Field Monitoring of Expansive Soil Behavior

Hsiu C. Lee, Patricia S. Pomper, and Warren K. Wray

Two field test sites were constructed to monitor the behavior of slab-on-ground foundation models constructed over expansive soils and the change in soil moisture conditions as a function of climate. One site was constructed in a dry climate (Amarillo) and the second site in a relatively wet climate (College Station); both sites were monitored monthly for 3 years. Immediately following construction of the Amarillo site, a 3 year drought ended and the subsequent 3 years were much wetter than normal. Because of the increased soil moisture content, the east end moisture cells stopped working, but the psychrometers on the west end of the slab model worked well over the full study period. Similarly, a 1½ year drought at College Station ended the month following site installation and the whole site experienced a general heave of the soil surface, including the slab model. The site continued to experience above average rainfall for approximately 24 months, after which a new period of drought began. During this wet period, nearly all of the 84 moisture cells stopped working because soil conditions were too wet, and more and more of the 160 psychrometers failed to yield suction readings as the study period continued. Fewer than 20 of the psychrometers were yielding readings by the end of the second year; however, the number of instruments providing readings had increased to more than 50 during the drought of the third year of the study.

Two field test sites were constructed to monitor the behavior of slab-on-ground foundation models constructed over expansive soil and the change in soil moisture conditions at each site as a function of climate. One site was constructed in a dry climate in Amarillo, Texas, and the second site was constructed in a relatively wet climate in College Station, Texas. The two sites were both constructed in 1985 and were monitored monthly subsequent to construction.

Two types of soil moisture monitoring instrumentation were installed at each site. One type of instrumentation was to measure the change in soil water content using a fiberglass moisture sensor. The second type of instrument was a thermocouple psychrometer to measure soil suction. In addition to the soil moisture monitoring instrumentation, more than 230 surface elevation points were established at each site to monitor the change in surface elevation, which was expected to occur as a result of the changing soil moisture conditions.

This paper describes the characteristics of the test sites, the instrumentation installed to monitor changes in soil moisture conditions, the success of the instrumentation, and the validity of the results obtained from these instruments. It also presents some conclusions regarding the success of this instrumentation in achieving the desired objectives of (1) frequently measuring climate-induced changes in soil moisture conditions, (2) measuring the corresponding changes in surface elevations both on and outside the slab model, and (3) relating the observed changes in surface elevation to predicted shrink/swell magnitudes based on the measured changes in soil suction.

DESCRIPTION OF TEST SITES

Amarillo Site

The "dry" climate site was in Amarillo, Texas, on the eastern edge of the grounds of the Family Hospital Center. The site sloped approximately one percent from northwest to southeast. Initial surface vegetation included short grasses and common lawn weeds. The hospital kept the grounds mowed but did not irrigate. All watering of the site was from natural precipitation. The groundwater table was not found within 27.5 ft of the ground surface and was reported to be at least 50 ft deep at this location by city officials. Thus, the groundwater table was deep enough not to affect the changes in soil moisture content caused by seasonal changes.

Four separate soil strata were identified at the site. The first stratum was a reddish brown silty clay approximately 18 in. thick. This soil was composed of fill material that was partially topsoil and partially construction residue. The second stratum was a dark gray silty clay approximately 2 ft thick. Both of the first two layers were classified as CL in the Unified Soil Classification System (USCS) or A-6 in the American Association of State Highway and Transportation Officials (AASHTO) Soil Classification System. The third layer was a light gray silty clay approximately 3 ft thick. Underlying the third stratum, to a depth of at least 27.5 ft, was a very similar light gray clay that was slightly more sandy and slightly less plastic. The third and fourth strata were both classified as CH in the USCS system and either A-7-5 or A-7-6 in the AASHTO system. Table 1 reports soil characterization results as determined from multiple tests for Atterberg limits, percent passing the No. 200 sieve, and the clay content of the total sample as determined by the hydrometer test for each foot of depth.

The in situ moisture content and the in situ soil suction were determined at each foot of depth for each of the 17 continuously sampled, 9 ft deep borings. The mean and the range of the 17 moisture contents at each depth are also shown in Table 1. The moisture contents indicated that, at the time of installation, the soil at the site was very dry near the surface but got progressively wetter to a depth of approximately 6 ft, whereupon the moisture content became a fairly constant value.

