Impact Of Climatic Variation On Design Parameters For Slab On Ground Foundations In Expansive Soils

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Abstract

Adequate design of post-tensioned residential slab-on-ground foundations in expansive soils is dependent on understanding the geotechnical and climatic factors inherent to the procedure. A method for design of ground-supported slab foundations was developed by the Post-Tensioning Institute (PTI). The design stiffness factors (edge moisture variation distance, e_m, and differential movement, y_m) are derived in part based on the average Thornthwaite Climatic Index, I_m, for the design area.

The purpose of this paper is to show, by case study, the importance of changes in water balance as measured by the I_m on expansive soil behavior and in particular to the PTI design stiffness parameters, e_m and y_m.

Surveyed differential movements of post-tensioned foundations in two expansive clay formations in the North Texas region, where average I_m, not including the influence of irrigation, is 0, are provided. Data is presented to illustrate that use of the average I_m value results in slab foundations that are under-designed. Re-calculation of the published average I_m value for the design area is recommended to account for changes in water balance caused by development, for example the increase in I_m from landscape watering or extreme dry periods.

The case histories show that the PTI values for e_m and y_m, using the re-calculated I_m, are in closer agreement with observed differential movement. The

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studies also show that PTI y_m values derived using average Thornthwaite values can be in error by 100 percent or more.

Introduction

Current industry practice in design of post-tensioned slab foundations is heavily dependent upon application of procedures presented in the PTI manual "Design and Construction of Post-Tensioned Slab-on-Ground" (1980). Included in the manual is Appendix A.3, which outlines procedures for developing soil design parameters used in the PTI analysis. Although the PTI method significantly advanced the art of engineering for slabs-on-ground when introduced in the early 1980's, Appendix A.3 contains data and recommendations that need to be more critically evaluated than currently practiced by the engineering community. Specifically, this paper discusses derivation of the Thornthwaite Climatic Index, I_m, and its 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 is shown in Figure 1. Appendix A.3 of the manual presents a means of deriving e_m and y_m for both the edge lift and center lift condition of movement.

Appendix A.3 contains various figures and tables for development of e_m and y_m. Required input is the type and amount of clay. The designer can then proceed through Appendix A.3 and derive the design values. This odyssey begins with a map of the United States or Texas that plots average Thornthwaite values. The map of Texas 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.

Analysis of Figures 3 and 4 indicates the reliance of the PTI method on the Thornthwaite Climatic 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 The Dallas/Fort Worth Region

The Thornthwaite Climatic Index, I_m, is an empirical method developed by C.W. Thornthwaite (1948) to classify climates. The method basically compares potential evapotranspiration and precipitation on a yearly basis, and then averages the values to arrive at a climatic rating. Positive values of I_m indicate humid climates. Negative values represent sub-humid 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 the potential range of values. Focusing on the Dallas area, Fig. A.3.3 of the PTI manual (Figure 2) suggests an I_m of zero centimeters (cm) (0 inches).

Calculation of the I_m was made for the Dallas area for the last 60 years using procedures presented by McKeen and Johnson (1990). The results of the calculations from 1955 to 1973 are presented in Figure 6. While the average does indeed fall around zero cm (-0.95 inch), the extremes range from -33 to 45 cm (-13 to +18 inches), with the positive extreme of 45 cm (+18 inches) occurring in 1957 with 140.1 cm (55.14 inches) of rainfall. This range is consistent with that reported by Thornthwaite.

As can be seen in Figure 6, 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 increases the “average” calculated I_m. Irrigation in the Dallas area can add the equivalent of 5 cm of rainfall per month for the five winter months and 10 cm per month for the remaining portion of the year. Results of the effect of irrigation on the calculated I_m are presented in Figure 7.

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 I_m 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 -25.4, 0 and +50.8 cm (-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, values typical of the Dallas area. The maximum depth to constant suction (2.1 meters or 7 feet) will be used in the analysis. The maximum moisture velocity of 1.8 cm/month (0.7 inches/month) will be used. Calculations used a slab length of 12.2 meters (40 feet), with 25.4-cm (10-inch) wide beams spaced at 3.7 meters (12 feet) on-center. The resulting e_m, soil suction and y_m values can be compared in Table 1.

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

Case Studies

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 foundation. 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 required beam depth. In general, beam depths were calculated based on a computer model incorporating the design formulas recommended in the PTI manual. Input variables include perimeter line and floor load; slab length; beam spacing and width; e_m; y_m; and allowable deflection. Output includes perimeter load and beam depth for each lift condition.

It should be noted that the depth to constant suction used for analysis is 2.1 meters (7 feet). This depth was used because it represents the maximum depth in Appendix A.3.

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. Chemical weathering of the shale produces a highly expansive soil. The weathered profile at this site extends to a depth of 16 feet, below which unweathered shale is present.

Design movements provided by the geotechnical engineer consisted of estimated potential vertical rise of 8.26 cm (3.25 inches) and differential movement of 5.72 cm (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 9.4 meters (31 feet) by 20.7 meters (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 25.4-cm (10-inch) wide by 61-cm (24-inch) deep beams spaced at approximately 3.35 meters (11 feet) on-center in both directions.

By May 1992, the foundation had undergone differential movements exceeding 8.9 cm (3.5 inches). The home owner reported severe cracking of sheetrock and 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 re-surveyed in December 1992, with measured differential movement exceeding 20.3 cm (8 inches). The results of the respective 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.

Soil borings were performed around the residence to evaluate subsurface conditions. The location of the borings is shown in Figure 8. Tests were performed to evaluate plasticity, moisture, total suction and constant volume absorption-pressure swell. Constant volume swell tests were performed in accordance with procedures outlined by Johnson and Snethen (1978). 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 nine pressure-swell tests is shown in Figure 12. Previous studies within the subdivision indicated the percent of the weathered zone finer than 2 microns varied from approximately 55 to 65 percent. Based on Activity Ratio (A_c) and Cation Exchange Activity (CEA_c), the clay type was a mixture, falling in the "interstratified" area of Fig. A.3.5 of the PTI manual. The montmorillonite tables were therefore used to determine design values.

Derivation of e_m, using an average I_m of 0 and procedures presented in Appendix A.3, results in the PTI design 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 5140 kPa (3.4 pF) at a depth of 2.1 meters (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.

