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SOIL SUCTION RESEARCH

Keith W. Berry
Colorado Department of Highways
4201 East Arkansas Avenue
Denver, Colorado 80222

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Federal Highway Administration

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16. Abstract

The purpose of this research was to validate the accuracy of the soil suction test and to determine the feasibility of using this procedure to predict the heave potential of subgrade material in highways cutting through expansive claystones and shales. Difficulty in determining the initial and final moisture contents resulted in questionable calculated heave values. In order to verify the accuracy of the soil suction test method, additional research using tighter control of moisture conditions is needed. This research has shown that the soil suction test is a viable method of determining the approximate swell potential of subgrade claystones and shales.

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SOIL SUCTION RESEARCH

Introduction

Highway pavements have been heavily damaged for many years in Colorado due to swelling subgrade material. This problem occurs where highways cut through shale and claystone formations, which contain montmorillonite or other minerals of high swelling properties.

Repair of highway pavements, damaged by swelling subgrade soils, results in high maintenance costs and inconvenience to the travelling public. Many such problems in the past occured because there has not been a standard, reliable method of testing heave potential of undisturbed shales or claystones.

Presently, the Colorado Highway Department uses the "Third Cycle Expansion Test" to test remolded soil. Unfortunately, this test is not relavent to undisturbed shales or claystones. A remolded soil will exhibit different swell characteristics due to the change in particle arrangement, density, and void ratio. Results of this test are applicable for embankment soils placed directly below highway pavements, but not for undisturbed claystones and shales lying directly below highway pavements in cut sections.

Another test, which can be conducted on undisturbed shale or claystone, involves the use of the consolidometer apparatus. This test requires the soil sample to be trimmed to a specific size and shape. This is sometimes difficult to achieve when the sample is hard and dry. Also, this type of test is usually very time consuming because it takes considerable time to reach equilibrium wetting.

A test that may be more suitable for testing swell potential of shale and claystone is the soil suction test procedure using thermocouple psychrometers. Considerable research has been done on this test method by the U.S. Army Engineer Waterways Experiment Station at Vicksburg, Mississippi.

The purpose of this research project is to develop a soil suction test procedure that produces accurate swell or heave values in a practical way. An important factor in this research is to determine the correct moisture equilibrium value. The selection of the proper equilibrium moisture is critical in accurately predicting the potential heave of subgrade shales and claystones. Another important part of this research is the development of a standard method of calculating the amount of swell, based on the soil suction test results. Amount of heave in pavements will be compared to calculated values to verify accuracy of the method developed.

Development of a practical method to measure potential heave of in-situ shale and claystone is very desirable. As mentioned previously, other tests such as the "Third Cycle Expansion Pressure Test" and the test for volume change, using the consolidometer apparatus, have shortcomings. Qualitative analysis of potential swelling soils are available in terms of Plasticity Index or mineral composition; however, it is difficult to assign accurate quantitative values with these methods.

Preliminary Engineering

Site Selection- Five field sites were chosen for this research project. Each site consists of a roadway which cuts through a shale or claystone formation. Evidence of pavement damage due to subgrade heaving, was noted at each site chosen. The location of the field sites are shown in figure 1. At least one site was located in each of the following geologic formations: (1) Denver, (2) Laramie, and (3) Pierre.

Engineers and/or maintenance personnel, who are familiar with the pavement damage history were contacted. The approximate amount of pavement heave was recorded. Other pertinent information such as drainage conditions and time of pavement distress was noted.

Purchase of Testing Equipment- Some of the equipment required for soil suction testing was on hand. However, the following additional items were purchased for this project:

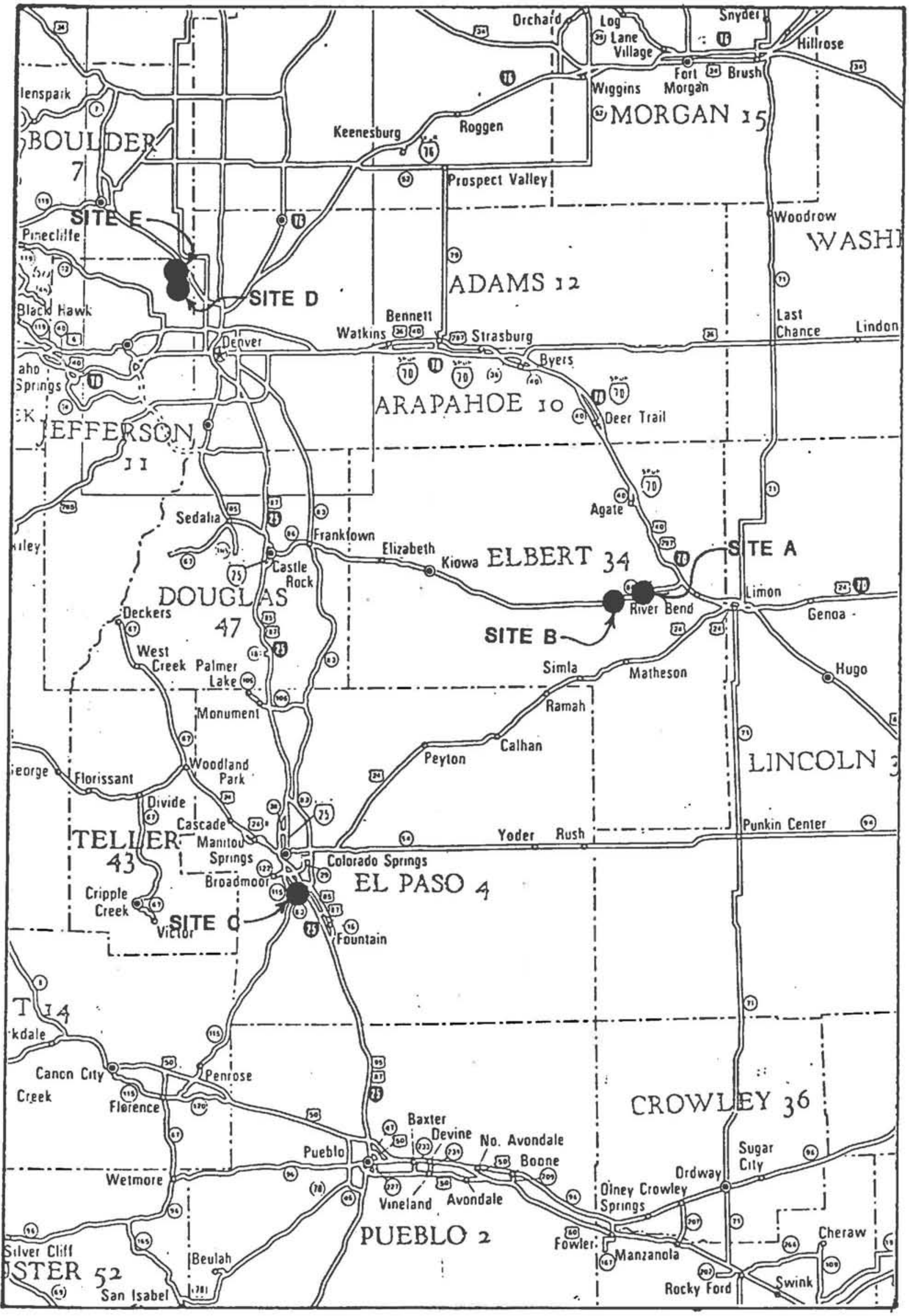
- 13 stainless steel beakers
- 1 psychrometer control unit
- 12 psychrometers
- necessary wire and connectors

Equipment Set-up- The soil suction equipment on hand, together with the newly purchased items, was used to construct two separate testing apparatuses. One apparatus is capable of testing 6 specimens and the other 10 specimens. Details of the apparatus set-up is explained in detail in Appendix A.

Field Sampling-

Two test holes were drilled at each selected site. The first hole was drilled to a minimum of 8 feet into subgrade soil

Figure 1. Map Showing Location of Field Sites



directly below roadway pavement. The second hole was drilled to an elevation equal to the first bottom-hole elevation and was located outside the roadway cut section.

Undisturbed samples were taken with the shelby tube at intervals of about 2 to 3 feet at the first hole. In most cases, disturbed soil samples were taken from the bottom 0.2 feet of shelby tube and placed in jars. The same sampling procedure was used in both test holes at each site and the samples in the second hole were taken at elevations approximately equal to those samples taken at the first hole.

Preservation of the undisturbed soil samples was accomplished by placing melted wax at both ends of the sampled material contained by the shelby tube. The liquid wax was applied to a thickness of about 0.5 inch and allowed to solidify by cooling. The disturbed soil samples were taken from the shelby tube, placed in glass jars and sealed with an air tight lid.

Survey of Field Sites

Test holes at all sites were located and referenced to the centerline of roadway. The centerline station was recorded in terms of Mile Post to the nearest one-tenth of a mile. A profile was drawn of the entire cut section at each site, including pictoral logs of the test holes, where the sites consisted of two-lane highways. A profile was drawn from centerline of median to outside Test Hole No.2, where sites consisted of four-lane highways. The profiles were constructed from survey data accurate to 0.1 feet vertical and 0.5 feet horizontal. See Appendix B.

Laboratory Testing

Most laboratory tests were conducted on samples obtained with shelby tubes. Sieve analysis and Atterberg Limit tests were conducted on all representative samples for soil classification purposes.

In-place moisture and density were determined for material from each test hole. Specific gravity, void ratio, and degree of saturation were determined for each soil sample. Soil suction tests were conducted on all undisturbed soil samples.

Testing Procedures

1. Classification - portions of all soil samples were first dry prepared by Colorado Procedure 20-72. Then a mechanical analysis was conducted using Colorado Procedure 21-72. The Atterberg Limits were determined by AASHTO T-89 and T-90. Results of these tests were used to identify all soil samples by the AASHTO designations.

2. In-Place Moisture- Moisture content determinations were made on soil samples from the shelby tube specimens.
3. In-Place Dry Density- Dry density determinations were made from the same shelby specimens, using AASHTO T-233-70.
4. Specific Gravity- Specific Gravity was determined for soil from each test hole by the AASHTO T-100 method.

5. Degree of Saturation- Percent of saturation was calculated from results of moisture content, dry density, and specific gravity determinations.