The in situ soil suction tests were accomplished using the filter paper method suggested by McQueen and Miller (*1*).

Department of Civil Engineering, Texas Tech University, Lubbock, Tex. 79409.

TABLE 1 SOIL PROPERTIES AT VARIOUS DEPTHS FOR THE AMARILLO TEST SITE

DEPTH (ft)	MOISTURE CONTENT (%)		PLASTIC LIMIT (%)		LIQUID LIMIT (%)		PLASTICITY INDEX (%)		PERCENT PASSING No. 200 SIEVE (%)		PERCENT CLAY (<0.002 mm) (%)		FILTER PAPER SOIL SUCTION (pF)	
	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)
0-1	8.3	(4.9-9.8)	23.2	(19.8-25.7)	37.3	(35.6-39.8)	14.1	(11.5-16.7)	62	(49-66)	47	(43-50)	5.3	(5.0-5.5)
1-2	10.5	(7.1-13.1)	19.8	(18.4-21.9)	35.0	(32.2-37.1)	15.3	(13.7-18.4)	57	(55-61)	46	(43-47)	5.0	(4.9-5.1)
2-3	13.8	(8.2-18.0)	20.5	(17.7-24.8)	33.9	(32.4-36.8)	14.1	(11.9-15.5)	59	(50-65)	42	(38-47)	5.0	(4.7-5.8)
3-4	17.8	(15.8-19.8)	26.0	(21.8-33.8)	64.3	(57.9-73.3)	38.4	(35.6-40.0)	82	(64-96)	62	(49-70)	4.8	(4.7-4.9)
4-5	19.7	(17.3-22.2)	29.3	(27.1-30.8)	77.2	(67.4-83.1)	54.2	(52.5-56.2)	75	(66-87)	59	(50-68)	4.7	(4.5-4.8)
5-6	21.7	(17.5-24.5)	36.5	(26.9-44.2)	75.8	(69.5-81.3)	39.3	(31.1-54.3)	83	(83-89)	63	(57-67)	4.6	(4.4-5.0)
6-7	24.2	(20.9-27.0)	31.0	(26.3-38.4)	74.3	(72.0-77.3)	43.4	(33.6-49.1)	83	(79-87)	64	(61-66)	4.4	(4.2-4.7)
7-8	22.7	(20.8-25.7)	28.6	(25.4-34.6)	68.7	(64.3-72.9)	40.1	(29.7-47.0)	78	(77-80)	64	(62-66)	4.4	(4.2-4.7)
8-9	23.5	(16.8-26.8)	27.4	(25.8-30.3)	66.3	(54.2-76.9)	34.8	(15.8-51.1)	81	(80-84)	61	(59-64)	4.3	(4.1-4.7)

The values were determined using S&S No. 589 White Ribbon filter paper and the McKeen calibration curve (*2*). The means and ranges of the 17 suction values are also reported in Table 1. The in situ soil suction values also indicated that the soil near the surface was very dry; the suction to a depth of 3 ft exceeded 5.0 pF. ("pF" nomenclature is used to define soil suction in terms of the common logarithm of the height in centimeters of a column of water needed to give an equivalent suction pressure; 5.0 pF is equivalent to 98.06 bars; see Appendix for other soil suction conversion factors.) The soil became wetter with increasing depth, but was still quite dry at a depth of 9 ft, the maximum depth of the continuous sampling. X-ray diffraction analysis of each soil strata was also performed. The results from this test indicated that smectite was the principal clay mineral constituent for each stratum.

College Station Site

College Station, Texas, was chosen as the "wet" site. The actual location was within the farm equipment compound of the Texas A&M University College of Agriculture. The area sloped at approximately three percent from east to west. At the time of installation, the surface of the site was covered with tall grasses and weeds. Three tall, mature trees shaded the site for parts of the day. The site was not irrigated; all precipitation occurring at the site was the result of natural rainfall.