Alternative values of e_m and y_m using a range of Thornthwaite values are provided in Table 3. I_m was varied from -25.4 cm (-10 inches) for the center lift condition (i.e., the driest value leading to shrinkage along the perimeter) to +50.8 cm (20 inches) for the edge lift condition (i.e., the average I_m, including the influence of irrigation leading to edge lift or heave). Analysis using the e_m and y_m values in Table 3 results in beam depths of 99 cm (39 inches), considering a beam spacing of 3.35 meters (11 feet). Clearly, beam depths of 99 cm (39 inches) would have provided a more rigid slab.

It can be noted from Table 3 that the design y_m for edge lift equaled 4.3 cm (1.7 inches); however, differential movement in the edge lift condition exceeded 20.3 cm (8 inches). Resolution of this apparent conflict between observed differential movement and "design" movements is beyond the scope of this paper. However, experience in the geologic formation has shown that beam depths between 91.4 and 101.6 cm (36 and 40 inches), spaced 3.05 to 3.7 meters (10 to 12 feet) on-center, are capable of withstanding movement of 20.3 to 25.4 cm (8 to 10 inches) with limited deflection. However, tilting of the foundation of a magnitude equaling the vertical movement would have taken place. Tilt of this magnitude 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 Formation tends to be more calcareous, however, than the Eagle Ford

Formation, and swell pressures and potential movements within the Taylor Formation 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 3.05 to 4.42 meters (10 to 14-1/2 feet) along the long dimension (14.9 meters or 49 feet) and at 4.42 meters (14-1/2 feet) along the short dimension (8.84 meters or 29 feet). Beams were designed to be 25.4 cm (10 inches) wide by 66 cm (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 7.6 cm (3 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 4.4 cm (1-3/4 inches) on the side of the residence with higher soil moisture. The elevation survey is provided in Figure 13.

Soil borings were performed around the residence to evaluate subsurface conditions. The location of the borings is 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 four pressure-swell tests is shown in Figure 16. Hydrometer results indicate the percent clay is on the order of 75 percent.

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 5140 kPa (3.4 pF) at a depth of 2.1 meters (seven feet) was used in the analysis. Values of y_m are taken from Figures A.3.15 and A.3.30.

Design beam depths considering the values in Table 4 are on the order of 74 cm (29 inches) compared to the 66 cm (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 160 cm (63 inches), considering a beam spacing of 4.4 meters (14-1/2 feet). The required beam depth decreases to 94 cm (37 inches) for beams spaced at 3.65 meters (12 feet) on-center.

As noted, the y_m value for edge lift is 5 cm (2 inches) using I_m of +50.8 cm (+20 inches). This compares with the measured differential movement of approximately 4.4 cm (1-3/4 inches).

Conclusions

It would appear that the range of I_m needs to be evaluated for a given locality to include the influence of irrigation, and 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 values calculated using a site-specific I_m, where I_m is calculated to include the influence of vegetation.

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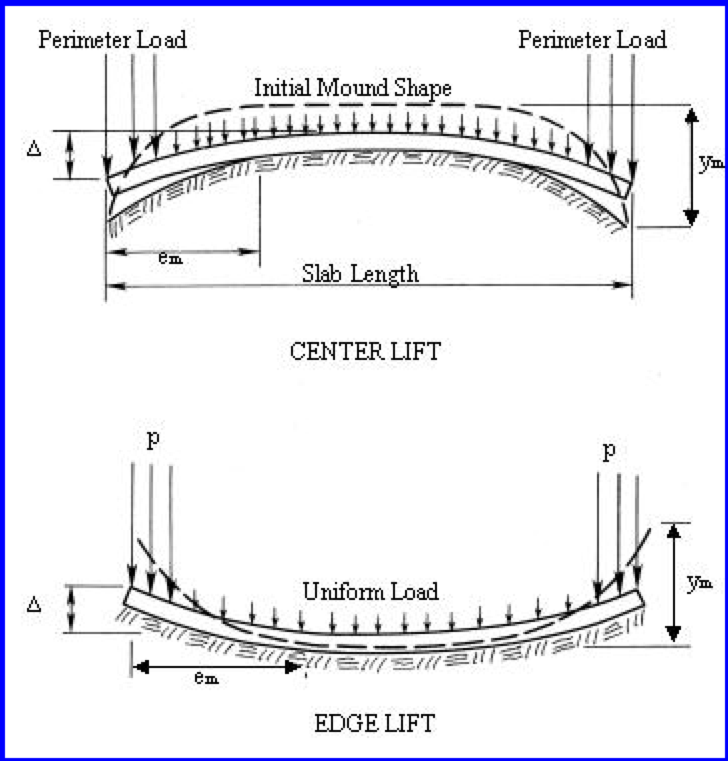

Figure 1. Illustration of "Edge" and "Center" Lift

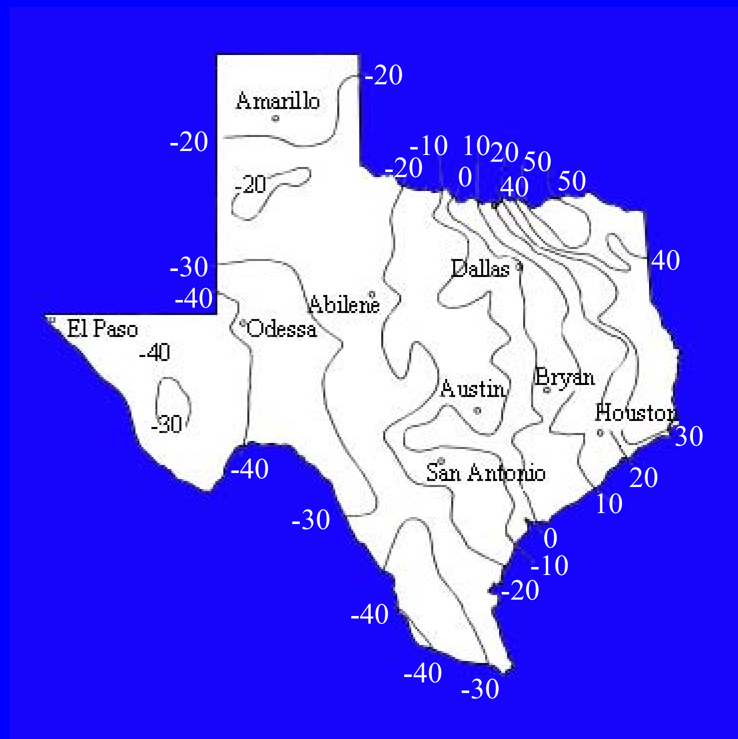

Figure 2. Average Values of the Thornthwaite Index for Texas.

