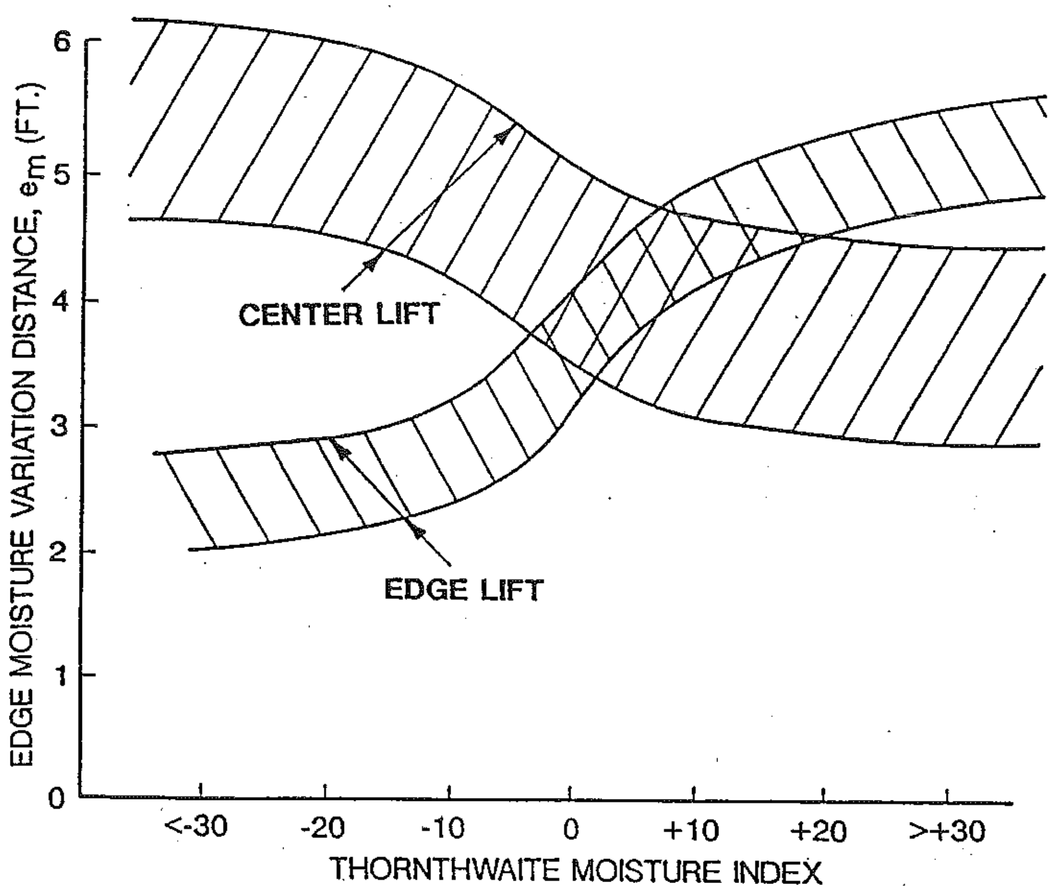


Figure 4. Edge Moisture Variation Distance e_m.

Percent Clay (%)	Depth to Constant Suction (FT)	Constant Suction (pF)	Velocity of Moisture Flow (inches /month)	DIFFERENTIAL SWELL (INCHES)							
				EDGE DISTANCE PENETRATION (FT)							
				1 FT	2 FT	3 FT	4 FT	5 FT	6 FT	7 FT	8 FT
40	3	3.2	0.1	0.002	0.003	0.005	0.007	0.008	0.010	0.012	0.013
			0.3	0.005	0.010	0.015	0.020	0.025	0.030	0.035	0.039
			0.5	0.009	0.017	0.025	0.033	0.041	0.049	0.056	0.064
			0.7	0.012	0.023	0.035	0.046	0.056	0.067	0.077	0.087
		3.4	0.1	0.004	0.007	0.011	0.014	0.018	0.021	0.025	0.028
			0.3	0.011	0.021	0.032	0.042	0.052	0.061	0.071	0.080
			0.5	0.018	0.035	0.052	0.068	0.084	0.099	0.113	0.128
			0.7	0.025	0.049	0.071	0.093	0.114	0.133	0.153	0.171
		3.6	0.1	0.009	0.018	0.026	0.035	0.043	0.051	0.059	0.067
			0.3	0.027	0.052	0.075	0.098	0.120	0.141	0.160	0.180
			0.5	0.044	0.084	0.121	0.155	0.187	0.218	0.246	0.274
			0.7	0.061	0.114	0.163	0.207	0.248	0.286	0.321	0.355
		3.8	0.1	0.022	0.043	0.063	0.082	0.100	0.118	0.135	0.152
			0.3	0.064	0.121	0.171	0.217	0.260	0.299	0.336	0.370
			0.5	0.105	0.191	0.264	0.329	0.387	0.440	0.488	0.533
			0.7	0.144	0.255	0.347	0.426	0.495	0.557	0.614	0.665
	5	3.2	0.1	0.004	0.007	0.011	0.015	0.019	0.022	0.026	0.030
			0.3	0.011	0.022	0.033	0.044	0.055	0.065	0.076	0.087
			0.5	0.019	0.037	0.055	0.073	0.090	0.107	0.125	0.141
			0.7	0.026	0.052	0.076	0.101	0.125	0.148	0.171	0.194
		3.4	0.1	0.008	0.016	0.024	0.032	0.039	0.047	0.055	0.062
			0.3	0.024	0.047	0.070	0.093	0.115	0.137	0.158	0.179
			0.5	0.040	0.078	0.116	0.152	0.187	0.221	0.255	0.287
			0.7	0.056	0.109	0.160	0.209	0.256	0.302	0.345	0.388
		3.6	0.1	0.020	0.039	0.059	0.078	0.096	0.115	0.133	0.150
			0.3	0.060	0.116	0.170	0.222	0.272	0.320	0.366	0.410
			0.5	0.099	0.190	0.275	0.355	0.430	0.501	0.568	0.633
			0.7	0.138	0.262	0.375	0.479	0.575	0.665	0.749	0.829
		3.8	0.1	0.049	0.096	0.142	0.186	0.228	0.269	0.309	0.347
			0.3	0.147	0.278	0.396	0.505	0.605	0.699	0.786	0.869
			0.5	0.244	0.447	0.623	0.779	0.919	1.047	1.164	1.274
			0.7	0.340	0.607	0.831	1.023	1.193	1.347	1.486	1.614
	7	3.2	0.1	0.006	0.013	0.019	0.026	0.032	0.038	0.045	0.051
			0.3	0.019	0.039	0.058	0.076	0.095	0.114	0.132	0.150
			0.5	0.032	0.064	0.095	0.126	0.157	0.187	0.217	0.246
			0.7	0.045	0.089	0.133	0.176	0.217	0.258	0.299	0.339
		3.4	0.1	0.014	0.028	0.042	0.055	0.069	0.083	0.096	0.109
			0.3	0.042	0.083	0.124	0.163	0.202	0.241	0.278	0.316
			0.5	0.070	0.138	0.204	0.268	0.330	0.391	0.450	0.508
			0.7	0.098	0.192	0.283	0.369	0.453	0.534	0.613	0.689
		3.6	0.1	0.035	0.070	0.104	0.137	0.170	0.202	0.235	0.266
			0.3	0.106	0.206	0.303	0.395	0.484	0.570	0.653	0.734
			0.5	0.176	0.340	0.493	0.637	0.772	0.901	1.023	1.140
			0.7	0.248	0.472	0.676	0.864	1.040	1.204	1.358	1.504
		3.8	0.1	-	-	-	-	-	-	-	-

Table A.3.27 Differential Swell Occurring at the Perimeter of a Slab for an Edge Lift Swelling Condition in a Predominantly Montmorillonite Clay Soil (40 Percent Clay).