Three separate soil strata were identified on the site. The top stratum consisted of 2 ft of a silty fill material mixed with large aggregate. The second stratum was a dark gray medium stiff silty clay approximately 5 ft thick. Underlying the second stratum was a grayish brown silty clay that extended to approximately the 16 ft depth. Both soils classified as CL in the USCS system and A-7-6 in the AASHTO system. At a depth of 16 ft, a thin lens of clean white sand was encountered. A grayish brown silty clay similar to the third stratum, classifying as CH and A-7-6, extended to the limit of the deepest boring of 25 ft. The groundwater table was not encountered within 25 ft of the surface. Table 2 reports soil characterization results as determined from multiple tests for Atterberg limits, percent passing the No. 200 sieve, and the clay content of the total sample as determined by the hydrometer test for each foot of depth.

The in situ moisture content and the in situ soil suction were determined at each foot of depth for each of the 17 continuously sampled, 9 ft deep borings. The mean and the range of the 17 moisture contents are also shown in Table 2. The moisture contents indicate that at the time of site installation, the soil was relatively dry. The soil suction values also indicated that the soil was relatively dry near the surface. However, at the 2–3 ft depth, the suction reduced to 4.3 pF, a value that remained unchanged to the 8–9 ft depth. This value is also approximately equal to the wilting point of plants. X-ray diffraction analysis of each soil strata was also performed. The results from these tests indicated that smectite was the principal clay mineral for each layer.

INSTRUMENTATION

Objectives

The two principal objectives from a data collection viewpoint were to collect information on vertical shrink/heave and changes in soil moisture conditions as the climate changed over a period of several seasons. The changes in surface elevation were ultimately to be related to the changes in the soil moisture conditions at the sites. To express quantitatively the soil moisture conditions, two variables—gravimetric moisture content and total soil suction—were selected for measurement. These soil moisture variables can be measured in situ with several commercially available sensors. Instrumentation selected for this study consisted of fiberglass fiber sensors manufactured by Soiltest, Inc., to measure changes in gravimetric moisture content, and thermocouple psychrometers manufactured by J.R.D. Merrill Co. to measure changes in

TABLE 2 SOIL PROPERTIES AT VARIOUS DEPTHS FOR THE COLLEGE STATION TEST SITE

DEPTH (ft)	MOISTURE CONTENT (%)		PLASTIC LIMIT (%)		LIQUID LIMIT (%)		PLASTICITY INDEX (%)		PERCENT PASSING No. 200 SIEVE (%)		PERCENT CLAY (<0.002 mm) (%)		FILTER PAPER SOIL SUCTION (pF)	
	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)	Mean	(Range)
0 - 1	6.4	(3.3-14/4)	16.7	(16.2-17.4)	26.1	(23.3-30.9)	9.4	(6.7-15.5)	33	(29-39)	23	(18-28)	4.9	(4.6-5.1)
1 - 2	8.9	(2.7-23.6)	20.3	(17.9-23.5)	40.0	(21.2-63.1)	19.7	(3.3-39.6)	36	(33-39)	23	(18-29)	4.5	(3.0-4.9)
2 - 3	18.7	(2.8-29.4)	22.4	(19.5-24.4)	51.9	(46.9-59.7)	29.4	(22.5-36.3)	62	(60-65)	52	(48-56)	4.3	(2.3-4.8)
3 - 4	17.4	(10.7-31.7)	19.6	(18.7-20.7)	45.1	(40.2-48.2)	25.5	(20.9-28.1)	62	(57-69)	49	(40-57)	4.3	(4.0-4.7)
4 - 5	16.9	(10.0-21.2)	23.3	(21.6-25.0)	48.0	(40.1-54.5)	24.7	(18.5-31.3)	62	(58-67)	48	(40-61)	4.3	(3.9-4.5)
5 - 6	17.9	(14.5-20.3)	18.7	(18.6-19.0)	45.5	(36.9-52.8)	26.8	(18.3-33.9)	65	(59-69)	42	(37-48)	4.3	(4.2-4.4)
6 - 7	20.8	(12.8-26.2)	23.2	(20.5-27.9)	48.8	(42.8-54.4)	25.6	(22.3-28.1)	64	(63-66)	50	(44-53)	4.3	(4.0-4.5)
7 - 8	23.9	(16.8-30.7)	29.3	(25.9-31.8)	57.6	(50.6-65.8)	28.3	(20.5-39.9)	79	(74-88)	59	(46-68)	4.3	(4.1-4.6)
8 - 9	29.1	(24.5-30.7)	30.5	(25.4-33.0)	64.4	(46.1-78.5)	34.0	(20.6-45.5)	94	(86-98)	72	(63-82)	4.2	(4.1-4.5)

soil suction and soil temperature; the psychrometer was covered with a No. 400 mesh stainless steel protective tip.