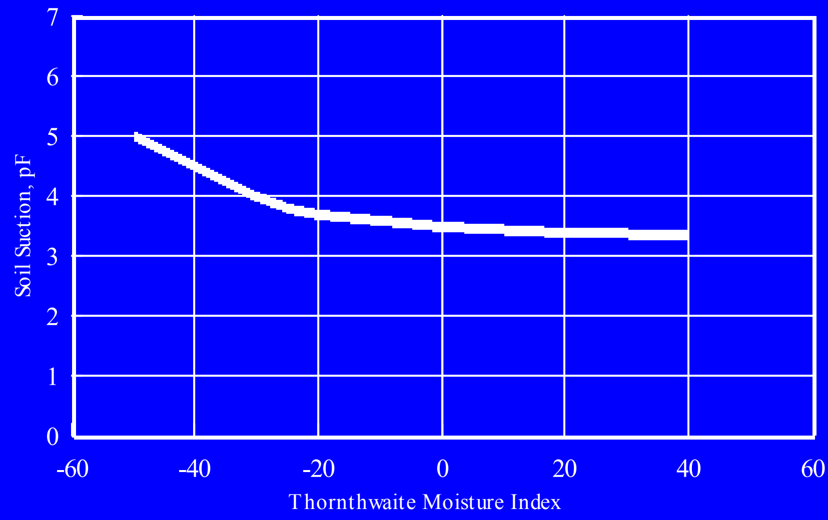

Figure 3. Values of Constant Suction

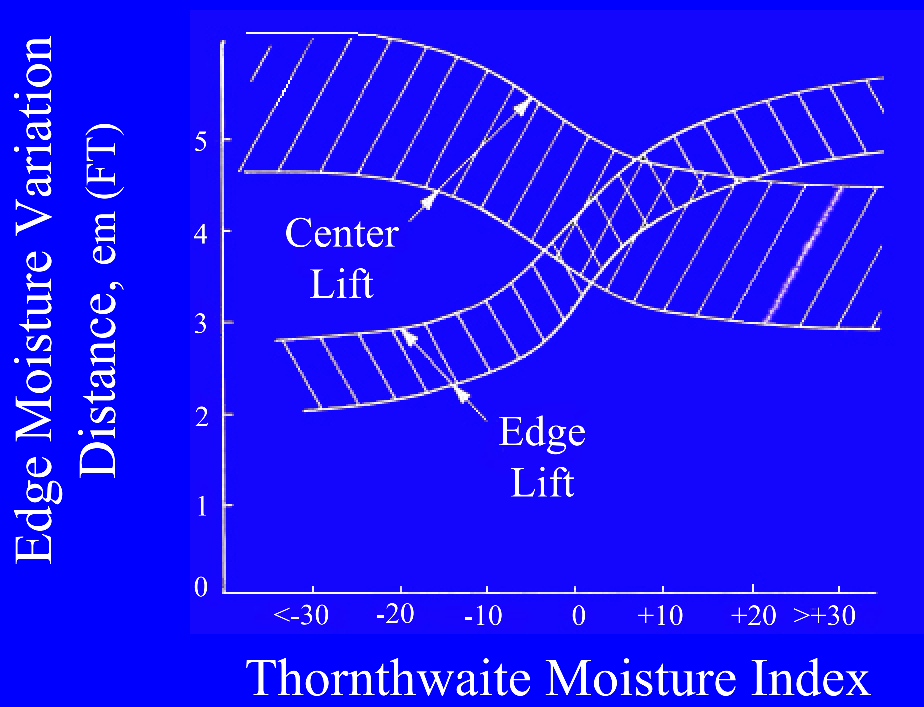

Figure 4. Edge Moisture Variation Distance em

Percent Clay (%) 1	Depth to Constant Suction (m) 2	Constant Suction (kPa) 3	Velocity of Moisture Flow (cm/ month) 4	Differential Swell (centimeters) Edge Distance Penetration (m)							
				1 m 5	2 m 6	3 m 7	4 m 8	5 m 9	6 m 10	7 m 11	8 m 12
40	2.1	3240	1.3	0.081	0.161	0.239	0.318	0.396	0.471	0.547	0.62
			1.8	0.113	0.224	0.335	0.444	0.547	0.65	0.753	0.854
		5140	1.3	0.176	0.348	0.514	0.675	0.832	0.985	1.134	1.28
			1.8	0.247	0.484	0.713	0.93	1.142	1.346	1.545	1.736
		8150	1.3	0.444	0.857	1.242	1.605	1.945	2.271	2.578	2.873
			1.8	0.625	1.189	1.704	2.177	2.621	3.034	3.422	3.79

Percent Clay (%) 1	Depth Constant Suction (ft) 2	Constant Suction (pF) 3	Velocity of Moisture Flow (in/ month) 4	Differential Swell (inches) Edge Distance Penetration (ft)							
				1 ft 5	2 ft 6	3 ft 7	4 ft 8	5 ft 9	6 ft 10	7 ft 11	8 ft 12
40	7	3.2	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	0.5	0.07	0.138	0.204	0.268	0.33	0.391	0.45	0.508
			0.7	0.098	0.192	0.283	0.369	0.453	0.534	0.613	0.689
		3.6	0.5	0.716	0.34	0.493	0.637	0.772	0.901	1.023	1.14
			0.7	0.248	0.472	0.676	0.864	1.04	1.204	1.358	1.504