Figure 5. Typical Design Table for y_m.

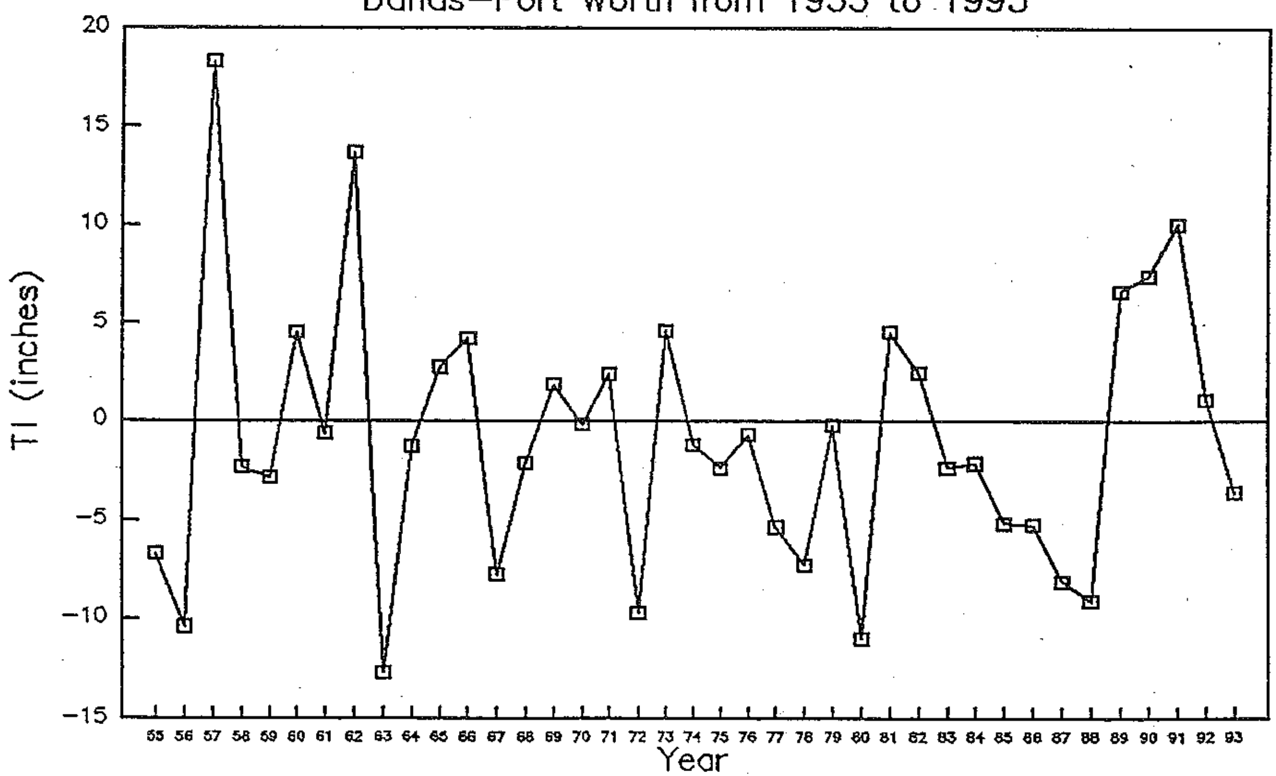
Analysis of Figures 3 and 4 indicates the reliance of the PTI method on the Thornthwaite Index. Variations in I_m directly influence the constant suction and more dramatically, e_m. Analysis of Figure 5 indicates the influence of these parameters on y_m.

ANALYSIS OF THORNTHWAITE INDEX IN DALLAS/FORT WORTH

The Thornthwaite Index, I_m, is an empirical method developed by C.W. Thornthwaite[2] in the 1940's to classify climates. The method basically compares potential evapotranspiration and precipitation on a yearly basis, then averages the values to arrive at a climatic rating. Positive values of I_m indicate humid climates. Negative values represent subhumid to arid climates. The importance of this statement is to realize that the I_m values presented in PTI Appendix A.3 are averages, and do not represent a range of values. Focusing on the Dallas area, Fig. A.3.3 of the PTI manual (Figure 2) suggests a Thornthwaite Index of zero inches.

Calculation of the Thornthwaite Index was made for the Dallas area for the last 60 years using procedures presented by McKeen and Johnson[3]. The results of the calculations since 1955 are presented in Figure 6. While the average does indeed fall around zero (-0.95) inches, the extremes range from -13 to +18 inches, with the positive extreme of +18 inches occurring in 1957 with 55.14 inches of rainfall. This range is consistent with that reported by Thornthwaite.