Moisture Cells

The concept behind the fiberglass electrical soil moisture instrument is described in Colman (*3*) and Colman and Hendrix (*4*). The instrument operates on the principle that the electrical resistivity of porous material (e.g., fiberglass) is related to its moisture content. When embedded in the soil, it absorbs soil water until equilibrium with the soil is reached. The resistivity reading is then calibrated against the moisture content of the soil. The fiberglass moisture cell is a sandwich composed of two monel screen electrodes separated by two layers of fiberglass cloth and wrapped around with three layers of the same material. The electrical resistance between screens, through the fiberglass cloth, varies in response to changes in moisture content of the soil in which it is placed.

The moisture cell calibration procedure followed that suggested by the manufacturer:

1. A moisture cell was placed in an approximately 1,000 g soil specimen, which was then wrapped in nylon fabric to prevent loss of soil during inundation.
2. The soil-moisture cell-nylon composite was weighed to the nearest 0.01 g.
3. Because the specimens were principally dry, the soil-moisture cell-nylon composite was then inundated in distilled water for a period of several hours.
4. At the end of the soaking period, the soil-moisture cell-nylon composite was removed, the surface blotted dry, a cell reading taken, and the composite weighed.
5. Step 4 was repeated several times until constant weights and moisture cell readings were obtained. This saturating process typically took several days.
6. Once stable soil wetness conditions were attained, the soil-moisture cell-nylon composite was allowed to air dry in a position that permitted air to have access to nearly all surfaces simultaneously.
7. Readings and weighings were taken at intervals that were based on the technician's experience. The composite was rotated after each weighing to ensure equal access to the composite surface by the room air and to negate the effects of gravity.
8. As the soil specimen dried, the drying process was assisted by an electric fan to ensure that the dry end of the calibration scale was reached (i.e., that the soil moisture content was drier than that which the instrument could detect).
9. At the conclusion of the wetting/drying cycle, approximately 100 g of the specimen was removed to determine a representative weight of the soil solids for each specimen. Then soil moisture contents were determined for each sensor reading and the results plotted on 5-cycle semilog paper. If the calibration curve lacked sufficient definition at any location, then the remainder of the calibration specimen was rewetted and the required additional calibration points were determined. Typically, 4 to 6 weeks were required to satisfactorily complete a calibration curve for the CH soil, although soils of smaller sample size and with less clay content can be calibrated in approximately 2 weeks. Figure 1 shows a typical moisture cell calibration curve.

The fiberglass moisture cell was selected in the study because of the apparent wide range of moisture contents over which the cell is useful and its apparent sturdiness. Moisture contents as high as pore-space saturation and moisture contents below the wilting point have been detected, according to the literature with the sensor. Its fiberglass cloth is more resistant to deterioration than are other porous materials (e.g., gypsum, which is soluble in soil water). Finally, its sturdy construction indicated that it would not require special handling or placement procedures because of its being delicate. A continuous record of in situ soil moisture changes can be easily obtained from an ohm readout device.