6. Soil Suction- Tests were conducted using the equipment, calibration and test procedure, data reduction, and interpretation as described in Appendix A.

Calculation Procedures

The formula used to calculate volume change is explained in Appendix A. Most of the factors used in the mathematical formula are derived from standard tests or procedures which requires very little personal judgement. However; two of the factors, which are extremely critical in determining the amount of heave, must be selected very carefully. These factors are Wo, the initial moisture content of the soil specimen, and Tmf, the final matrix soil suction which is dependent on the final moisture content of the soil specimen.

Various pertinent information, including test results (some of which are factors used for calculation of heave), relative to the soil samples is shown in Table A. Heave calculations for sites A,B,D and E are indicated in Table B.

Three different heave values were calculated for each site. The different heave values were obtained by selecting initial and final moisture by the following three methods:

(1) Individual moisture content for each layer that was sampled.

(2) Average moisture content of all layers sampled.

(3) Minimum moisture content recorded outside cut section and maximum moisture content recorded in subgrade material.

The value of Wo (initial moisture content) is entered directly into the heave calculation formula. Whereas, the value of Wf (final or equilibrium moisture content) is used to determine Tmf (final matrix soil suction) which is entered into the formula.

The value of Tmf is determined from a soil suction versus water content relationship plot (similar to figure 2), using soil suction values derived from laboratory tests conducted on subgrade soil samples.

Discussion of Test Results

A basic assumption adopted for this research was that soil samples taken from test holes outside the highway cut sections represent the subgrade soil (under the pavement) as it was when the pavement was placed. Therefore; for calculation purposes, the in-situ moisture (wo) values were obtained from tests conducted on soil samples from test holes outside the cut sections.

Because evidence of pavement heave had occured at all field sites, it was evident that the moisture content of the subgrade soil had increased subsequent to pavement construction. Laboratory tests indicated a significant increase in moisture at all sites, except Site C (see Table A), which showed a slight decrease in moisture. Undoubtedly, the in-situ moisture of soil samples from outside the cut section at Site C is much higher than the original in-situ moisture of the subgrade material prior to construction of the highway cut. Apparently, the increase in moisture was caused by migration from the roadway ditch, which is only about 25 feet from the test hole. At Site C, the No. 2 test hole was located improperly. As a result, data from Site C will

TYPICAL SOIL SUCTION VERSUS WATER CONTENT RELATIONSHIP

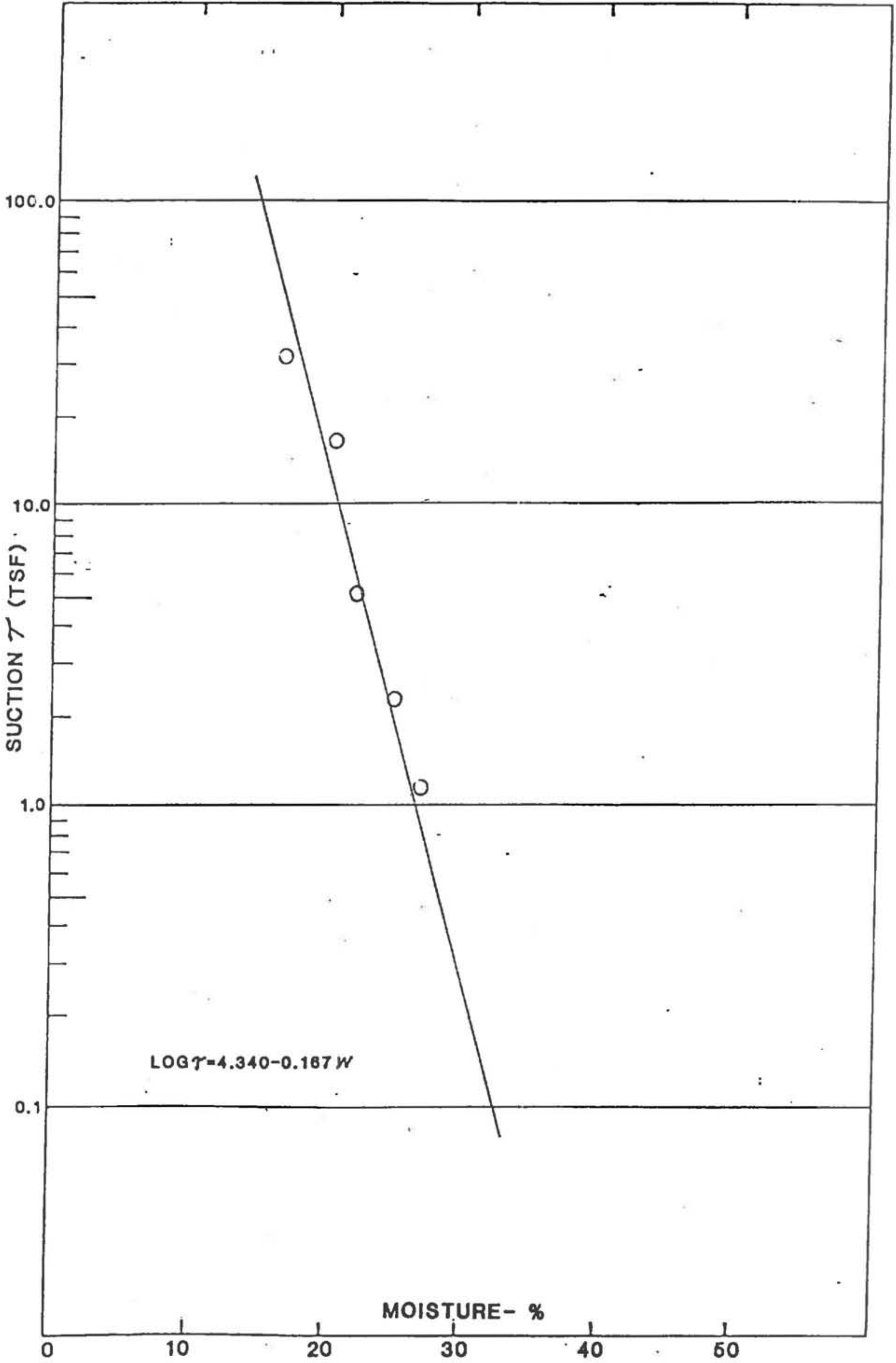


Figure 2

not be used in making heave calculations.

Test results from Sites A, B, D and E indicate rather inconsistent moisture values in the subgrade, as well as, at the corresponding depth outside the roadway cut as shown in Table A. The average increase in moisture content of the subgrade materials (as determined by laboratory tests) vary as follows:

(1) Layer by layer-
    Site A- 8.0%
    Site B- 1.9%
    Site D- 3.7%
    Site E- 4.4%

(2) Average for entire zone-
    Site A- 8.5%
    Site B- 1.1%
    Site D- 3.0%
    Site E- 3.2%

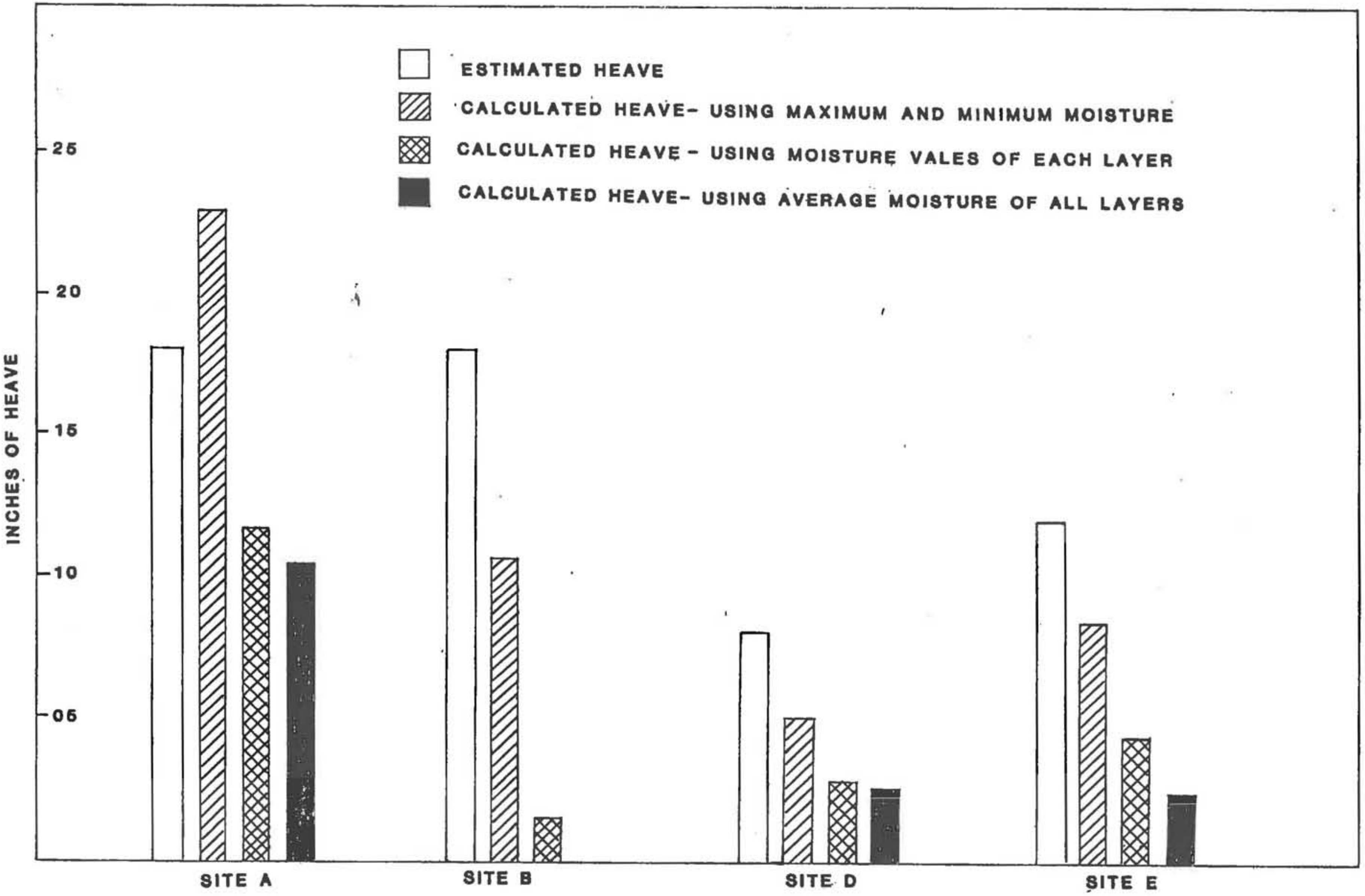
(3) Maximum and Minimum at site-
    Site A- 16.7%
    Site B- 11.3%
    Site D- 5.8%
    Site E- 7.5%

Calculating the amount of heave, using three different moisture determinations as above, generally gave heave values lower than the amount of heave which occured at these sites. The best correlation between actual heave in the field and calculated heave was obtained when maximum final moisture values and minimum initial moisture values were used. See Figure 3.