Figure 5. Typical Design Table for y_m

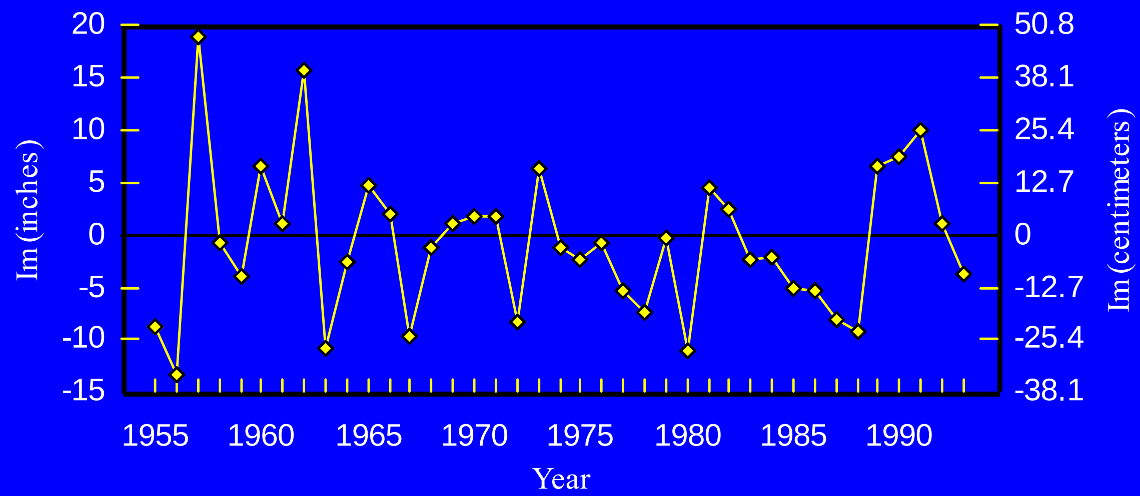

Figure 6. Variation in Thornthwaite Index, I_M
Dallas/Fort Worth from 1955-1993

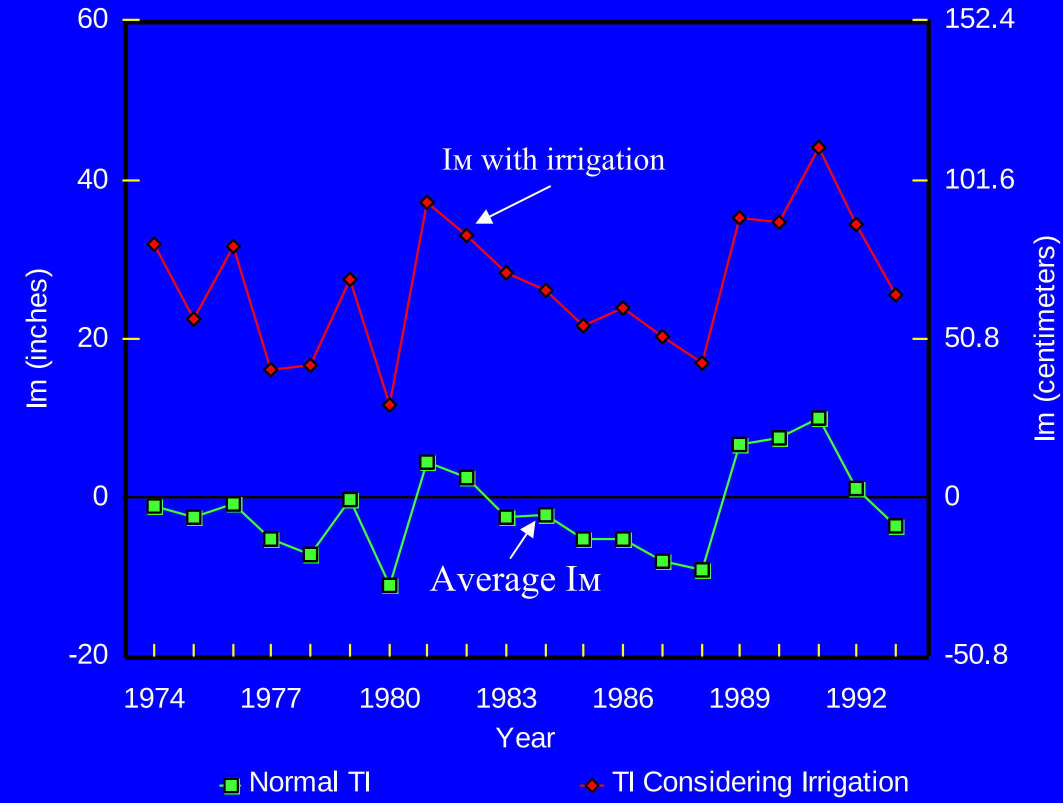

Figure 7. Variation of Thornthwaite Index, Iм
D/FW Airport, 1974 - 1993