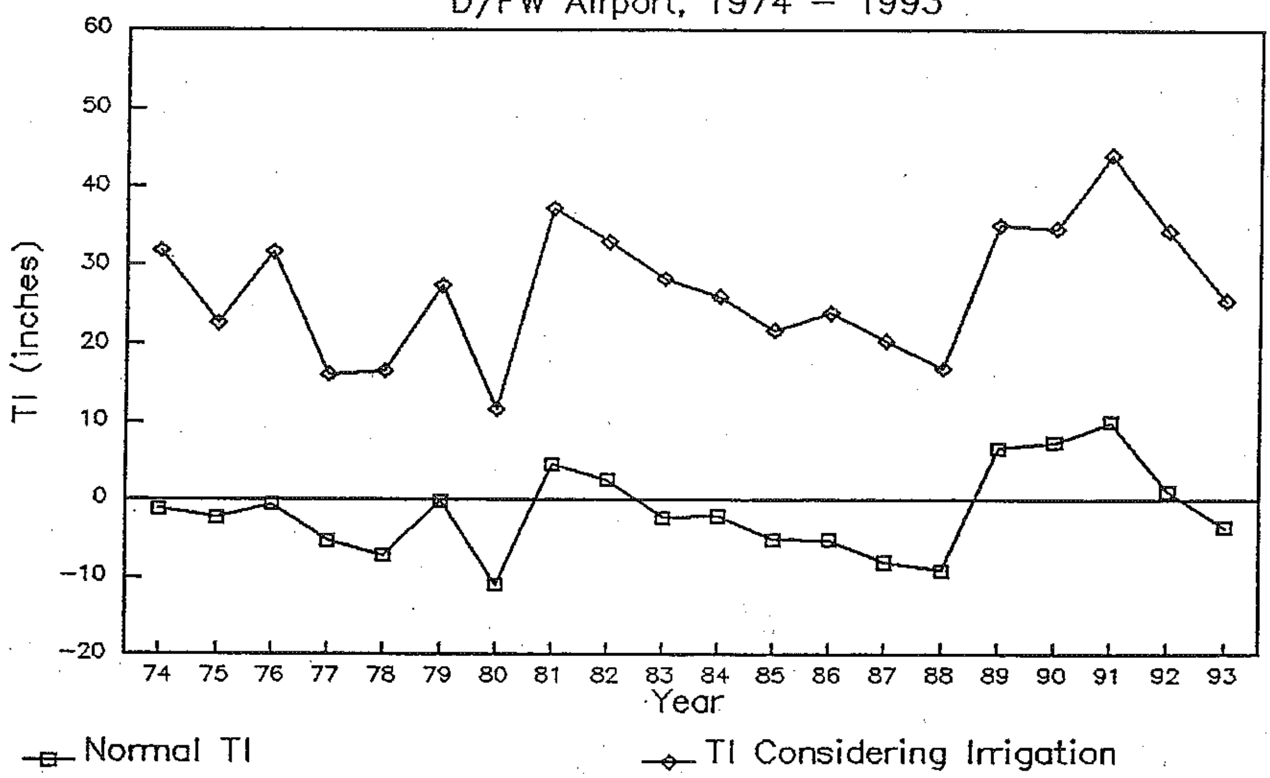
Figure 6. Variation in Thornthwaite Index, Im
Dallas—Fort Worth from 1955 to 1993



Conversation with different designers in the Dallas area indicates the extreme values are seldom, if ever, taken into account. As can be seen in the preceding graph, the Thornthwaite Index does not always fall on an "average" condition. Any year that is significantly wetter or drier than the average will test the integrity of the "average" design.

The addition of irrigation also increase the calculated I_m. Irrigation in the Dallas area can add the equivalent of two inches of rainfall per month for the five winter months, and four inches per month for the remaining portion of the year. Results of the effect of irrigation on the calculations are presented in Figure 7.

Figure 7. Variation of Thornthwaite Index, Im
D/FW Airport, 1974 – 1993



Analysis of Figure 7 provides an indication of the moisture range to be expected. For example, a home constructed in 1980 or 1988 (dry years), and irrigated could be expected to undergo significant movement associated with edge lift.

COMPARISON OF PTI DESIGN PARAMETERS AFFECTED BY I_m

To illustrate the impact the Thornthwaite Index has on design, a hypothetical case has been developed to compare e_m and y_m values for both average and extreme values of I_m. For this study, values of -10, 0 and +20 inches will be used. The values that will vary with I_m are e_m and constant soil suction, pF. The percent and type of clay will stay constant at 50 percent montmorillonite. The maximum depth to constant suction (seven feet) will be used in the analysis. The maximum moisture velocity of 0.7 inches/month will be used. Calculations use a slab length of 40 feet, with 10-inch wide beams spaced at 12 feet on-center. The resulting e_m, soil suction and y_m values can be compared in Table 1.

Table 1
Comparison of Design Parameters for Different Values of I_m

Condition	Thornthwaite Index	Suction pF	Edge Moisture Variation Distance (Em, feet)	Soil Movement (Ym, in.)	Estimated Beam Depth (in.)
Center Lift	0	3.4	4.0	0.97	18
Edge Lift	0	3.4	5.0	0.48	09
Center Lift	-10	3.6	6.0	4.59	30
Edge Lift	+20	3.6	5.0	1.36	29

As can be seen from this comparison, the value of I_m can significantly affect the structural design of the slab.

CASE STUDIES

General

Two case studies are presented. The first is to illustrate that the "edge" lift values obtained from Appendix A.3 can be low by a significant value compared to the magnitude of differential movement in the "edge" lift condition. The second study illustrates the influence of the revised procedure for evaluation of I_m on the design of slab foundations. Both cases are from residential subdivisions where significant claims regarding distress were reported and investigated. The cases represent the average claim, and neither represents an isolated occurrence.

A rigorous structural analysis was not performed to evaluate the exact beam depth. In general, required beam depths were calculated based on a computer model incorporating the design formulas recommended in the PTI manual.

It should be noted that the depth to constant suction used for analysis is seven feet. This depth was used because it represents the maximum depth in Appendix A.3. It is the writers' opinion that, in some formations and locations, the seven-foot depth is not applicable. Debate of this issue is left for future papers.

Case 1, Carrollton, Texas

This case consists of a two-story residence within Carrollton, Texas. The foundation system consists of a post-tensioned slab-on-ground reportedly designed in accordance with the PTI procedures. The residence is located within residual soils of the Eagle Ford Group. The Eagle Ford consists of a clay shale. Weathering of the shale produces a highly expansive soil.

Design movements provided by the geotechnical engineer consisted of estimated potential vertical rise of 3.25 inches and differential movement of 2.25 inches. PTI design values were not provided in the geotechnical report.

The home was constructed in the Spring of 1990 and was approximately 31 feet by 68 feet in plan dimension. A limited amount of vegetation was planted around the residence, and a sprinkler system was installed.

The foundation consisted of 10-inch wide by 24-inch deep beams spaced at approximately 11 feet on-center in both directions. Straight-shaft piers were constructed below beam intersections to limit settlement. The piers were not connected to the foundation.

By May 1992, the foundation had undergone differential movements exceeding 3.5 inches. The home owner reported severe cracking of sheetrock, mis-aligned doors and windows. There was also evidence of differential movement of the roof frame and cracks within the brick veneer. The foundation was resurveyed in December, 1992 with measured differential movement exceeding eight inches. The results of the elevation surveys are shown in Figures 8 and 9. With the exception of the garage area, there was no evidence of cracks within the slab although severe warping of the slab associated with edge lift occurred along with general tilt from the high to low side.