Thermocouple Psychrometers

Soil Suction

Unlike pure free water, water in soil is subjected to several forces that restrict or direct the movement of soil moisture

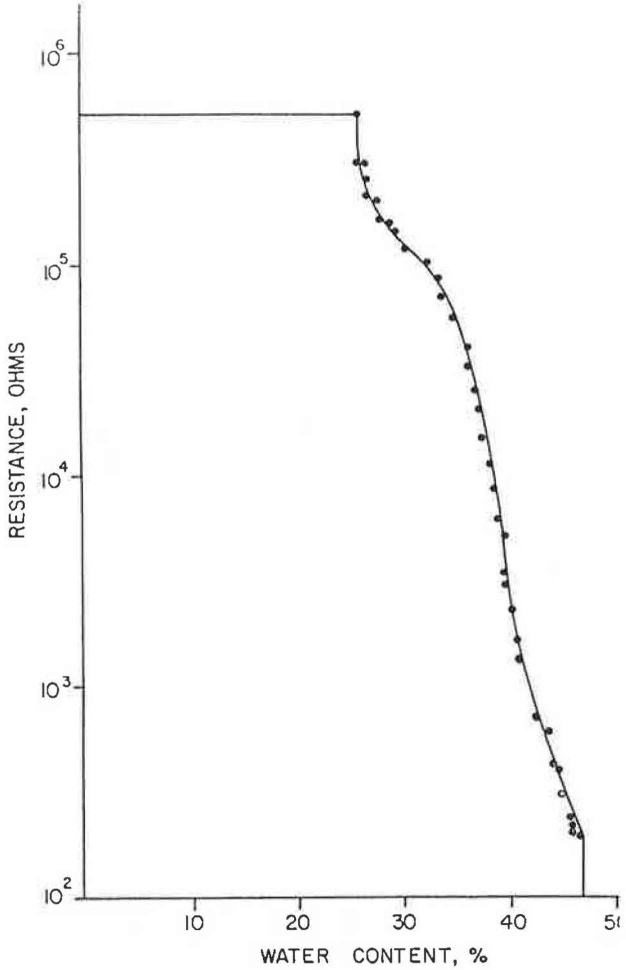

FIGURE 1 Typical calibration curve for a Soiltest moisture cell.

and result in a reduction of free energy. The difference in free energy between soil water and pure free water is termed soil water potential. A more precise definition is given by the International Society of Soil Science (ISSS) (*5*): "The amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water (at the point under consideration)." As suggested by ISSS, the soil water potential can be subdivided into components on the basis of the forces responsible for the difference in free energy between the soil moisture and pure free water, namely, matrix potential, osmotic potential, gravitational potential, and potential due to external gas pressure (pneumatic potential).

When gravitational and external gas pressure potentials are negligible, the soil water potential is termed "soil suction." This is the tensile pressure that must be applied to a unit area of water to prevent the water from entering the soil. In laymen's terms, it can be described as a measure of a soil's affinity for water (*6*). In general, the drier the soil, the greater is the soil suction.

Total soil suction, or difference in free energy, is related to the relative humidity of air in equilibrium with the soil water—a ratio of water vapor pressure of air in equilibrium with soil water to that of air in equilibrium with pure free water at the same temperature and pressure—by the following thermodynamic equation:

$$h = \frac{-RT}{g} \ln \frac{p}{p_0} \tag{1}$$

where

h = soil suction,
R = universal gas constant,
T = absolute temperature,
g = acceleration due to gravity,
p = vapor pressure of air in equilibrium with the soil water,
p_0 = vapor pressure of free water at the same temperature and pressure, and
p/p_0 = relative humidity.

The relative humidity ($H = p/p_0 \times 100$) will be less than 100 percent because the vapor pressure of soil water is less than that of pure free water. The reduction of vapor pressure in soil water over pure free water is the combined effect of matrix suction and osmotic suction. Thus, the soil suction value given by Equation 1 is a measure of the sum of the matrix suction and the osmotic suction and is termed "total suction."

Thermocouple Psychrometers

A thermocouple psychrometer (TCP) determines the relative humidity of soil moisture using the Peltier effect (i.e., production or absorption of heat at the junction of two dissimilar metals when a current is passed through the junction). Basically, the thermocouple is constructed using chromel and constantan wires, which together form a measuring junction. Two reference junctions are created slightly behind the measuring junction by attaching each of the constantan and chromel wires to separate copper wires of a larger diameter. Electrical current is then passed through the thermocouple to cool the measuring junction and condense a small bead of water on the junction. After the current is switched off, the condensed bead of water begins to evaporate, further cooling the junction. The change in voltage caused by cooling from the evaporation of the bead of water is then measured with a microvolt readout device. The microvolt readings are then calibrated with soil suction by using solutions of known water potential.