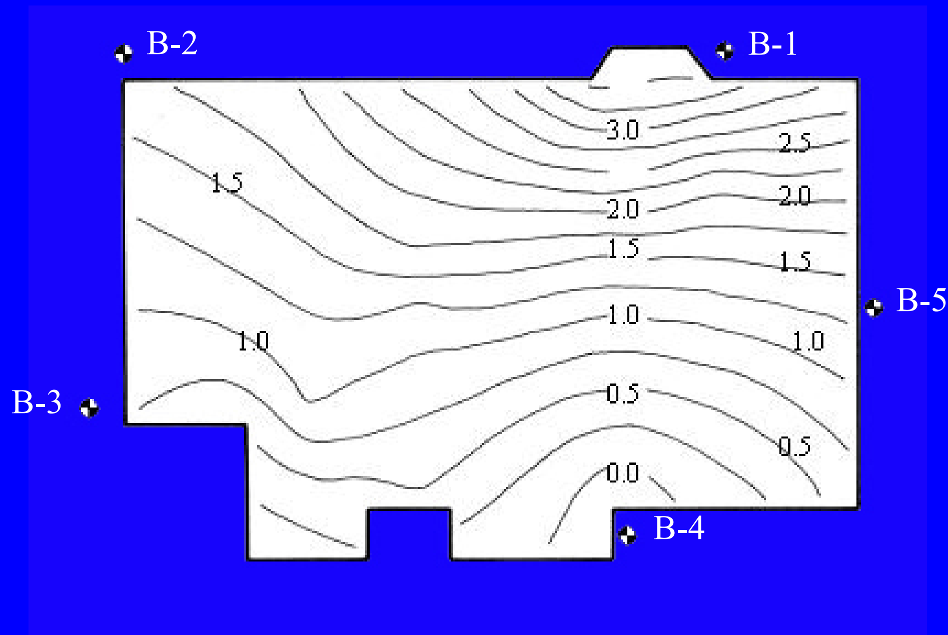

Figure 8. Case Study No. 1, Initial Relative Elevation Survey

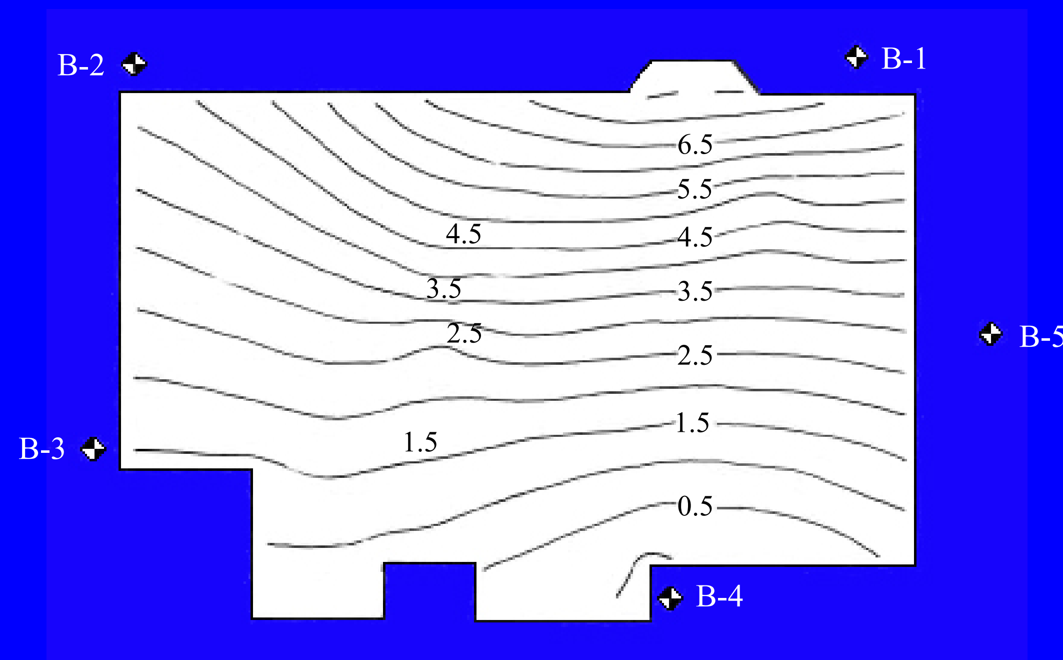

Figure 9. Case Study No. 1, Second Relative Elevation Survey

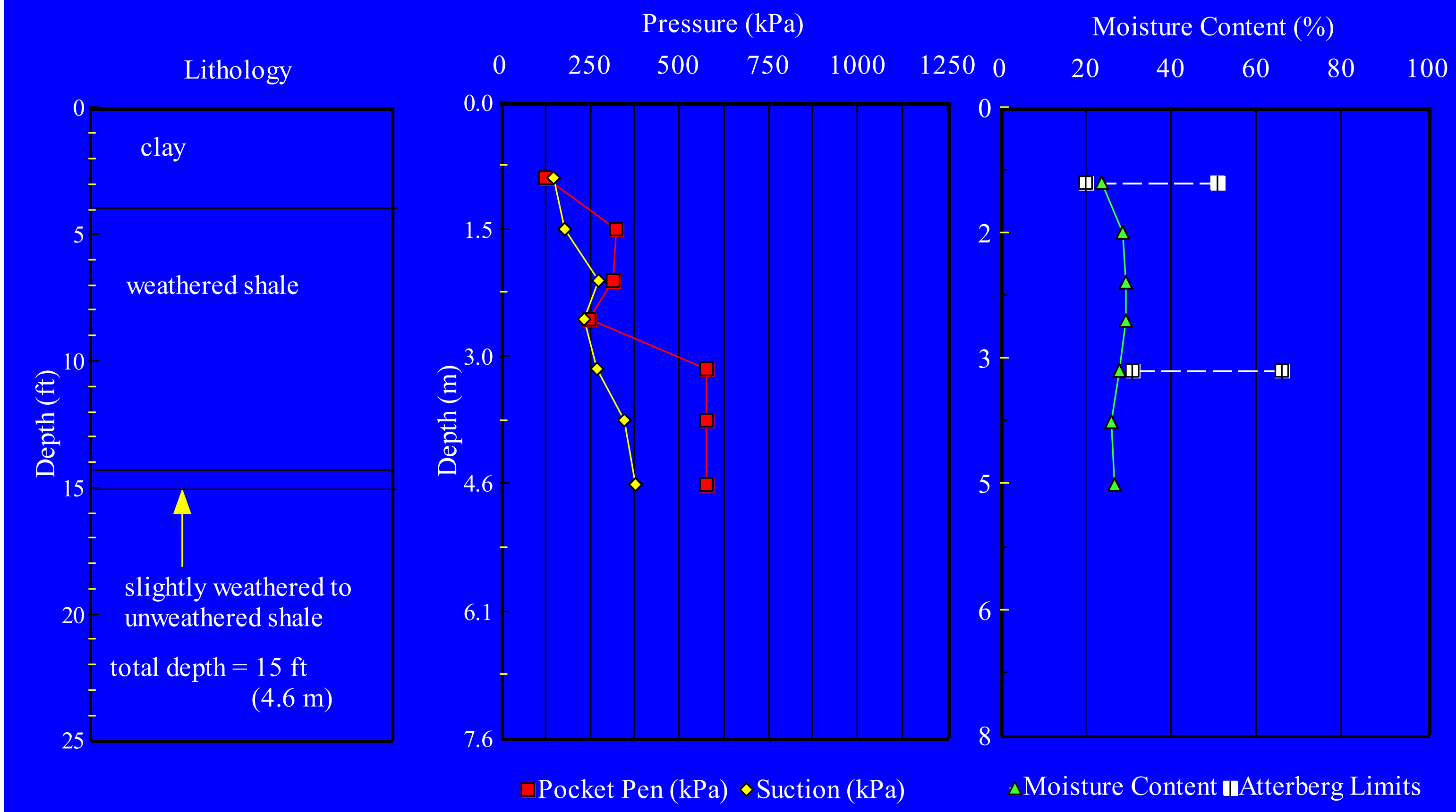

Figure 10. Case Study No. 1, Boring Log B-1.