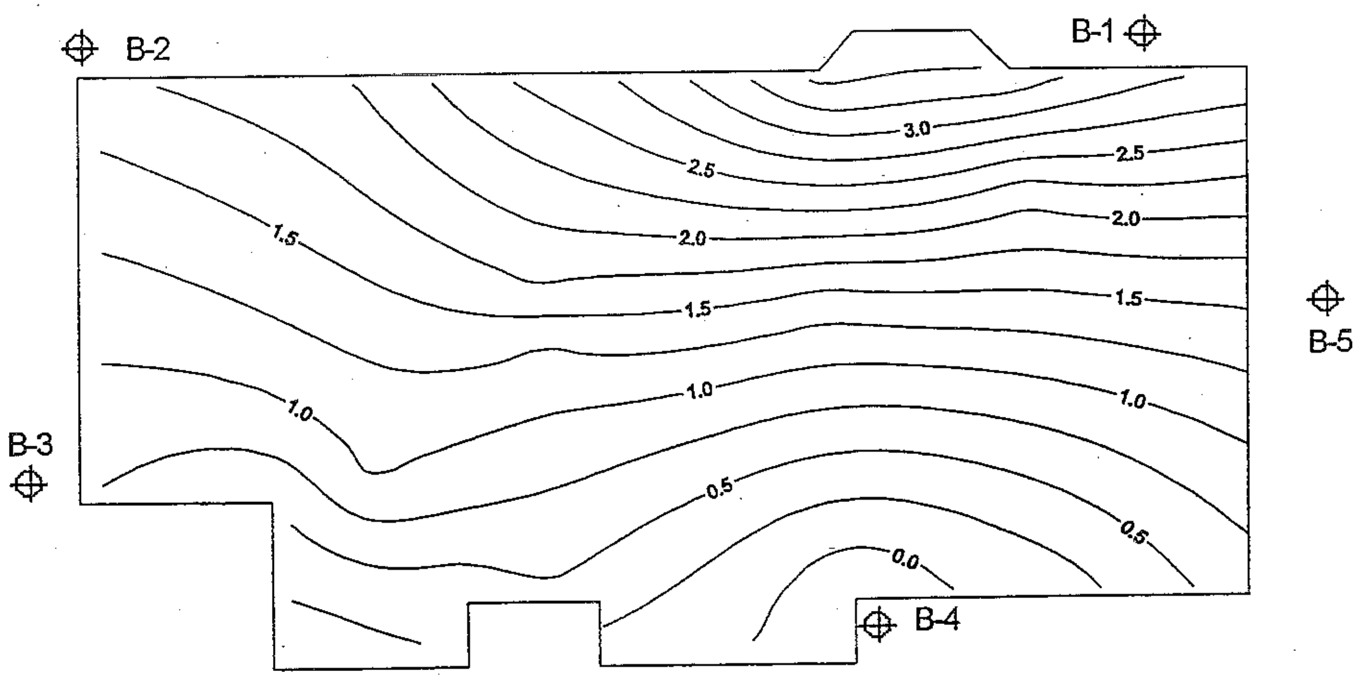


Figure 8. Case Study No. 1, Inital Relative Elevation Survey.

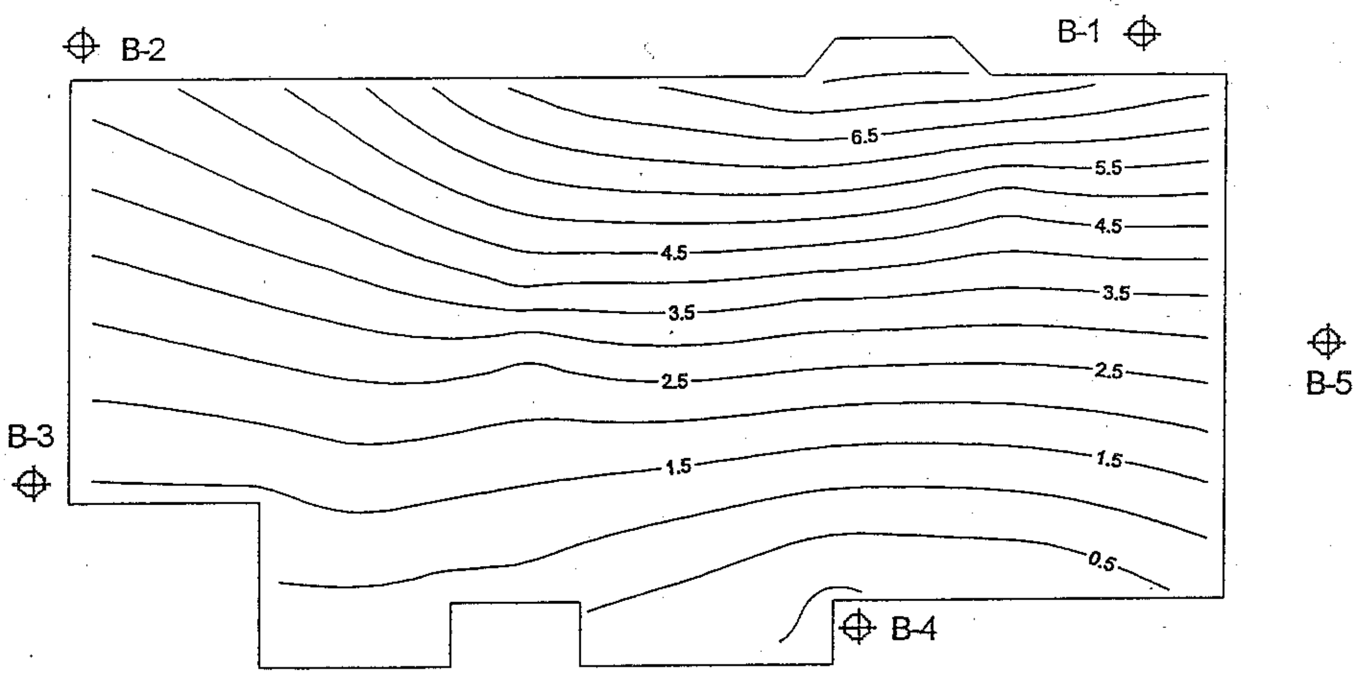


Figure 9. Case Study No. 1, Second Relative Elevation Survey.

Soil borings were performed around the residence to evaluate subsurface conditions. The location of the borings are shown on Figures 8 and 9. Tests were performed to evaluate plasticity, moisture, total suction, and absorption-pressure swell. Suction tests were performed in accordance with ASTM D-5298. Two boring logs representing the high and low side of the residence are shown in Figures 10 and 11. Moisture content, plasticity and suction are shown graphically on the logs. The range of results of eight pressure-swell tests is shown in Figure 12. Previous studies within the subdivision indicated the percent of the weathered zone finer than 2 microns was on the order of 55 to 65 percent.