The fact that reasonable heave values were obtained with certain increases in moisture does indicate that the soil suction tests conducted in this research project did correctly identify these subgrade shales and claystone as having the potential to swell the amount they did.

Most suction values obtained during this research were fairly

COMPARISON OF CALCULATED HEAVE VALUES (3 DIFFERENT MOISTURE VALUES) WITH ESTIMATED HEAVE VALUES



uniform and produced good suction versus moisture curves during the short period of time the tests were conducted. However, difficulty was encountered in wetting and drying many of the specimens to uniform moisture contents. The suction values for these specimens were eratic and resulted in non-uniform plots for soil suction versus moisture curves.

Many of the psychrometers produced different suction values when re-calibrated nine months after the original calibration. Because of their fragile nature, the psychrometers require re-calibration two or three times a year. About three weeks is required for this procedure.

Conclusions

Before this research began it was assumed that the moisture content of claystone or shale, located outside the roadway cut section at an elevation equal to the corresponding subgrade material, would represent the moisture content of the subgrade immediately prior to pavement placement. Also, it was assumed that the moisture content of the subgrade material sampled and tested for this research project would represent the final (equilibrium) or maximum moisture content.

Analysis of moisture values (shown in table A) indicates these assumptions were not completely accurate. The moisture values obtained outside the cut areas were higher than expected and the moisture values obtained from the existing subgrade material were slightly lower than was expected. The author believes surface water from the roadway ditches migrated outward to increase the moisture content of the claystone and shale sampled outside the cut section. The author also believes the moisture content of the subgrade claystones and shales, which were sampled in August and October, was less than the moisture content that existed in the Spring of the year. As a result of initial moisture (wo) values being too high and the final or equilibrium moisture values being too low, the calculated heave values were less than the heave that actually occured in the roadway pavemements.

The soil suction values (τ) determined from laboratory tests showed reasonably good soil suction versus water content relationships when plotted on semilog paper. If initial and final moisture values could be accurately ascertained, the amount of heave of these shales and claystones could be calculated fairly close.

This test can be used in identifying the approximate swell potential of subgrade material. A curve plotted on semilog paper, using soil suction values obtained from soil suction tests, can be used to approximate swell potential by assuming initial and final moisture contents.

Recommendations

The soil suction test should not be used as a routine test to identify potentially expansive soils. Plastic Index and Liquid Limit values, derived from Atterberg tests, should be used for this purpose.

The soil suction test, as described in Appendix A, should be conducted on shale and claystone subgrade (which has been identified as potentially expansive) on projects planned for the immediate future. Calculation of swell for these tests should be determined by using moisture values (initial and final) based on in-situ moisture and drainage conditions.

Results of these tests should be compared to odometer tests conducted on identical material. Until these additional tests are concluded and a detailed analysis completed, adoption of this soil suction test as a standard procedure would be premature. Should results of the soil suction and the odometer tests produce percent swell values in close agreement, then adopotion of the soil suction test (Appendix A) for inclusion in the CDOH Procedural Manual would be recommended.

REFERENCES

(1) Materials Test Procedural Manual, Division of Highways, State of Colorado, "Third Cycle Expansion Pressure Test."

(2) Materials Manual, Division of Highways, State of Colorado

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(5) Johnson, L.D., Evaluation of Laboratory Suction Tests for Prediction of Heave in Foundation Soils, Soils Pavement Laboratory, U.S. Army Engineer Waterways Experiment Station, P.O. Box 631, Vicksburg, Miss., 39180, August, 1977

APPENDIX A

SOIL SUCTION TESTING

Soil suction is a quantity that can be used to characterize the effect of moisture on soil volume. Soil suction, expressed in terms of pressure, is a measure of the pulling force exerted on water by the soil mass.

One of the best techniques used to measure soil suction is the thermocouple psychrometer. The psychrometer measures the relative humidity in the soil by a technique called peltier cooling. By causing a small direct current of about 4 to 8 milliamperes to flow through the thermocouple junction for about 15 seconds in the correct direction, this junction will cool and water will condense on it when the dew point temperature is reached. Condensation of this water inhibits further cooling of the junction and the voltage difference between the thermocouple and reference junctions can be measured using a micro-voltmeter. With proper calibration the thermocouple psychrometer output in microvolts can be converted directly to soil suction in terms of tsf (tons per square foot). Typical thermocouple psychrometer output voltages vary from less than 1 microvolt for relative humidities close to 100 percent or total soil suctions less than 1 tsf to about 25 microvolts for relative humidities of about 95 percent or total soil suctions of about 60 tsf.

Equipment

The following equipment is required to perform the soil suction test:

1) Six psychrometers.
2) Six stainless steel beakers.

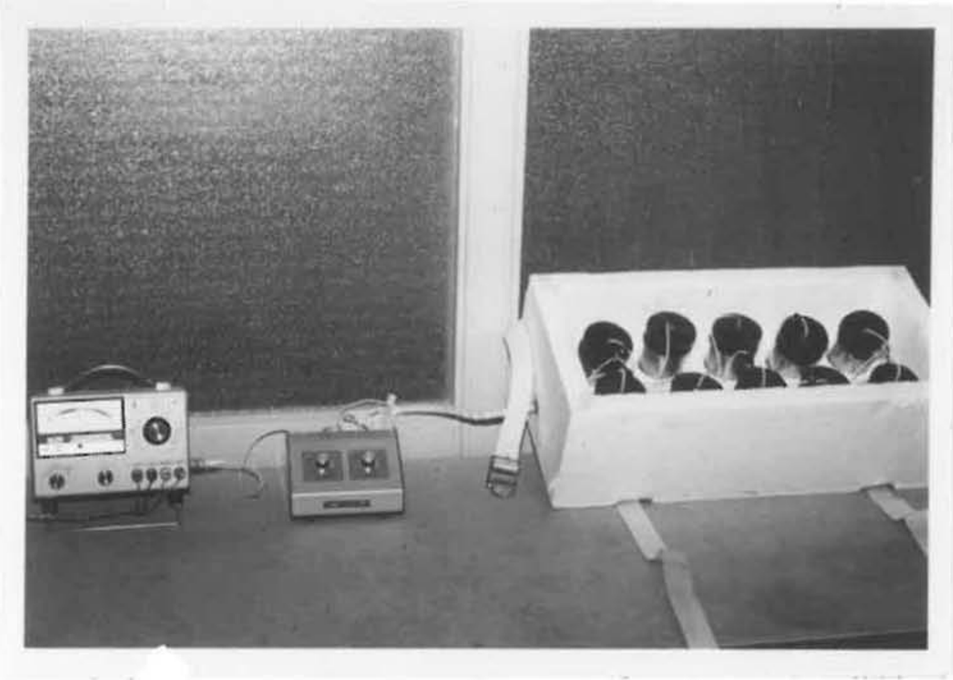
3) Six rubber stoppers.
4) One psychrometer control unit.
5) One microvoltmeter.
6) One polystyrene thermal box.
7) Necessary wire and connectors.
8) Specimen cutting equipment (i.e.; wire saw, knife, etc.)
9) Stopwatch.
10) Tare containers.
11) Balance, sensitive to 0.1 gm.
12) Calibration standards (WESCOR Osmolality standards).

The first step in setting up the equipment is drilling a hole (0.25 in. diameter) through the rubber stoppers. The thermocouple psychrometer wires are fed through the hole so the psychrometer tip extends about 1 in. from the bottom of the rubber stopper. The protective sheathing around the psychrometer tip should form an air tight seal around the hole in the rubber stopper. The electrical connectors are affixed to the psychrometer wires for easy connection to the switch box. The rubber stoppers are used to seal the sample containers, which are placed in the thermal box to minimize temperature variations. The switches are wired so that the output voltages (temperature and soil suction) can be monitored on each of the psychrometers in turn. The equipment should be kept in a room where ambient termperature variations are minimal. Photographs 1 and 2 show the test equipment. Figure 4 shows a detailed drawing of same.

After the equipment is set up, as described above, the thermocouple psychrometers must be calibrated.