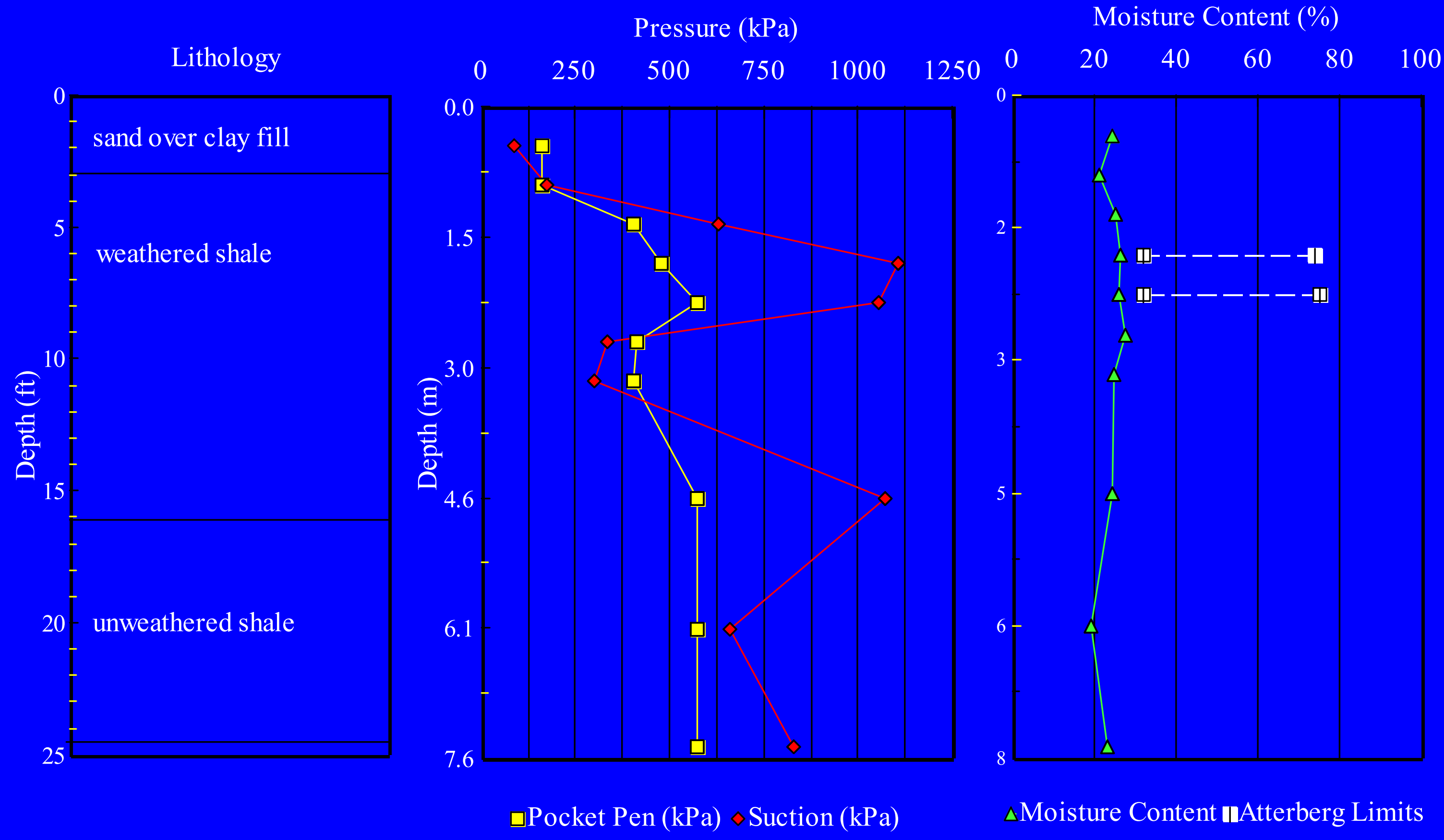

Figure 11. Case Study No. 1, Boring Log B-5

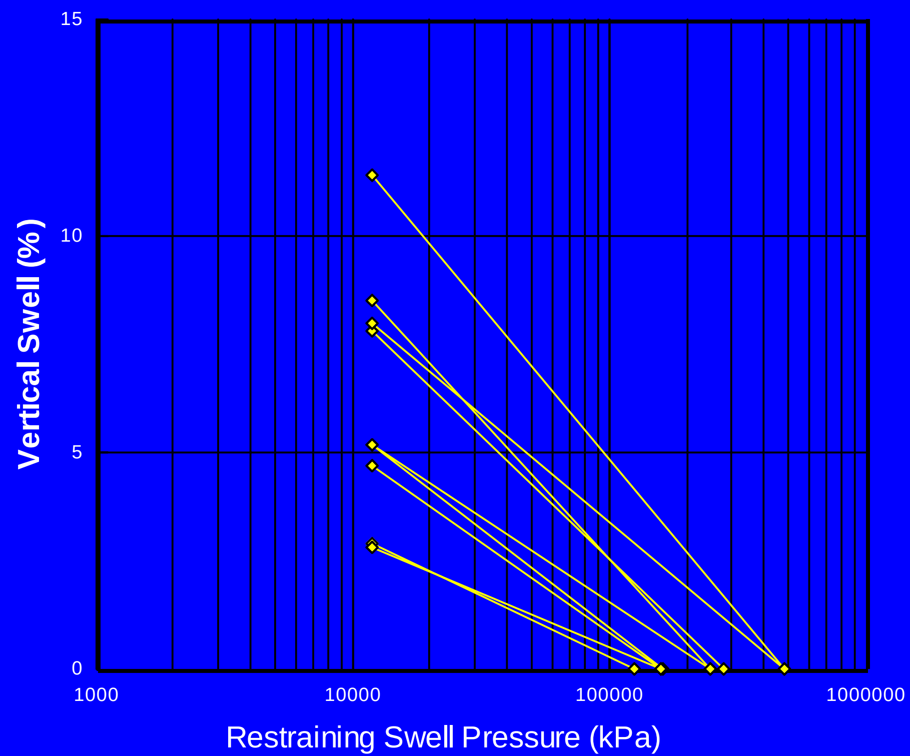

Figure 12. Cast Study No. 1, Summary of Swell Tests

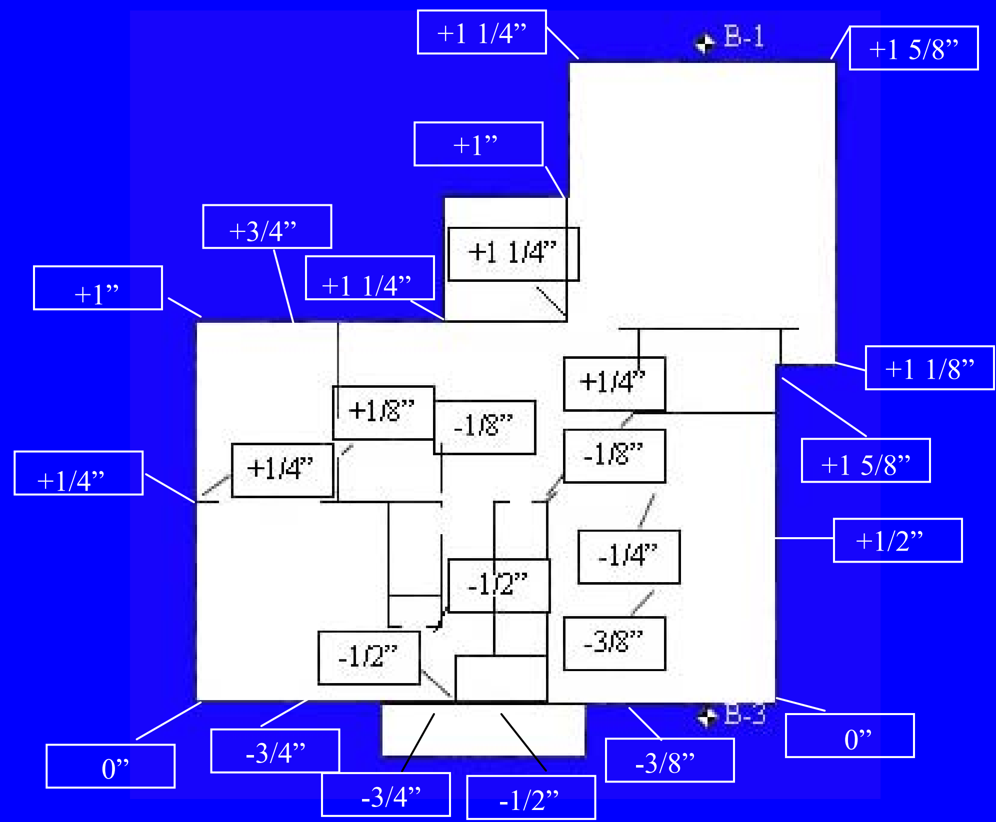

Figure 13. Case Study No. 2, Relative Elevation Survey

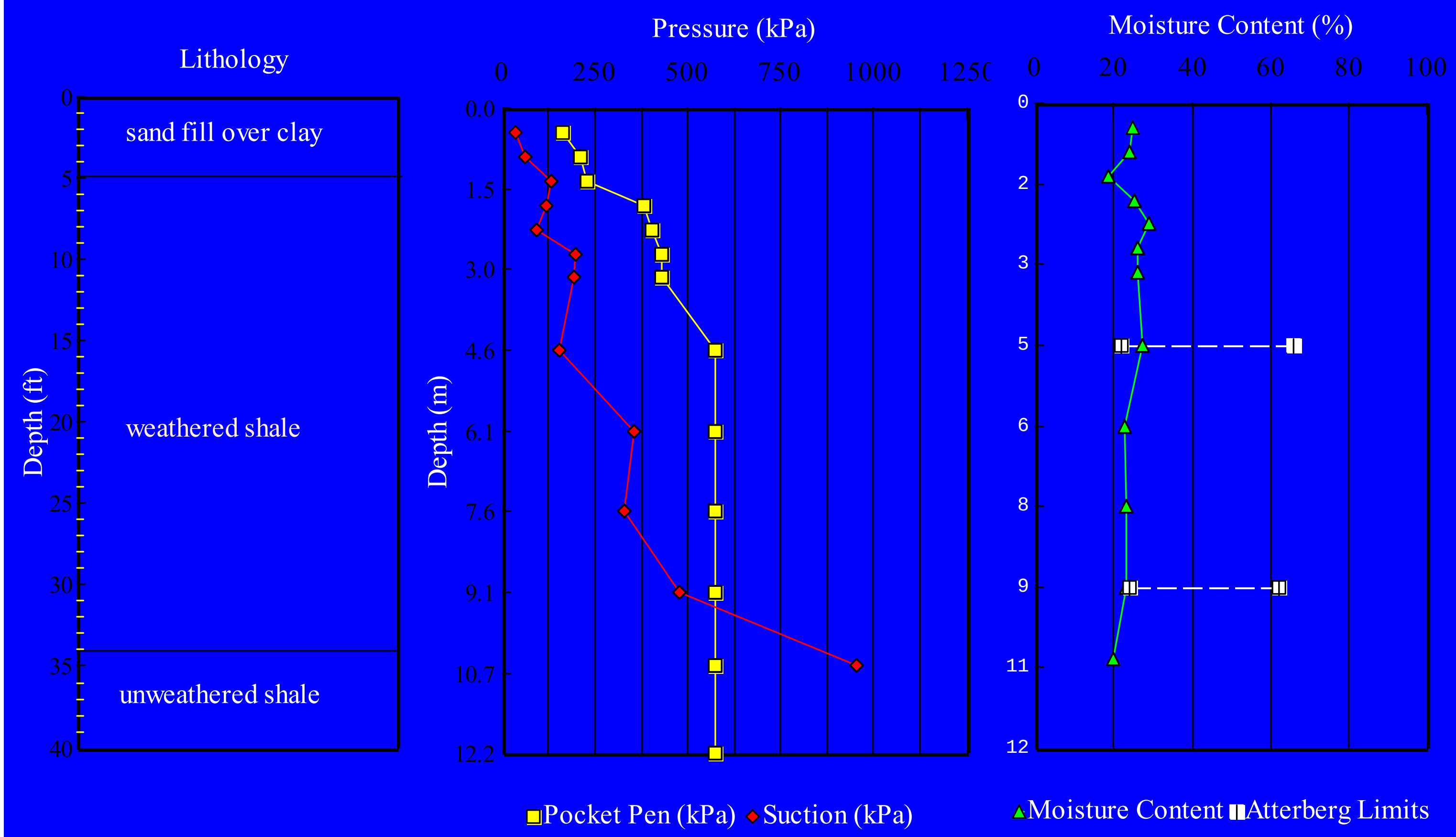

Figure 14. Case Study No. 2, Boring Log B-1

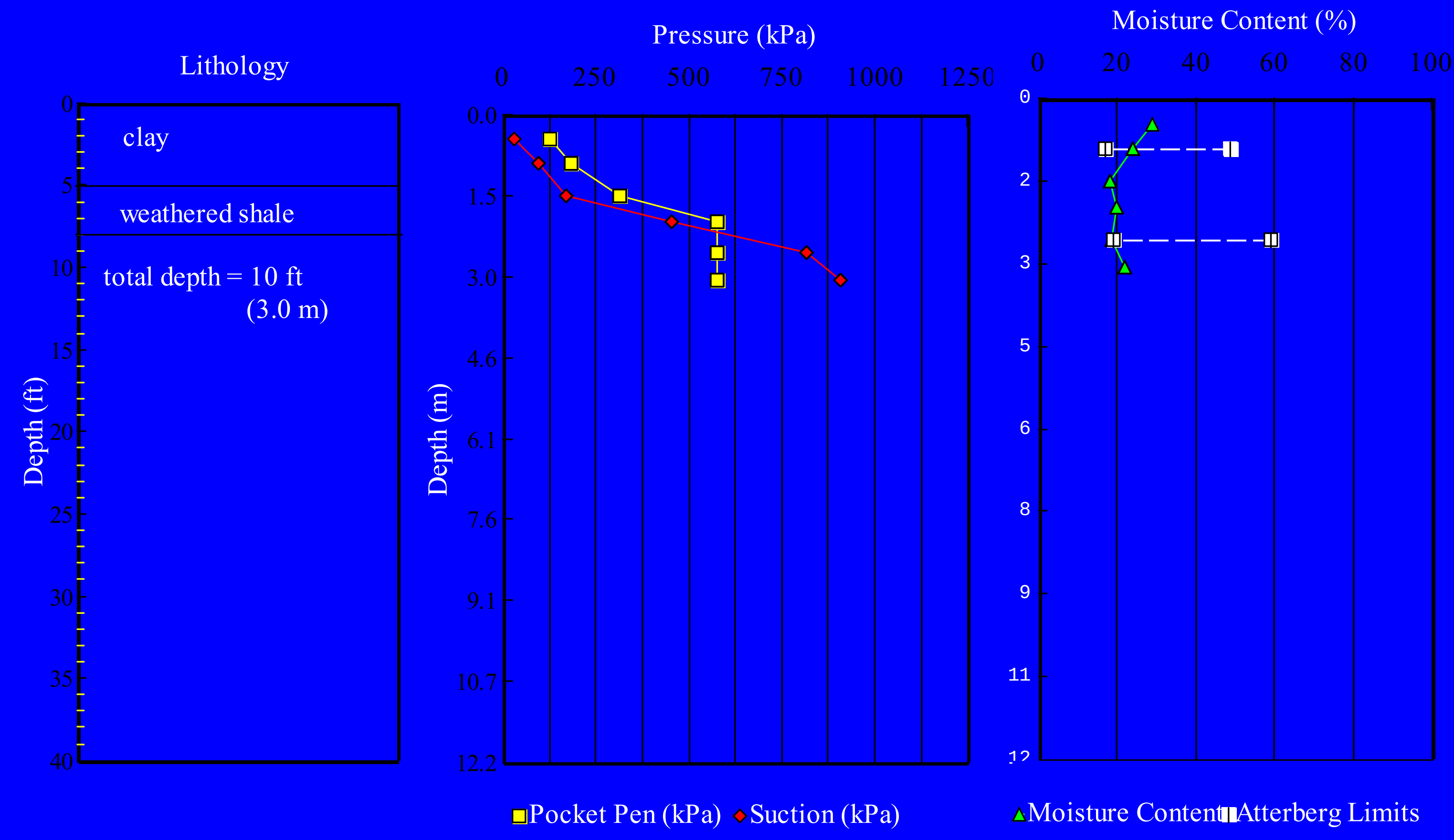

Figure 15. Case Study No. 2, Boring Log B-3

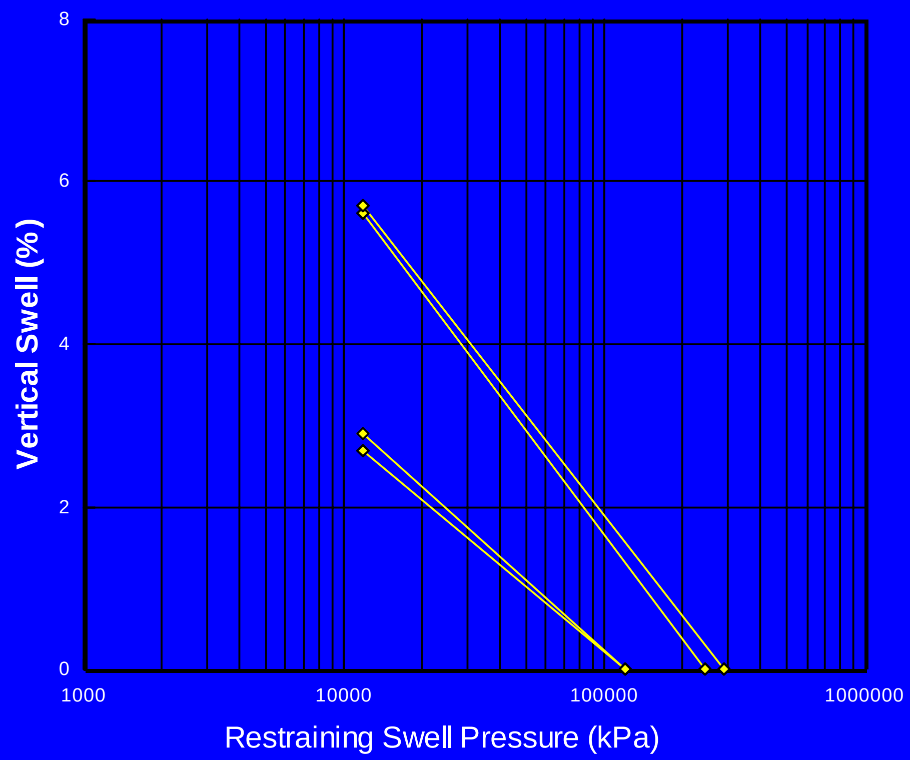

Figure 16. Case Study No. 2, Summary of Swell Tests