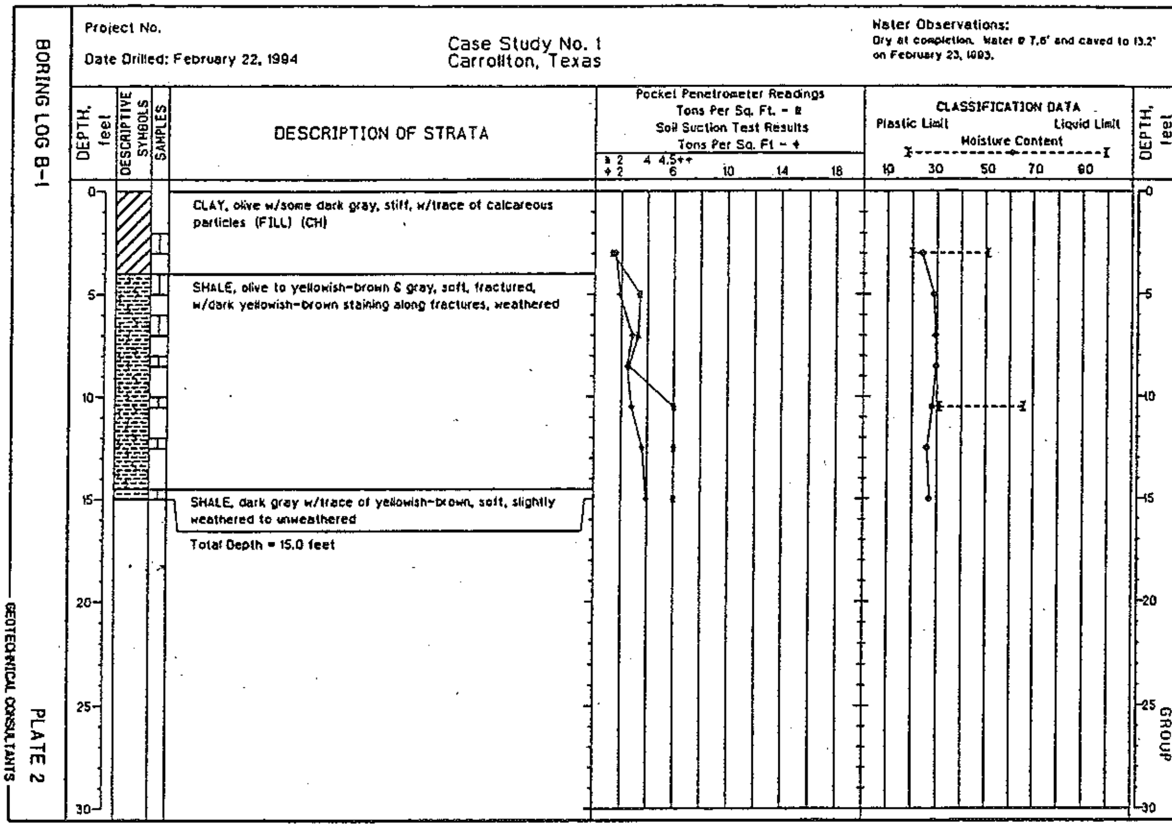


Figure 10. Case Study No. 1, Boring Log B-1.

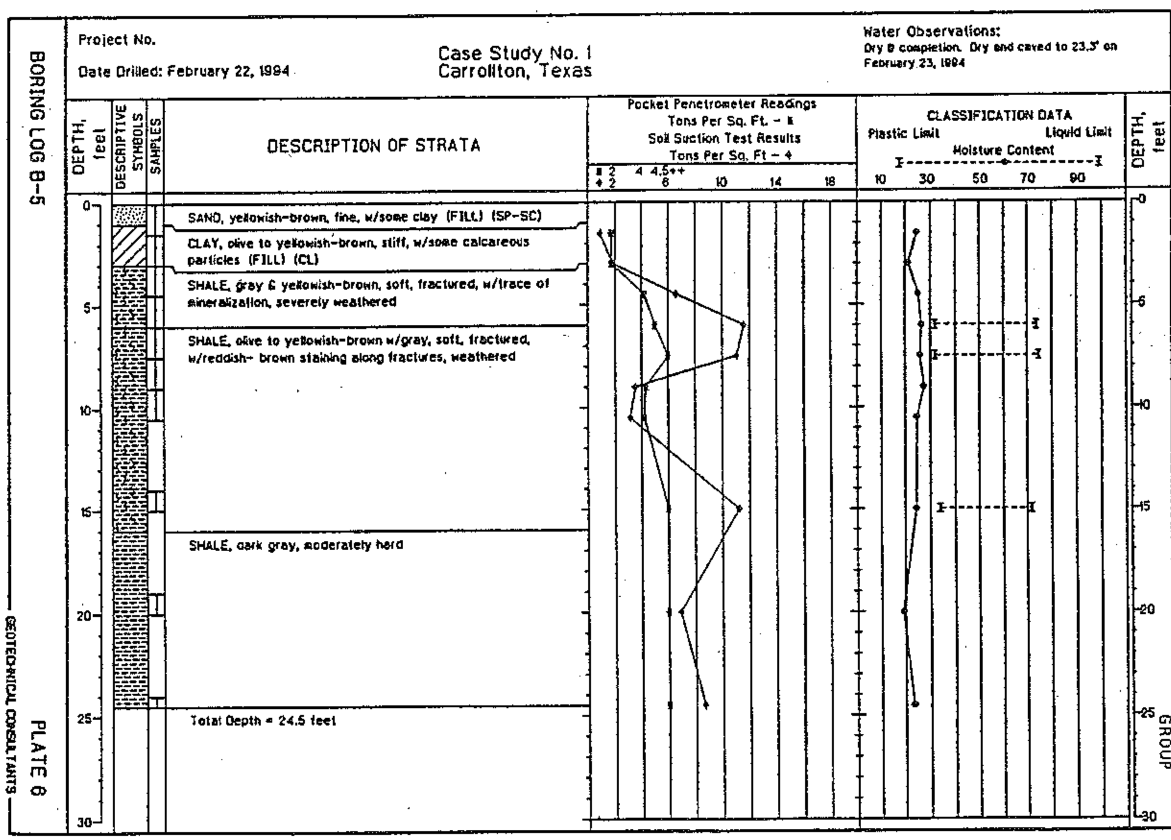


Figure 11. Case Study No. 1, Boring Log B-5.