Calibration

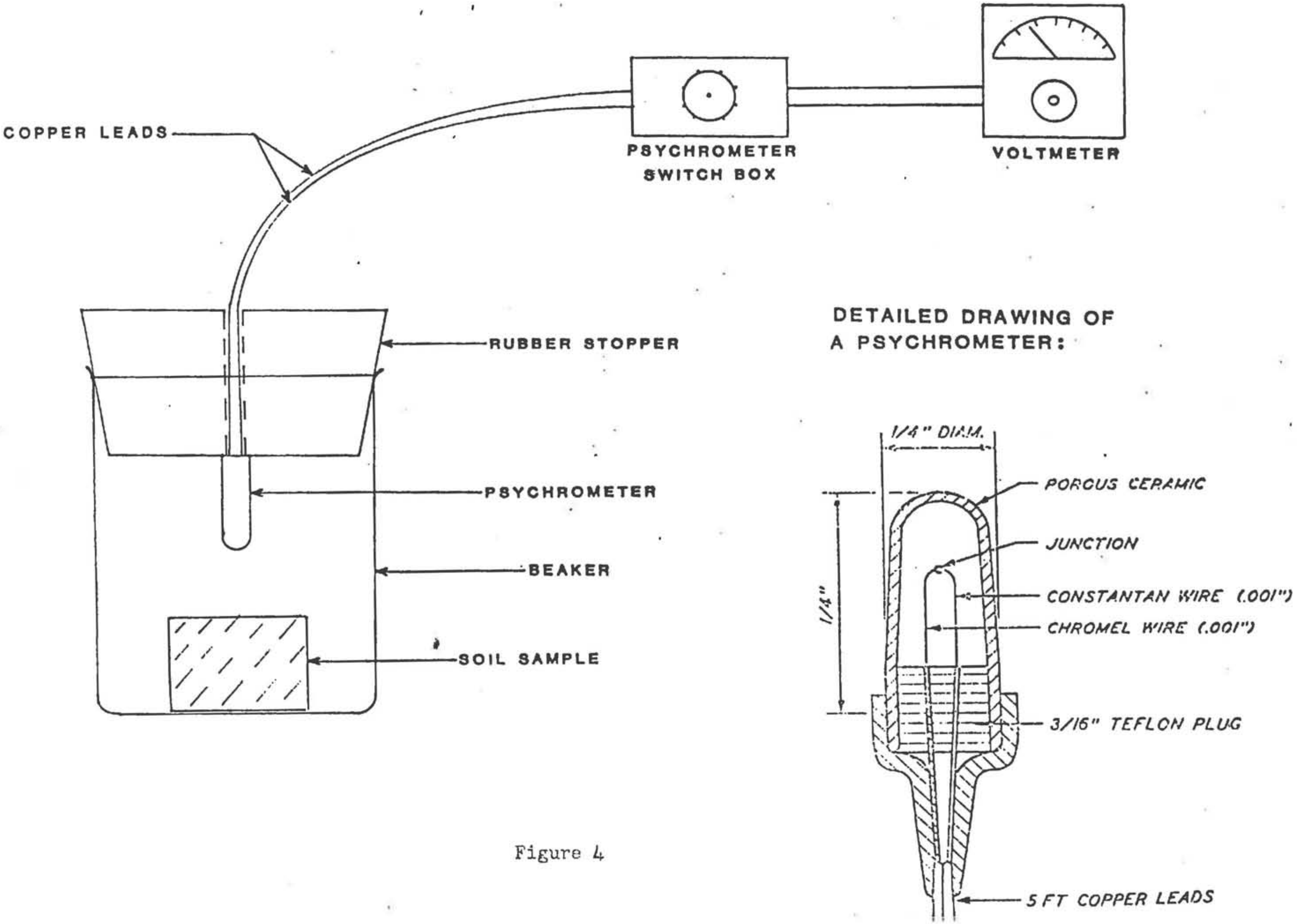
Calibration of the equipment involves normal operation of the equipment with standard solutions, which result in known relative humidities, placed in the sample containers. The



PHOTOGRAPH NO. 1
SOIL SUCTION TESTING EQUIPMENT

PHOTOGRAPH NO. 2
CLOSEUP OF A PSYCHROMETER

DETAILED DRAWING OF SOIL SUCTION TESTING APPARATUS



DETAILED DRAWING OF A PSYCHROMETER:

Figure 4

different relative humidities result in corresponding retention forces or soil suction values. Several standard solutions are tested, and the resulting micro-voltmeter output, when converted to a standard temperature of 25C yields a linear calibration line for the individual thermocouple psychrometer.

The calibration begins by placing a small piece of filter paper (type and grade variable) in the bottom of each sample container along with 3 ml. of the calibration standard. A minimum of three, preferably four, calibration standard concentrations should be used to adequately define the calibration line (i.e., 290, 1000, and 1800 mOs/kg). The equivalent moisture retention force or soil suction, in tons per square foot, is calculated by multiplying the concentration by 2.62×10^{-2} (i.e., 1800 mOs/kg x 0.0262 = 47.2 tsf). After sealing the sample containers with the rubber stoppers and placing them in the thermal container, allow the temperature to equilibrate for approximately 24 hrs. Begin taking temperature and soil suction output readings every day until the output readings stabilize. The time to stabilization varies with the concentration of the calibration standard but will generally be in the range of 4 to 7 days.

The thermocouple voltage output (millivolts) is converted to temperature (°C) using the following conversion:

$$\text{Temperature, } ^{\circ}\text{C} = \frac{\text{output in millivolts}}{0.0395 \text{ millivolts}/^{\circ}\text{C}} \qquad (1)$$

The psychrometer (soil suction) voltage output, Et (microvolts) is converted to the equivalent output at the calibration temperature of 25°C, E25, by

$$E25 = \frac{Et}{0.325 + 0.027T} \qquad (2)$$

When at least three stable output readings are obtained, the average of the three readings is plotted versus the corresponding moisture retention force or soil suction on arithmetic scales as shown in Figure 5. A convenient scale for plotting the calibration line for the range of indicated calibration standard concentrations is 2.5 tsf/cm for the ordinate and 2.5 micro-volts /cm for the abscissa. Typical thermocouple psychrometer calibration lines are linear and can be expressed using the following equation:

$$\tau = mE25 - n \qquad (3)$$

where

τ = soil suction, tsf
m = slope of the calibration line
n = y-intercept of the calibration line

The slope will always be positive, and the y-intercept should be equal to or less than zero. Under normal use a semi-annual check of the calibration should be conducted to assure that the equipment is operating properly.

Test Procedure

The test procedure begins by cutting the undisturbed sample (taken from the shelby tube) into five or six equal sized specimens that approximate cubes with dimensions of 1.0 inch on a side. One specimen is placed directly into a metal sample container and sealed with a rubber stopper. This specimen represents the natural condition (in-situ moisture). The remaining specimens are either wetted with varing amounts of

Typical Thermocouple Psychrometer Calibration Line

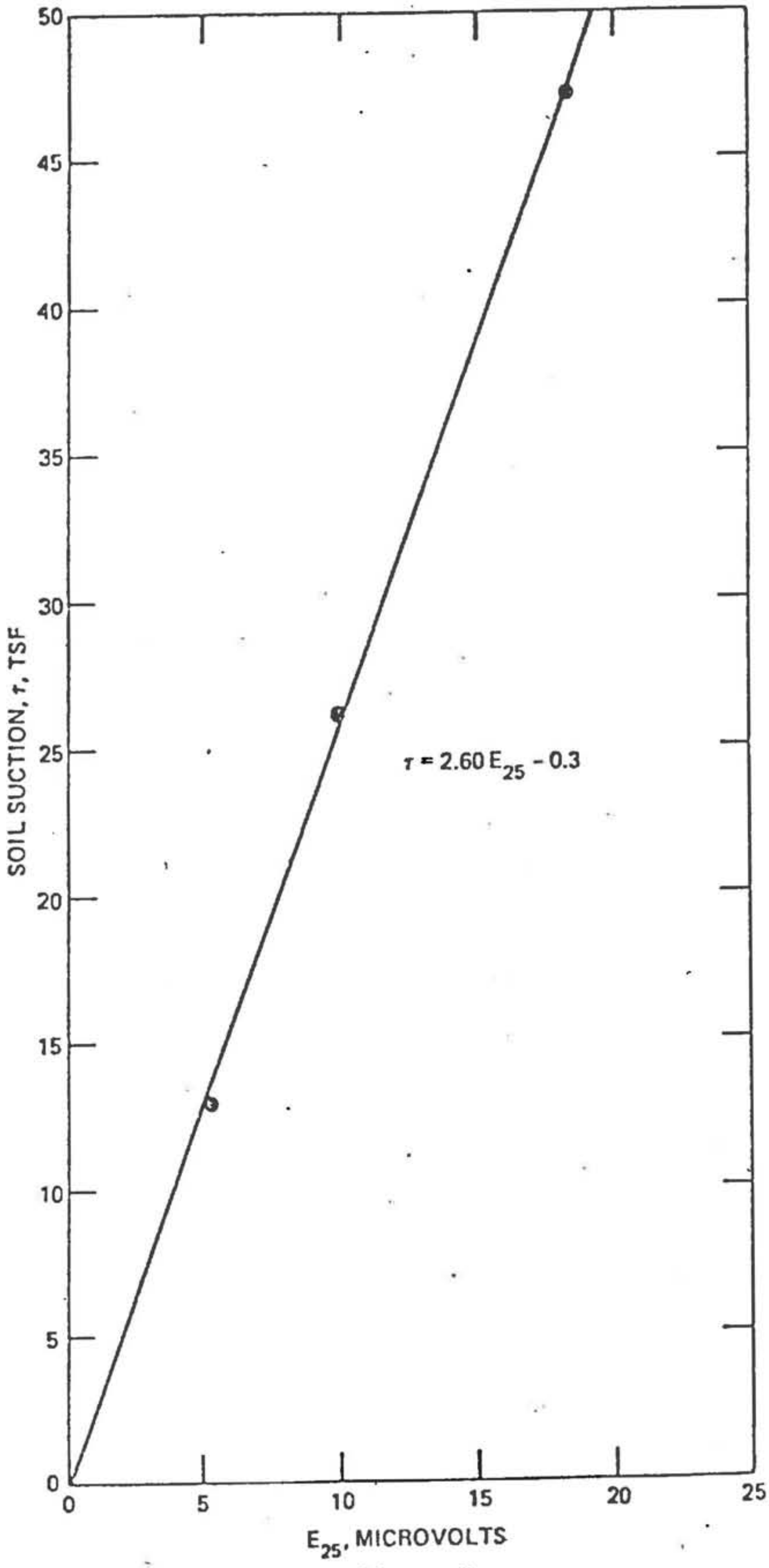


Figure 5

distilled water or dried at room temperature at varying lengths of time to establish a range of water content conditions. Once the specimens have been wetted or dried to different water content conditions, they should be placed in the remaining sample containers and sealed with the rubber stoppers. The specimens should be allowed to equilibrate in the sealed containers (usually about 48 hours) and then tested.

The actual test sequence using the previously described equipment involves:

1). Selecting a thermocouple psychrometer using the appropriate switch and reading the temperature output in millivolts.

2). Changing the switch from thermocouple to psychrometer, setting the meter to zero, applying a cooling current for 15 seconds, and reading the psychrometer output in microvolts.

3). Repeating 1) and 2) for each of the thermocouple psychrometers in the equipment setup.

After completing the test sequence, the specimens are removed, and the dry densities (volume displacement method) and water contents are determined for each.