Condition 1	Thornth- waite waite Index 2	Suction pF 3	Edge Moisture Variation Distance (Em) 4	Soil Movement (Ym) 5	Estimated Beam Depth 6
Center Lift	0 cm 0 in	3.4	1.2 m 4.0 ft	2.46 cm 0.97 in	46 cm 18 in
Edge Lift	0 cm 0 in	3.4	1.5 m 5.0 ft	1.22 cm 0.48 in	23 cm 09 in
Center Lift	-10	3.6	1.8 m 6.0 ft	11.66 cm 4.59 in	76 cm 30 in
Edge Lift	20	3.6	1.5 m 5.0 ft	3.45 cm 1.36 in	74 cm 29 in

Table 1. Comparison of Design Parameters of Different Values of I_M

Mode of Movement	em		ym	
	meters	feet	cm	inches
Center Lift	1.5	5	3.04	1.2
Edge Lift	1.2	4	1.52	0.6

Table 2. e_m and y_m Using I_M Equal to 0

Mode of Movement	e_m		y_m	
	meters	feet	cm	inches
Center Lift	1.80	6.0	14.43	5.68
Edge Lift	1.50	5.0	4.27	1.68

Table 3. e_m and y_m Using I_M Equal to –10 and +20

Mode of Movement	em		ym	
	meters	feet	cm	inches
Center Lift	1.5	5	3.66	1.44
Edge Lift	1.2	4	1.8	0.71

Table 4. e_m and y_m Using I_M Equal to 0

Mode of Movement	em		ym	
	meters	feet	cm	inches
Center Lift	1.8	6.0	17.17	6.76
Edge Lift	1.5	5.0	5.08	2.00

Table 5. e_m and y_m Using I_M Equal to –10 and +20