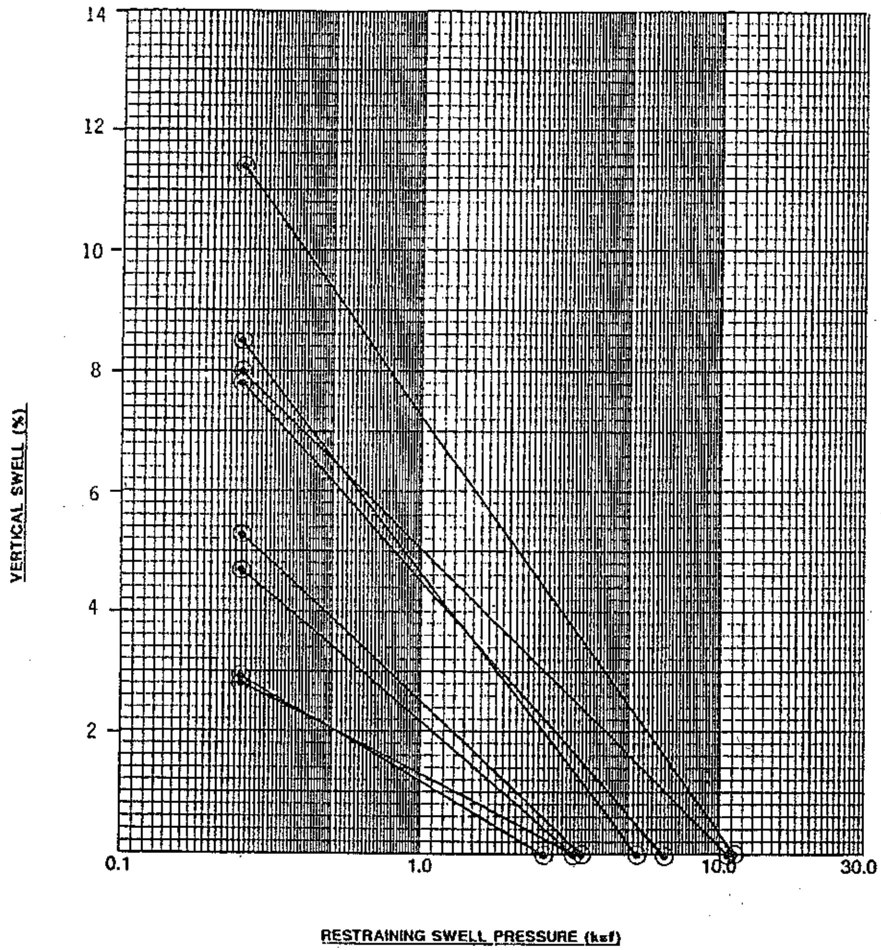


Figure 12. Case Study No. 1, Summary of Swell Tests.

Derivation of e_m using an average Thornthwaite Index of 0 and procedures presented in Appendix A.3 results in values shown in Table 2. Values of e_m are derived based on the upper curves shown in Figure 4. Design values of y_m for the center and edge lift condition obtained from Tables A.3.14 and A.3.29 of Appendix A.3 (60 percent montmorillonite, constant suction of 3.4 pF at a depth of seven feet) are also shown in Table 2. Analysis of the derived beam depth and spacing using these values is consistent with the constructed condition.

TABLE 2
e_m and y_m Using I_m Equal to 0

Mode of Movement	e_m, feet	y_m, inches
Center Lift	5.0	1.20
Edge Lift	4.0	0.60

Alternative values of e_m and y_m using a range of Thornthwaite values is provided in Table 3. I_m was varied from -10 for the center lift condition (i.e., the driest value leading to shrinkage along the perimeter) to +20 for the edge lift condition (i.e., the wettest condition leading to edge lift or heave). Analysis using the e_m and y_m values in Table 3 results in beam depths of 39 inches considering a beam spacing of 11 feet. Clearly, beam depths of 39 inches would have provided a more rigid slab.

TABLE 3

e_m and y_m Using I_m Equal to -10 and +20

Mode of Movement	e_m, feet	y_m, inches
Center Lift	6.0	5.68
Edge Lift	5.0	1.68

It can be noted from Table 3 that the design y_m for edge lift equalled 1.7 inches; however, differential movement in the edge lift condition exceeded eight inches. Resolution of this apparent conflict between observed differential movement, and "design" movements are beyond the scope of this paper. However, experience in the geologic formation has shown that beam depths between 36 and 40 inches, spaced 10 to 12 feet on-center, are capable of withstanding movement of 8 to 10 inches with limited deflection. However, tilting of the foundation of a magnitude equaling the vertical movement would have taken place. This type of movement is generally unacceptable.

Case 2, Mesquite, Texas

This case consists of a one-story residence with a post-tensioned slab. The residence is located within residual soils of the lower Ozan or Taylor Formation. The Taylor consists of a clay shale which weathers to produce a highly expansive soil. Swell pressures and potential movements within the Taylor are, in general, less severe in nature than those of the Eagle Ford.

Design movements provided to the structural engineer are not available. The foundation plan indicates beams were spaced at 10 to 14-1/2 feet along the long dimension (49 feet) and at 14-1/2 feet along the short dimension (29 feet). Beams were designed to be 10 inches wide by 26 inches deep. The perimeter beam is discontinuous along the outside garage wall.

The home was constructed in November, 1992. Vegetation around the house is relatively sparse, being concentrated at the front of the residence. Differential movements across the floor slab of 2-1/8 inches have occurred to date. Cracks are present within the brick veneer and within the sheetrock on the interior of the house. The floor slab is cracked across the garage.

The foundation exhibits movement in an edge lift condition. Differential movement between the center of the slab and edge is approximately 1-3/4 inches on the side of the residence with higher soil moisture. The elevation survey is provided in Figure 13.

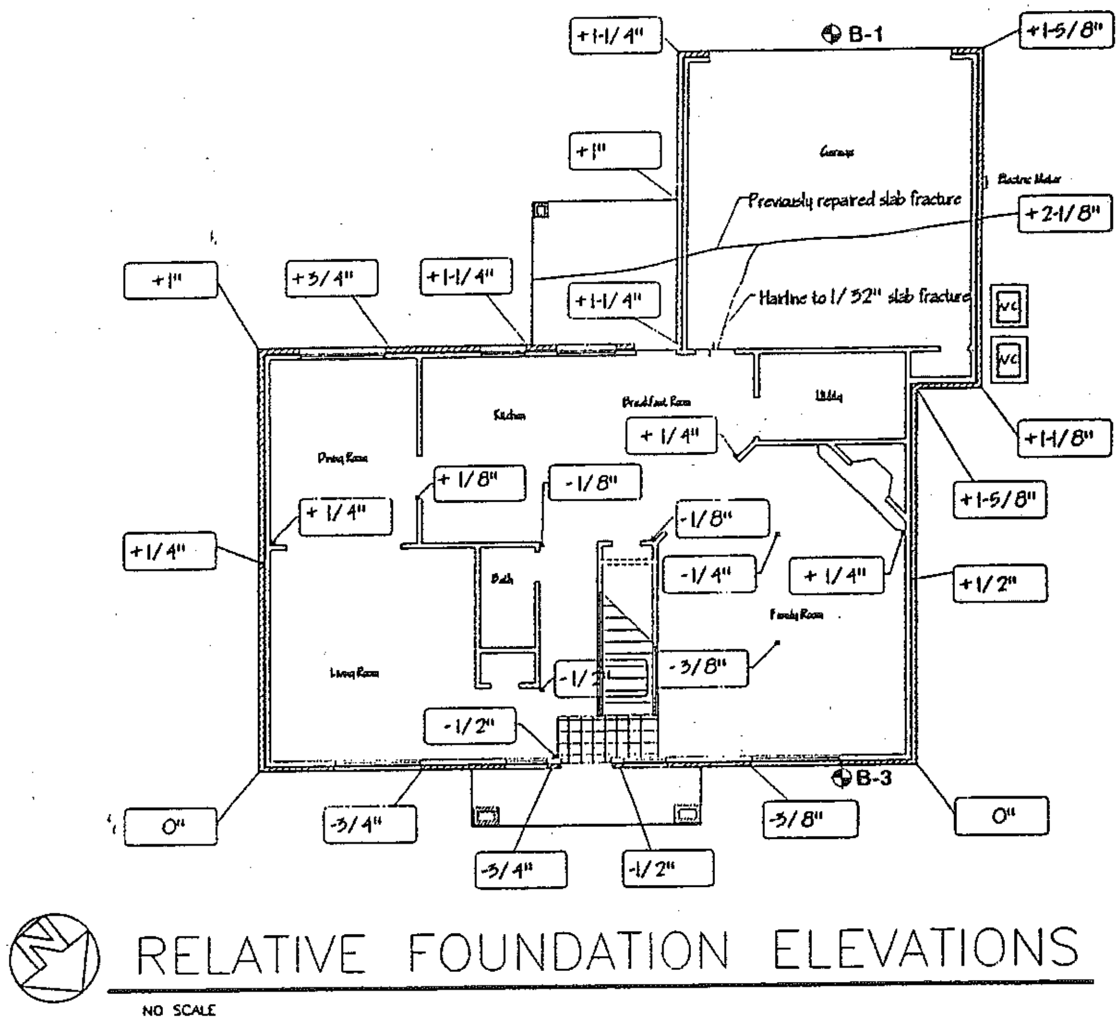


Figure 13. Case Study No. 2, Relative Elevation Survey.