Calibration

Each thermocouple psychrometer was individually calibrated in the following manner:

1. The TCP was suspended in one end of a closed stainless steel calibration chamber that was compatible with the Merrill psychrometers. This chamber could be sealed to prevent the exchange of the atmosphere of known relative humidity inside the chamber with that of the ambient laboratory room atmosphere.
2. A piece of No. 40 Whatman filter paper was saturated in an NaCl solution of known molality and water potential

and then sealed in the opposite end of the calibration chamber used in Step 1.

3. The sealed calibration chamber was then immersed in a large tank of water. The ambient temperature of the room was controlled to remain at 65° ± 2°F. The water bath prevented sudden changes in temperature caused by air conditioning/heating equipment starting and stopping and fluctuations caused by doors to the laboratory opening and closing. The water bath temperature consistently remained at 65° ± 0.5°F.

4. The relative humidity in the small calibration chamber was permitted to come into equilibrium. The period typically required to reach equilibrium was approximately 1 hr; however, the minimum period employed was 2 hr, to ensure that complete equilibrium had been attained before proceeding to the next step.

5. The microvolt output from the readout device was checked periodically, beginning at an elapsed time of approximately 1 hr into the equilibration period. If the microvolt output remained constant, then a recorded calibration reading was taken at an elapsed time of 2 hr.

6. The microvolt reading was then plotted as a function of the water potential corresponding to the molality of the NaCl solution used in each calibration step.

7. The calibration chamber was removed from the water bath, opened, the filter paper removed, and the chamber cleaned and dried. Another piece of filter paper saturated in a different molal NaCl solution was then inserted into the calibration chamber and the procedure repeated until a definitive curve was produced. A typical calibration curve is shown in Figure 2.

The psychrometer is reported to have a measurable range of 3.0 to 6.2 pF (*6*). Thus, it becomes unreliable when the soil moisture content approaches saturation (≈3.0 pF). However, its range is such that it was judged to be able to provide reliable measurements over most soil moisture conditions expected to be encountered in this study. The psychrometer can measure only total suction; thus, if the matrix or osmotic components are desired, other methods of measurement must be employed. In certain subsurface conditions, the thermocouple can become corroded and fail to function, particularly in soils with high salinity; however, high-salinity soils were not the case in either location in this study. Relative humidity (and thus the psychrometer reading) is dependent on temperature. Therefore, thermocouple psychrometers were selected for this study. The thermocouple provided the temperature within a few millimeters of the tip of the thermocouple. This temperature measurement permitted the psychrometric reading to be corrected for temperature. Because of the possibility of instrument loss from thermocouple corrosion, damage during installation, or other unforeseen reasons, 100 percent redundancy in instrumentation was employed at each test site.

Surface Elevation Changes

Movement of the ground surface, both beneath as well as outside the slab-on-ground foundation model, was to be an important measurement of the study. To measure these changes in surface elevation, elevation points were established in a grid pattern with measurement points 3 ft on-center in each direction, including points 3 ft and 6 ft outside the perimeter of the slab model. The Amarillo site had a total of 247 elevation points with a line of points on the transverse centerline, whereas the College Station site totalled 234 points with no measurement points installed along the transverse centerline. The points outside the slab model consisted of 16d nails driven into the ground with red plastic flagging identifying each location. The points on the membrane were constructed of 6 in. high by ½ in. diameter PVC pipe glued to a 3 in. square plastic plate. The vertical PVC pipe was cut on a diagonal at