Data Reduction and Interpretation

The soil suction data is reduced by first converting the thermocouple output (millivolts) to temperature (°C) using equation (1). The psychrometer output (microvolts) is converted to an equivalent output at the calibration temperature using equation (2). The soil suction of the individual specimens is determined by substituting the equivalent psychrometer output into the psychrometer calibration line equation. The data is then plotted versus water content on a semilog plot to establish the log soil suction versus water content relationship, Figure 5, which is linear and has the form

$$\log \tau = A - Bw \qquad (4)$$

where

A = y-intercept
B = slope
w = water content, percent

Generally, three-cycle semilog paper is sufficient to accommodate all of the data points. A convenient scale factor for the abscissa (water content) is 10 percent per inch. By keeping track of the points representing natural conditions, all of the data points are used to establish the $\tau - w$ relationship. If some variation occurs at the upper or lower end of the curve because the limits of the measurement range are approached, the data points between soil suction values of 2 and 20 tsf should be used to establish the $T - w$ relationship. The slope, B, of the line is determined by calculating the inverse of the change in water content over one cycle of the log scale. The intercept, A, is calculated by applying Equation 4 at soil suction equal to 1 tsf.

Besides the A and B parameters, the prediction of volume change using soil suction data, a volumetric compressibility factor (α) is required that relates to change in volume to a corresponding change in water content. The value of α can be approximated by using the formula: $\alpha = 0.0275$ P.I. $- 0.125$. If the value of P.I. is 40 or greater, then a value of 1.0 can be used for α.

Other parameters needed to calculate volume change are suction index (C_τ), Initial void ratio (e_o), Initial moisture content (Wo), Final matrix soil suction (τ_{mf}) and Final applied pressure (σ_f). All but C_τ and τ_{mf} have been explained or determined from laboratory tests. Suction index (C_τ) reflects the rate of change of void ratio with respect to soil suction and can be derived by the formula: $C_\tau = \alpha \, Gs/100B$. Final matrix soil suction (τ_{mf}) is the value determined from a plot of the log soil suction versus water content relationship, based on the final or equilibrium moisture.

Calculation of Volume Change (Heave)

The amount of heave, for a given strata thickness can be calculated using the following formula:

$$\Delta H/H = C_\tau/1+e_o \, [(A - BW_o) - \log(\tau_{mf} + \sigma_f)]$$

where:

H = Stratum thickness
C_τ = Suction index, α Gs/100B
e_o = Initial void ratio
W_o = Initial moisture content, percent
τ_{mf} = Final matrix soil suction, tsf
α = Compressibility factor (0.0275 P.I. - 0.125)
σ_f = Final applied pressure (overburden plus external load)

APPENDIX B

TABLE A

LABORATORY TEST RESULTS

SITE & SAMPLE NO.	DEPTH	AASHTO CLASSIFICATION	L.L.	P.I.	IN-PLACE DRY DENSITY	SPECIFIC GRAVITY	INITIAL VOID RATIO	IN-SITU MOISTURE CONTENT	SOIL SUCTION (T.S.F.)	
									τ_o	τ_{mf}
Site A-										
1A	2.0-3.6	A-7-6(32)	58	39	90.9	2.59	0.78	26.63	12.0	0.0
1B	3.6-4.0	A-7-6(30)	51	28				26.63		
1C	5.0-8.0	A-7-6(57)	73	50	89.3	2.70	0.71	31.58	3.1	0.0
1D	8.0-10.0	A-7-6(50)	67	44	92.8	2.71	0.82	29.92	15.0	3.8
1E	11.0-12.8	A-7-6(66)	86	56	88.7	2.64	0.86	33.20	80.0	2.5
1F	12.8-13.0	A-7-6(30)	51	28						
2A	10.1-11.2	A-7-6(16)	42	23	101.7	2.65	0.63	16.53	39.0	
2B	12.0-13.1	A-7-6(33)	54	32	98.9	2.61	0.65	19.59	8.7	
2C	14.0-15.7	A-7-6(62)	82	53	95.4	2.70	0.77	24.74	29.0	
2D	15.7-16.0							22.31		
2E	17.0-18.5	A-7-6(71)	87	61	97.1	2.66	0.71	25.57	17.5	
Site B-1A	2.0-4.0	A-7-5(34)	71	38	84.9	2.72	1.00	33.60	12.0	10.5
1B	4.0-8.0	A-7-6(17)	66	43	88.5	2.71	0.91	28.2	10.0	4.5
1C	8.0-11.0									
1D	11.0-13.0	A-7-6(15)	56	31	87.0	2.71	0.94	25.0	21.0	5.7
2A	10.5-12.5	A-7-5(59)	84	54	86.4	2.71	0.96	33.3	6.1	
2B	13.5-15.5	A-7-6(12)	59	35	86.4	2.69	0.94	25.6	7.9	
2C										
2D	18.6-21.5	A-7-6(9)	52	28	85.2	2.67	0.96	22.3	13.0	

TABLE A

LABORATORY TEST RESULTS

SITE & SAMPLE NO.	DEPTH	AASHTO CLASSIFICATION	L.L.	P.I.	IN-PLACE DRY DENSITY	SPECIFIC GRAVITY	INITIAL VOID RATIO	IN-SITU MOISTURE CONTENT	SOIL SUCTION (T.S.F.)	
									τ_o	τ_{mf}
Site C-1A	2.0-4.0	A-7-6(36)	56	31	109.3	2.74	0.56	19.39		3.5
1B	4.0-6.0	A-7-6(30)	51	26	107.0	2.68	0.56	19.50		1.6
1C	6.0-8.0	A-7-6(43)	54	41	103.9	2.70	0.62	21.59		0.5
1D	8.0-10.0	A-7-6(30)	51	26	101.2	2.71	0.63	20.42		1.4
2A	6.0-8.0	A-7-6(32)	53	28	102.9	2.71	0.64	20.07	1.5	
2B	8.0-10.5	A-7-6(34)	56	32	105.1	2.73	0.61	22.19	1.7	
2C	10.5-12.5	A-7-6(38)	59	33	107.7	2.73	0.58	21.77	2.4	
2D	12.5-14.5	A-7-6(37)	60	32	104.0	2.73	0.63	23.64	3.0	
Site L-1A	3.0-5.0	A-7-6(29)	51	32	107.4	2.72	0.58	17.76	6.6	1.3
1B	5.0-7.0	A-7-6(35)	52	33	111.6	2.72	0.52	18.43	30.5	4.0
1C	7.0-10.0	A-7-6(28)	42	27	115.5	2.63	0.42	15.89	9.0	1.3
1D	10.0-11.0	A-7-6(33)	50	32	117.0	2.63	0.40	14.54	23.0	5.6
2A	27.0-30.0	A-7-6(27)	44	27	118.0	2.62	0.38	15.40	0.8	
2B	30.0-32.0	A-7-6(15)	34	18	112.0	2.60	0.44	12.61	3.2	
2C	32.0-32.5	A-7-6(20)	39	23	106.8	2.66	0.55	12.99	2.5	

TABLE A

LABORATORY TEST RESULTS

SITE & SAMPLE NO.	DEPTH	AASHTO CLASSIFICATION	L.L.	P.I.	IN-PLACE DRY DENSITY	SPECIFIC GRAVITY	INITIAL VOID RATIO	IN-SITU MOISTURE CONTENT	SOIL SUCTION (T.S.F.)	
									τ_s	τ_{mf}
Site E-1A	3.0-5.0	A-7-6(40)	65	41	100.2	2.72	0.69	24.30	49.0	3.3
1B	5.0-8.0	A-7-6(36)	58	34	95.3	2.69	0.76	22.70	18.5	2.0
1C	8.0-10.0	A-7-6(35)	55	32	101.8	2.70	0.65	21.42	4.5	5.6
1D	10.0-12.0	A-7-6(41)	57	37	113.0	2.71	0.49	18.02	0.0	0.4
2A	10.0-12.0	A-7-6(35)	52	33	105.9	2.64	0.55	16.29	2.4	
2B	13.0-15.0	A-7-6(36)	50	34	92.8	2.62	0.76	16.77	1.4	
2C	15.0-17.0	A-7-6(48)	65	44	99.3	2.65	0.66	22.06	1.8	

TABLE B

CALCULATION OF HEAVE- SITE A

$$\Delta H/H = C_\gamma/1+e_o\left[\left(A-BW_o\right)-\log\left(\gamma_{mf}+\alpha\sigma_f\right)\right]$$

(1) Using moisture values of each layer:

Sample 1A $\Delta H/3 = 0.098/1.78[(5.366-0.263\times16.53)-\log(0.0+0.13)] = 0.10$ ft., $\therefore \Delta H = 3.6$ in.

1C $\Delta H/3 = 0.094/1.71[(7.378-0.286\times24.74)-\log(0.0+0.31)] = 0.04$ ft., $\therefore \Delta H = 2.4$ in.

1D $\Delta H/2 = 0.343/1.82[(2.943-0.079\times22.31)-\log(3.8+0.55)] = 0.10$ ft., $\therefore \Delta H = 2.4$ in.

1E $\Delta H/3 = 0.185/1.86[(5.004-0.143\times25.57)-\log(2.5+0.73)] = 0.27$ ft., $\therefore \Delta H = \underline{3.2}$ in.

Total = 11.6 in. ←

(2) Using average moisture of all layers:

Sample 1A $\Delta H/3 = 0.098/1.78[(5.366-0.263\times21.75)-\log(0.0+0.13)] = 0.30$ ft., $\therefore \Delta H = 1.1$ in.

1C $\Delta H/3 = 0.094/1.71[(7.378-0.286\times21.75)-\log(0.1+0.31)] = 0.08$ ft., $\therefore \Delta H = 2.9$ in.

1D $\Delta H/2 = 0.343/1.82[(2.943-0.079\times21.75)-\log(3.6+0.55)] = 0.11$ ft., $\therefore \Delta H = 2.7$ in.

1E $\Delta H/3 = 0.185/1.86[(5.004-0.143\times21.75)-\log(6.4+0.73)] = 0.10$ ft., $\therefore \Delta H = \underline{3.7}$ in.

Total = 10.4 in. ←

(3) Using maximum W_f moisture and minimum W_o moisture:

Sample 1A $\Delta H/3 = 0.078/1.78[(5.366-0.263\times16.53)-\log(0.0+0.13)] = 0.10$ ft., $\therefore \Delta H = 3.6$ in.