Soil borings were performed around the residence to evaluate subsurface conditions. The location of the borings are shown on Figure 13. Tests were performed to evaluate plasticity, moisture, total suction, and absorption pressure-swell. Two boring logs representing the high and low sides of the house are shown in Figures 14 and 15. Moisture content, plasticity and suction are shown graphically on the logs. The range of results of five pressure-swell tests is shown in Figure 16. Hydrometer results for a neighboring subdivision indicate the percent clay is on the order of 75 percent.

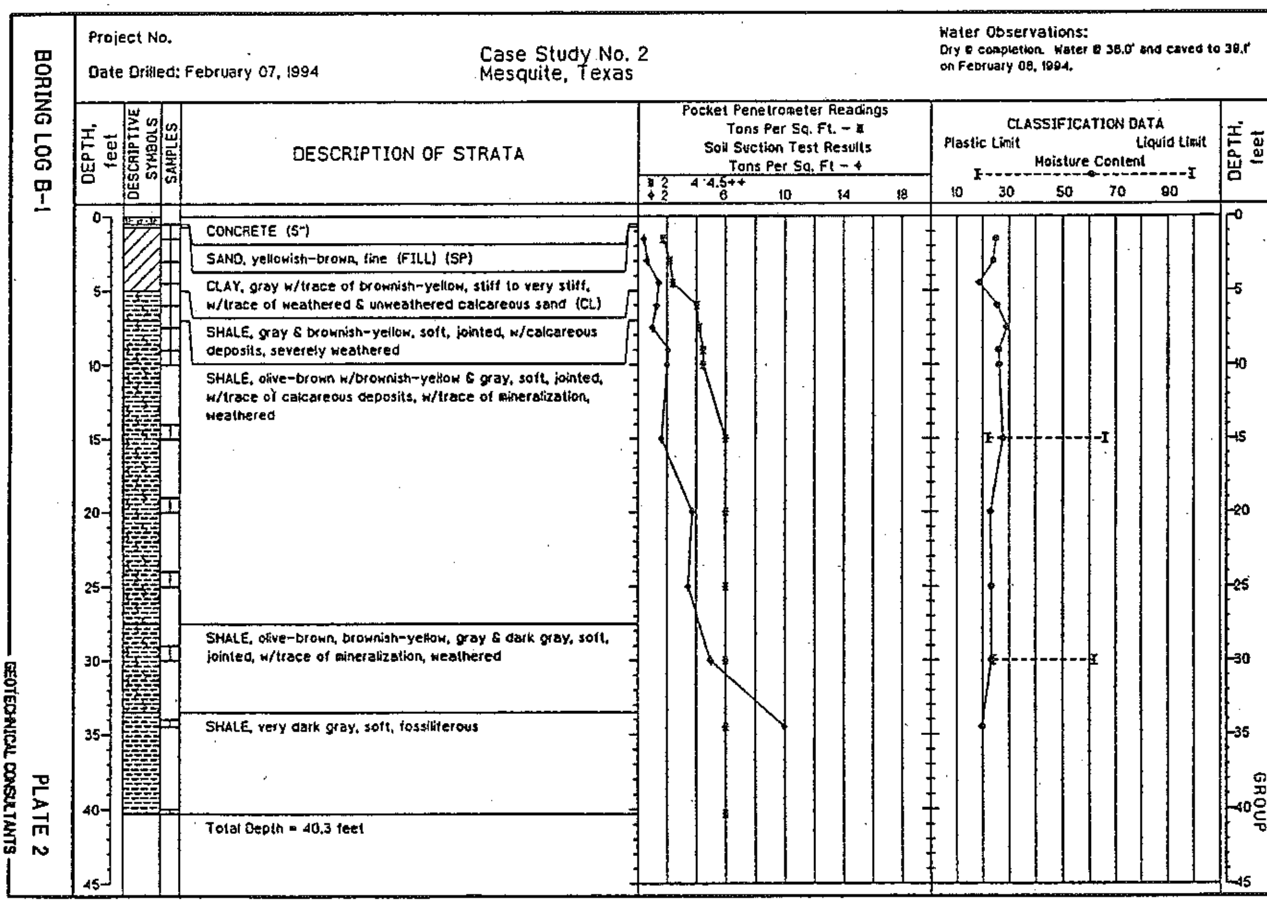


Figure 14. Case Study No. 2, Boring Log B-1.

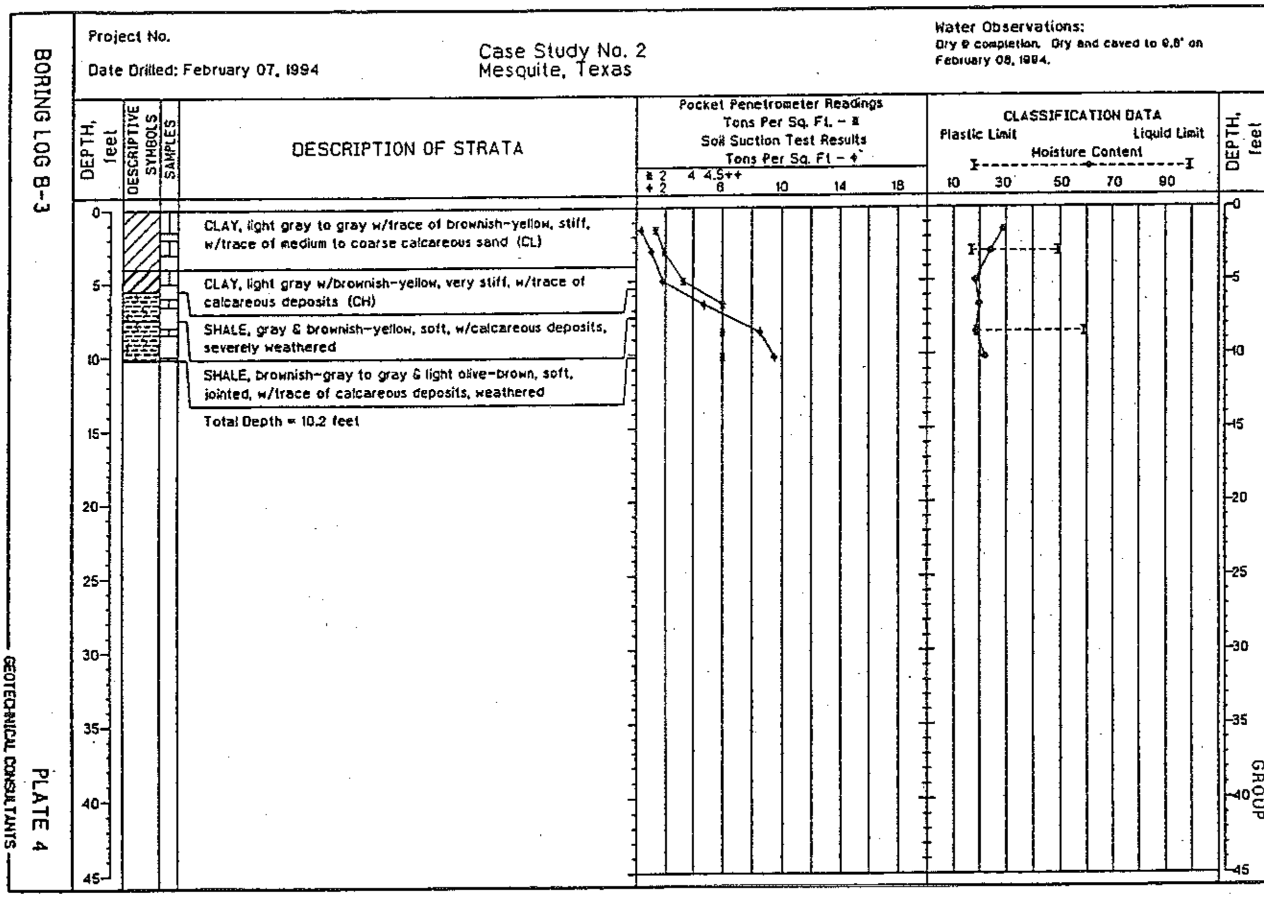


Figure 15. Case Study No. 2, Boring Log B-3.

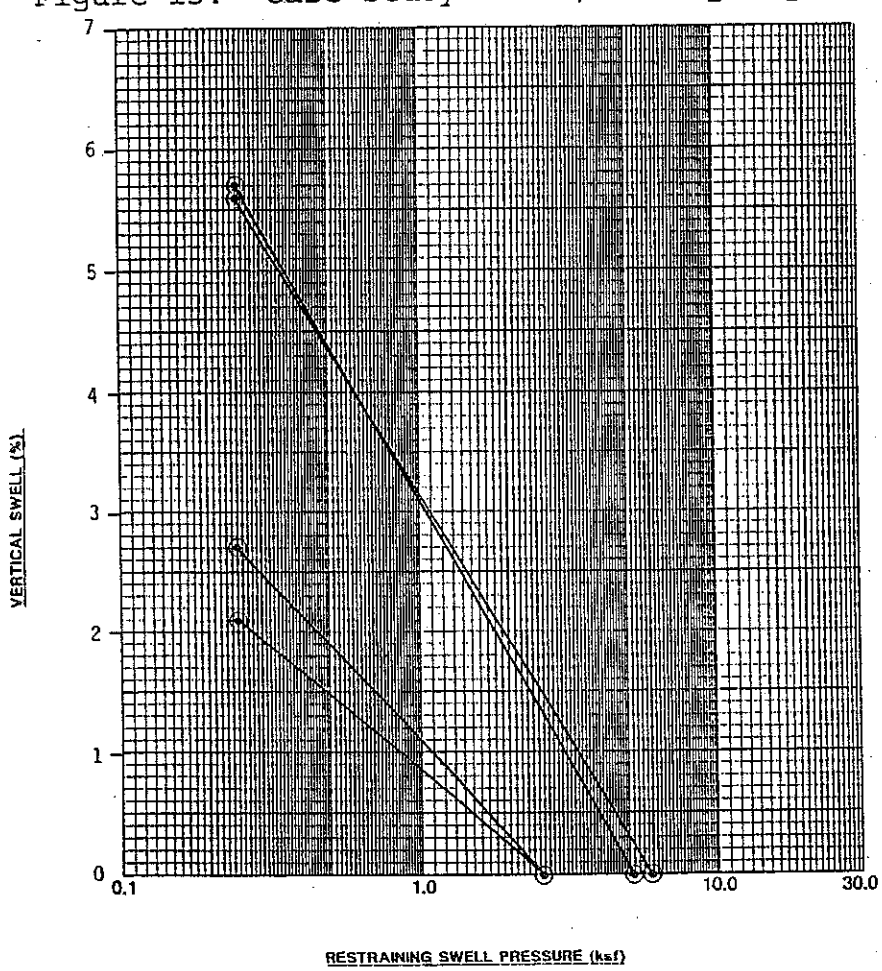


Figure 12. Case Study No. 2, Summary of Swell Tests.

The derived values of e_m and y_m for I_m of 0 are shown in Table 4. Seventy percent montmorillonite clay with a constant suction of 3.4 pF at a depth of seven feet was used in the analysis. Values of y_m are taken from Figures A.3.15 and A.3.30.

TABLE 4

e_m and y_m Using I_m Equal to 0

Mode of Movement	e_m, feet	y_m, inches
Center Lift	5.0	1.44
Edge Lift	4.0	0.71

Beam depths considering the values in Table 4 are on the order of 29 inches compared to the 26 inches actually used. Alternative values of e_m and y_m using Thornthwaite values ranging from -10 to +20 are shown in Table 5. Analysis using the e_m and y_m values in Table 5 results in beam depths of 63 inches considering a beam spacing of 14-1/2 feet. The required beam depth decreases to 37 inches for beams spaced at 12 feet on-center.

TABLE 5

e_m and y_m Using I_m Equal to -10 and +20

Mode of Movement	e_m, feet	y_m, inches
Center Lift	6.0	6.76
Edge Lift	5.0	2.00

As noted, the y_m value for edge lift is 2 inches using I_m of +20. This compares with the measured differential movement of approximately 1-3/4 inches.

CONCLUSIONS

It would appear that the range of I_m needs to be evaluated for a given locality, then "design" values covering 80, 90, or 95 percent of the range used to evaluate e_m and y_m. Using a range of I_m would result in more rigid slabs, which in turn, should result in less foundation distress during the normal variation in yearly rainfall.

Soil parameters used for the PTI analysis based on "average" Thornthwaite values can be significantly different from valued calculated.

REFERENCES

1. Post-Tensioning Institute (PTI), 1980, "Design and Construction of Post-Tensioned Slabs-On-Ground", PTI, Phoenix, Arizona.

2. Thornthwaite, C. W., "An Approach Toward a Rational Classification of Climate", 1948, Geographical Review, Vol. 38, No. 1, pp. 55-94.

3. McKeen, R. G. and Johnson, L. D., "Climate-Controlled Soil Design Parameters for Mat Foundations", 1990, ASCE, Journal of Geotechnical Engineering, Vol. 116, No. 7, pp. 1073-1094.