1C $\Delta H/3 = 0.094/1.71[(7.378-0.286\times16.53)-\log(0.1+0.31)] = 0.17$ ft., $\therefore \Delta H = 6.1$ in.

1D $\Delta H/2 = 0.343/1.82[(2.743-0.079\times16.53)-\log(2.1+0.55)] = 0.23$ ft., $\therefore \Delta H = 5.5$ in.

1E $\Delta H/3 = 0.185/1.86[(5.004-0.143\times16.53)-\log(2.5+0.73)] = 0.21$ ft., $\therefore \Delta H = \underline{7.6}$ in.

Total = 22.8 in. ←

Note: Actual heave at this site was estimated to be 18 inches.

TABLE B

CALCULATION OF HEAVE- SITE B

$$\Delta H/H = C_\tau/_{1+e_o}\left[\left(A - BW_o\right) - \log\left(\tau_{mf} + \alpha\sigma_f\right)\right]$$

(1) Using moisture values of each layer :

Sample 1A $\Delta H/2 = {}^{0.197}/_{2.0}[(5.191 - 0.127 \times 33.30) - \text{Log}(10.5 + 0.17)] = 0.00\,\text{ft.}; \therefore \Delta H = 0.0\,\text{in.}$

1B $\Delta H/4 = {}^{0.198}/_{1.91}[(4.357 - 0.137 \times 25.60) - \text{Log}(4.4 + 0.31)] = 0.02\,\text{ft.}; \therefore \Delta H = 1.0\,\text{in.}$

1D $\Delta H/2 = {}^{0.073}/_{1.94}[(5.963 - 0.213 \times 22.30) - \text{Log}(5.6 + 0.73)] = 0.02\,\text{ft.}; \therefore \Delta H = \underline{0.5\,\text{in.}}$

Total =1.5 in ←

(2) Using average moisture of all Layer : :

Sample 1A $\Delta H/2 = {}^{0.197}/_{2.0}[(5.191 - 0.127 \times 27.80) - \text{Log}(4.1 + 0.17)] = 0.00\,\text{ft.}; \therefore \Delta H = 0.0\,\text{in.}$

1B $\Delta H/4 = {}^{0.198}/_{1.91}[(4.357 - 0.137 \times 27.80) - \text{Log}(3.5 + 0.31)] = 0.00\,\text{ft.}; \therefore \Delta H = 0.0\,\text{in.}$

1D $\Delta H/2 = {}^{0.073}/_{1.94}[(5.963 - 0.213 \times 27.80) - \text{Log}(7.7 + 0.73)] = 0.00\,\text{ft.}; \therefore \Delta H = \underline{0.0\,\text{in.}}$

Total =0.0 in. ←

(3) Using maximum W_f moisture and minimum W_o moisture :

Sample 1A $\Delta H/2 = {}^{0.197}/_{2.0}[(5.197 - 0.127 \times 22.30) - \text{Log}(10.5 + 0.17)] = 0.13\,\text{ft.}; \therefore \Delta H = 3.1\,\text{in.}$

1B $\Delta H/4 = {}^{0.198}/_{1.91}[(4.357 - 0.137 \times 22.30) - \text{Log}(0.8 + 0.31)] = 0.13\,\text{ft.}; \therefore \Delta H = 6.2\,\text{in.}$

1D $\Delta H/2 = {}^{0.093}/_{1.94}[(5.963 - 0.213 \times 22.30) - \text{Log}(0.8 + 0.73)] = 0.05\,\text{ft.}; \therefore \Delta H = \underline{1.2\,\text{in.}}$

Total =10.5 in. ←

Note : Actual heave at this site was estimated to be 18 inches.

TABLE B

CALCULATION OF HEAVE- SITE D

$$\Delta H/H = C_\tau/1+e_o\left[\left(A-BW_o\right)-\log\left(\tau_{mf}+\alpha\sigma_f\right)\right]$$

(1) Using moisture values of each layer :

Sample 1A $\Delta H/2 = 0.064/1.58[(5.684-0.323\times 15.40)-\text{Log}(1.3+0.25)] = 0.02$ ft., $\therefore \Delta H = 0.5$ in.

1B $\Delta H/2 = 0.144/1.52[(3.161-0.147\times 12.61)-\text{Log}(4.0+0.37)] = 0.06$ ft., $\therefore \Delta H = 1.4$ in.

1C $\Delta H/3 = 0.055/1.42[(4.616-0.294\times 12.77)-\text{Log}(1.2+0.49)] = 0.02$ ft., $\therefore \Delta H = 0.8$ in.

1D $\Delta H/1 = 0.062/1.4[(5.296-0.323\times 12.99)-\text{Log}(4.9+0.61)] = 0.01$ ft., $\therefore \Delta H = \underline{0.1 \text{ in.}}$

Total = 2.8 in. ←

(2) Using average moisture of all layers :

Sample 1A $\Delta H/2 = 0.064/1.58[(5.684-0.323\times 13.67)-\text{Log}(1.3+0.25)] = 0.04$ ft., $\therefore \Delta H = 1.0$ in.

1B $\Delta H/2 = 0.144/1.52[(3.161-0.147\times 13.67)-\text{Log}(7.6+0.37)] = 0.02$ ft., $\therefore \Delta H = 0.5$ in.

1C $\Delta H/3 = 0.055/1.42[(4.616-0.294\times 13.67)-\text{Log}(0.7+0.49)] = 0.02$ ft., $\therefore \Delta H = 0.7$ in.

1D $\Delta H/1 = 0.062/1.4[(5.296-0.323\times 13.67)-\text{Log}(1.0+0.61)] = 0.03$ ft., $\therefore \Delta H = \underline{0.4 \text{ in.}}$

Total = 2.6 in. ←

(3) Using maximum W_F moisture and minimum W_o moisture :

Sample 1A $\Delta H/2 = 0.064/1.58[(5.684-0.323\times 12.61)-\text{Log}(0.8+0.25)] = 0.06$ ft., $\therefore \Delta H = 1.4$ in.

1B $\Delta H/2 = 0.144/1.52[(3.161-0.147\times 12.61)-\text{Log}(4.0+0.37)] = 0.06$ ft., $\therefore \Delta H = 1.4$ in.

1C $\Delta H/3 = 0.055/1.42[(4.616-0.294\times 12.61)-\text{Log}(0.2+0.49)] = 0.04$ ft., $\therefore \Delta H = 1.6$ in.

1D $\Delta H/1 = 0.062/1.4[(5.296-0.323\times 12.61)-\text{Log}(0.5+0.61)] = 0.05$ ft., $\therefore \Delta H = \underline{0.6 \text{ in.}}$

Total = 5.0 in. ←

Note : Actual heave at this site was estimated to be 8 inches :

TABLE B

CALCULATION OF HEAVE- SITE E

$$\frac{\Delta H}{H} = \frac{C_\gamma}{1+e_o}\left[\left(A - BW_o\right) - \log\left(\gamma_{mf} + \alpha\sigma_f\right)\right]$$

(1) Using moisture values of each layer :

Sample 1A $\Delta H/2 = 0.179/1.69\,[(4.040 - 0.152 \times 16.29) - \mathrm{Log}(3.3 + 0.25)] = 0.11$ ft.; $\therefore \Delta H = 2.6$ in.

1B $\Delta H/3 = 0.127/1.76\,[(3.941 - 0.172 \times 16.77) - \mathrm{Log}(2.0 + 0.30)] = 0.05$ ft.; $\therefore \Delta H = 1.8$ in.

1C $\Delta H/2 = 0.125/1.65\,[(4.132 - 0.164 \times 22.06) - \mathrm{Log}(5.6 + 0.55)] = 0.00$ ft.; $\therefore \Delta H = 0.0$ in.

1D $\Delta H/2 = 0.121/1.49\,[(3.600 - 0.200 \times 22.06) - \mathrm{Log}(0.3 + 0.67)] = 0.00$ ft.; $\therefore \Delta H = \underline{0.0}$ in.

Total = 4.4 in. ←

(2) Using average moisture of all layers :

Sample 1A $\Delta H/2 = 0.179/1.69\,[(4.040 - 0.152 \times 18.37) - \mathrm{Log}(8.2 + 0.25)] = 0.03$ ft.; $\therefore \Delta H = 0.8$ in.

1B $\Delta H/3 = 0.127/1.76\,[(3.941 - 0.172 \times 18.37) - \mathrm{Log}(3.0 + 0.30)] = 0.02$ ft.; $\therefore \Delta H = 0.7$ in.

1C $\Delta H/2 = 0.125/1.65\,[(4.132 - 0.164 \times 18.37) - \mathrm{Log}(5.3 + 0.55)] = 0.03$ ft.; $\therefore \Delta H = 0.7$ in.

1D $\Delta H/2 = 0.121/1.49\,[(3.600 - 0.200 \times 18.37) - \mathrm{Log}(0.0 + 0.67)] = 0.01$ ft.; $\therefore \Delta H = \underline{0.2}$ in.

Total = 2.4 in. ←

(3) Using maximum W_f moisture and minimum W_o moisture :

Sample 1A $\Delta H/2 = 0.179/1.69\,[(4.040 - 0.152 \times 16.29) - \mathrm{Log}(3.3 + 0.25)] = 0.11$ ft.; $\therefore \Delta H = 2.6$ in.

1B $\Delta H/3 = 0.127/1.76\,[(3.941 - 0.172 \times 16.29) - \mathrm{Log}(1.0 + 0.30)] = 0.07$ ft.; $\therefore \Delta H = 2.7$ in.

1C $\Delta H/2 = 0.125/1.65\,[(4.132 - 0.164 \times 16.29) - \mathrm{Log}(1.8 + 0.55)] = 0.08$ ft.; $\therefore \Delta H = 2.0$ in.

1D $\Delta H/2 = 0.121/1.49\,[(3.600 - 0.200 \times 16.29) - \mathrm{Log}(0.0 + 0.67)] = 0.04$ ft.; $\therefore \Delta H = \underline{1.0}$ in.

Total = 8.3 in. ←

Note : Actual heave at this site was estimated to be 12 inches.

TABLE C

CROSS SECTION OF HIGHWAY CUT AT SITE A

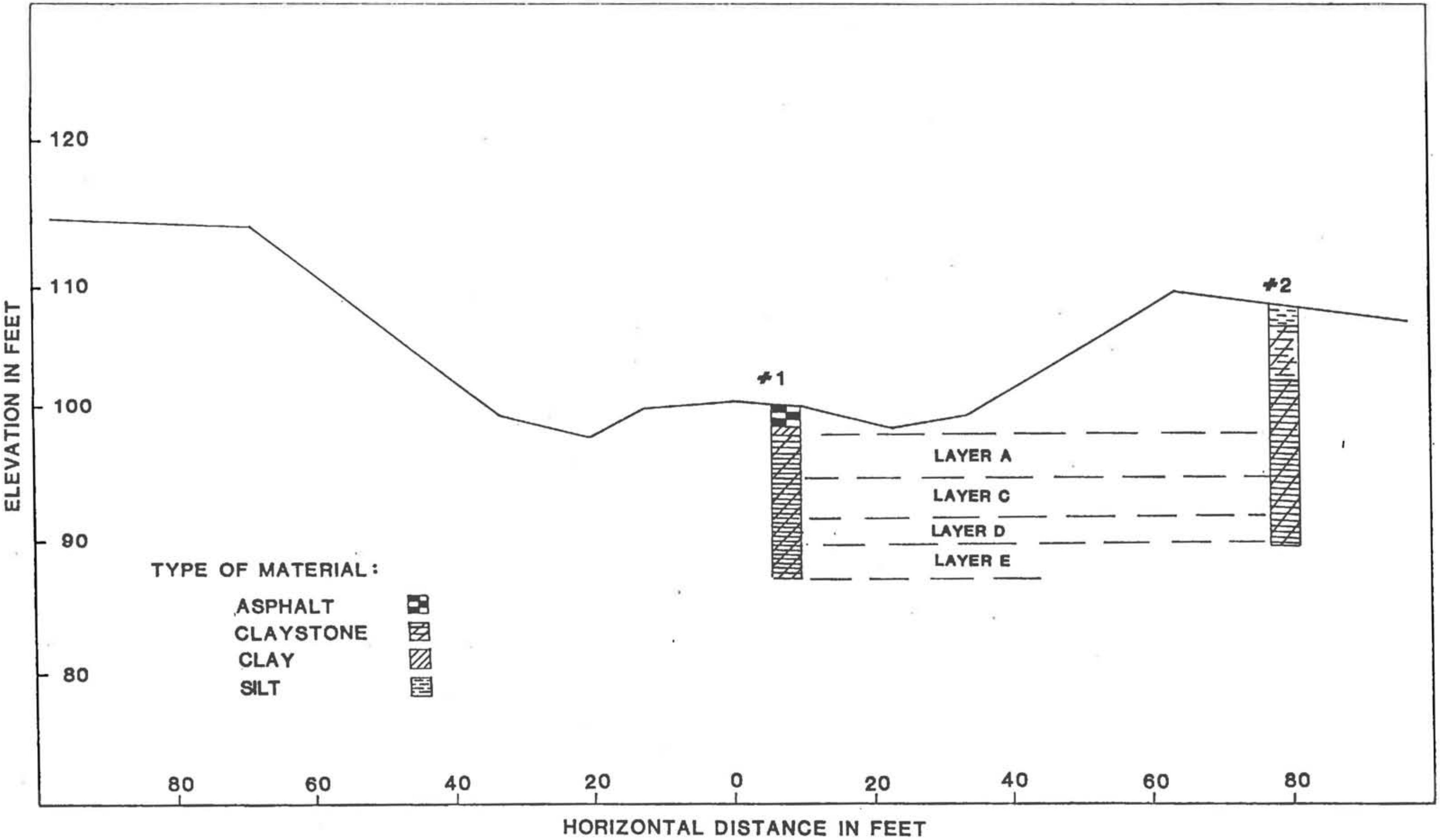


TABLE C

CROSS SECTION OF HIGHWAY CUT AT SITE B

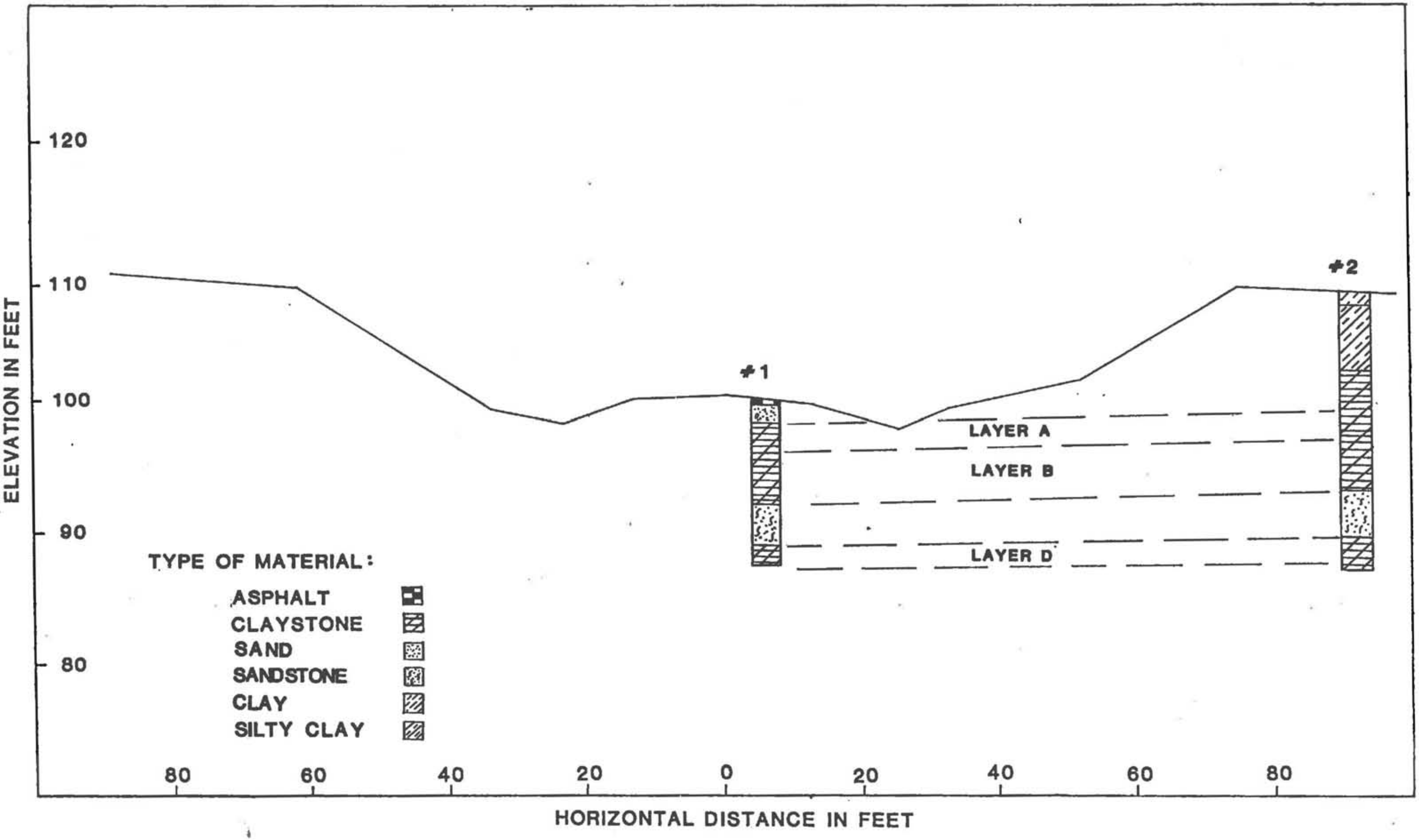


TABLE C

CROSS SECTION OF HIGHWAY CUT AT SITE C

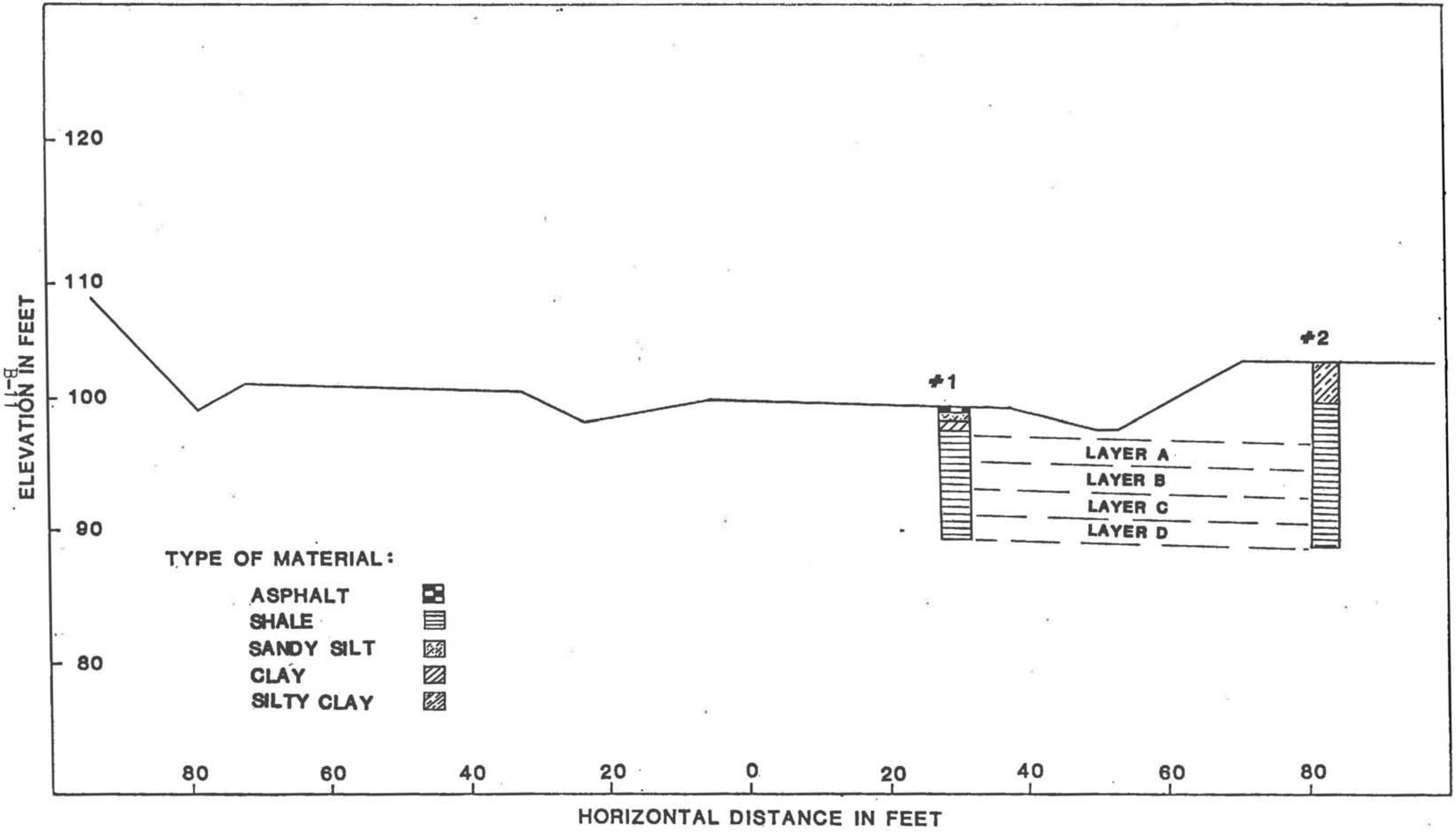


TABLE C

CROSS SECTION OF HIGHWAY CUT AT SITE D

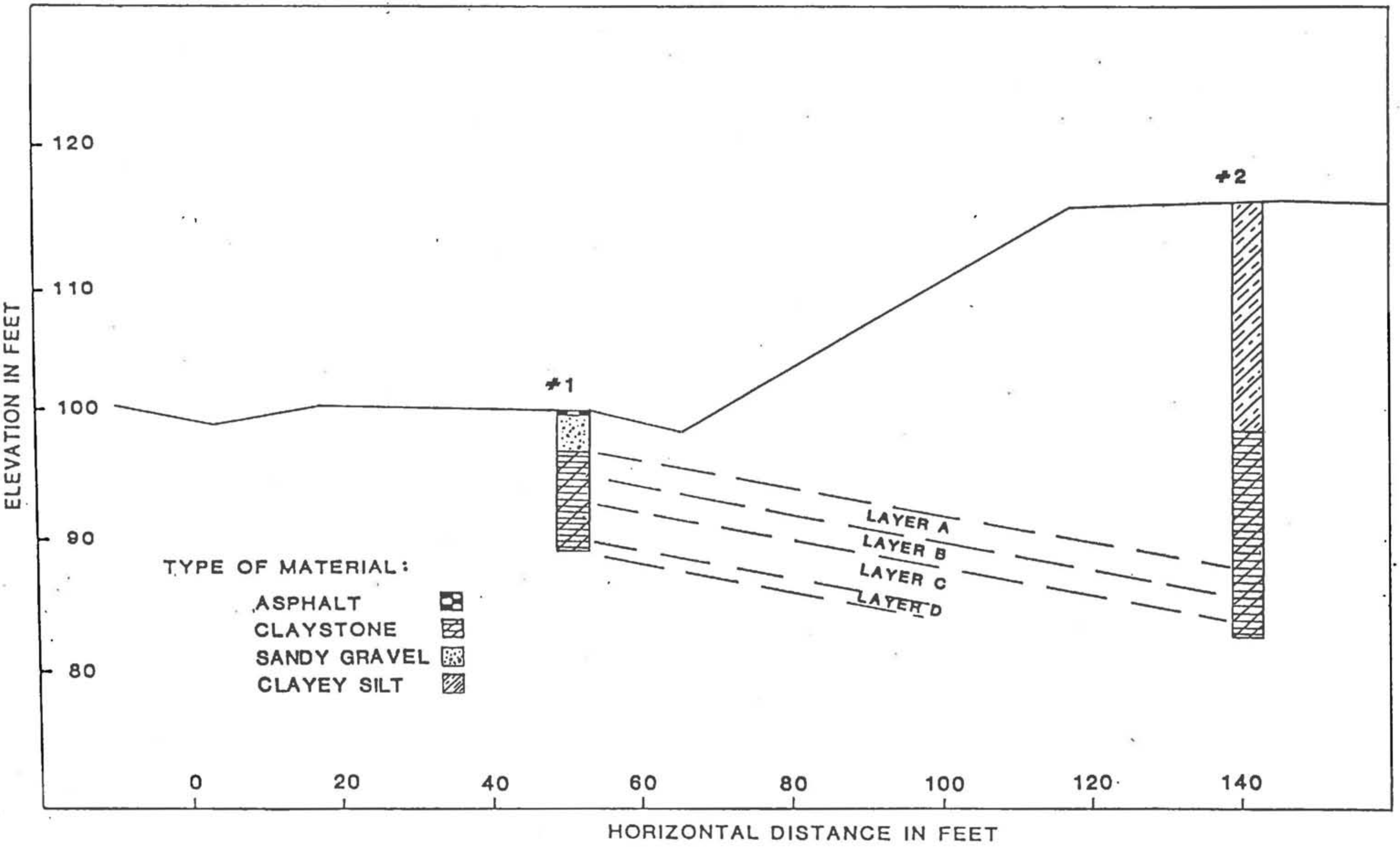
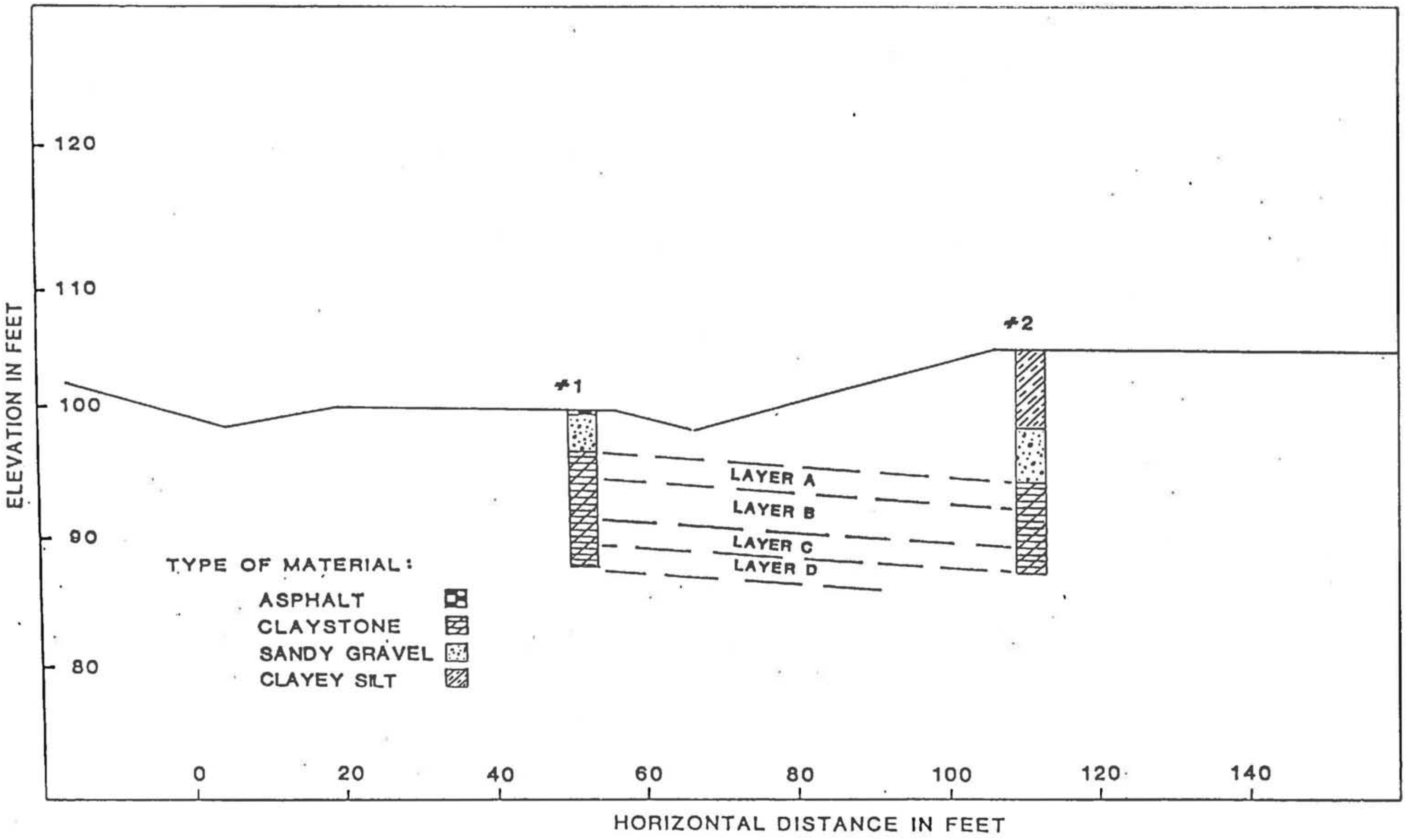


TABLE C

CROSS SECTION OF HIGHWAY CUT AT SITE E



APPENDIX C

DEFINITIONS

Soil Suction - It is a measure of the pulling force exerted on water by a soil.

Montmorillonite - A clay mineral which increases in volume with an increase in moisture content.

In-Situ Moisture - The percent of moisture within an undisturbed soil or rock.

Equilibrium Moisture - The maximum or final moisture content within subgrade material.

Third Cycle Expansion Pressure Test - A method of determining the amount of vertical expansion pressure exhibited by a soil specimen (remolded at a specific moisture and density) when inundated with water. The test procedure is designated as Colorado Procedure L-3103.

Consolidometer - A device to hold a soil sample in a ring which is either fixed to the base of the consolidometer or floating (supported by friction on periphery of sample) with porous stones on each face of the sample. The consolidometer provides a means of submerging the sample, for applying a vertical load and for measuring the change in thickness of the sample.

Shelby Tube - A thin-wall sample spoon used to obtain "Undisturbed" soil samples. The wall thickness is approximately

1/16 in. and the diameters usually range from 2 to 4 inches.

Psychrometer - A device for measuring relative humidity.

Void Ratio - The ratio of the volume of void space to the total volume of the particles within a mass.

Atterberg Limits - The Different states of soil consistency as defined by the Liquid Limit, Plastic Limit, and Shrinkage Limit tests.