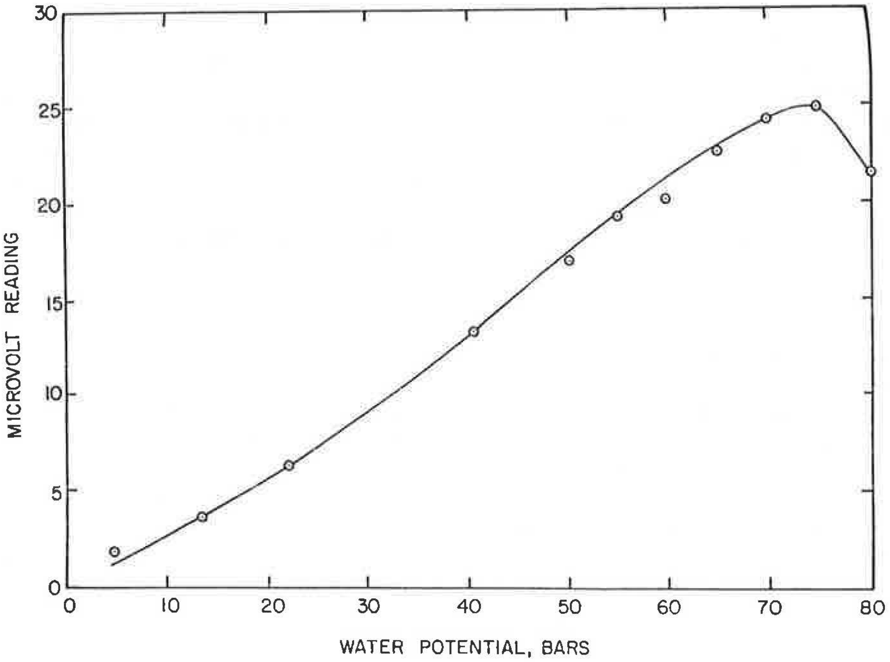

FIGURE 2 Typical thermocouple psychrometer calibration curve.

the top, so that a definite high point was provided for consistent elevation measurement points. The flat plate bottom of the elevation points was placed directly on the plastic membrane on 3 ft centers and covered with approximately 2 in. of sand. Surface elevations were measured along conventional engineering surveying equipment. All elevations were referenced to a permanent bench mark set at an elevation of 27.5 ft (Amarillo) or 25 ft (College Station). Details of the bench mark construction is presented elsewhere (*8*).

Instrumentation Layout

The instrumentation was placed beneath the covered surface in two identical parallel rows spaced 2 ft north and 2 ft south, respectively, of the longitudinal centerline. The rows were aligned parallel to the longitudinal dimension of the slab model and were symmetrical about the transverse centerline. The plan view of the instrument locations is shown in Figure 3.

Instrumentation Installation

Thermocouple psychrometers were placed in each location at depths of 1, 3, 5, 7, and 9 ft below the surface. All but the three centermost instrument locations in each row also had moisture cells installed at depths of 1, 3, and 5 ft below the surface. Figure 4 shows the vertical arrangement (termed a stack) of one row of the instrumentation. Each instrumentation location was augered using a truck-mounted auger, capturing and separating the removed soil in 1 ft increments. An egg-sized "ball" of soil from the appropriate depth was then molded around each sensor and carefully lowered back into the hole to the proper depth. Then the soil was carefully compacted back into the hole at the depth from which it was removed (at least to the nearest foot). The instrumentation was checked frequently to ensure that it was still operating before backfill and compaction proceeded too far, to prevent removal and replacement of a damaged device. The instrumentation holes were advanced by commercial testing lab personnel. Texas Tech University personnel performed all other installation activities.

CLIMATE

Amarillo Test Site

Amarillo has a dry steppe climate marked by mild winters. The average annual precipitation is 19.10 in. More than three-quarters of this annual amount typically occurs in the period May through October, usually in the form of thunderstorms. Monthly and annual precipitation amounts are extremely variable. Winter is usually a dry season, with most precipitation occurring as light snow. The mean daily high and low temperatures in the summer months are 88°F and 64°F, respectively. The mean daily high and low temperatures during the winter months are 50°F and 25°F, respectively.

The 5 years preceding site installation were drier than normal. This drought ended in August, 1985 (Month 1 of the study), and, although seasonal fluctuations were present, conditions during the study period were overall much wetter than normal. The 44-year historical Thornthwaite Moisture Index (TMI) for Amarillo is −21.9 in./yr. The five years preceding the study had an average TMI of −27.3 in./yr, but the TMIs for the three 12-month periods of this study were a very wet −7.4, −12.5, and −2.1 in./yr, respectively. KGNC radio station, located less than one-quarter mile from the site, re-

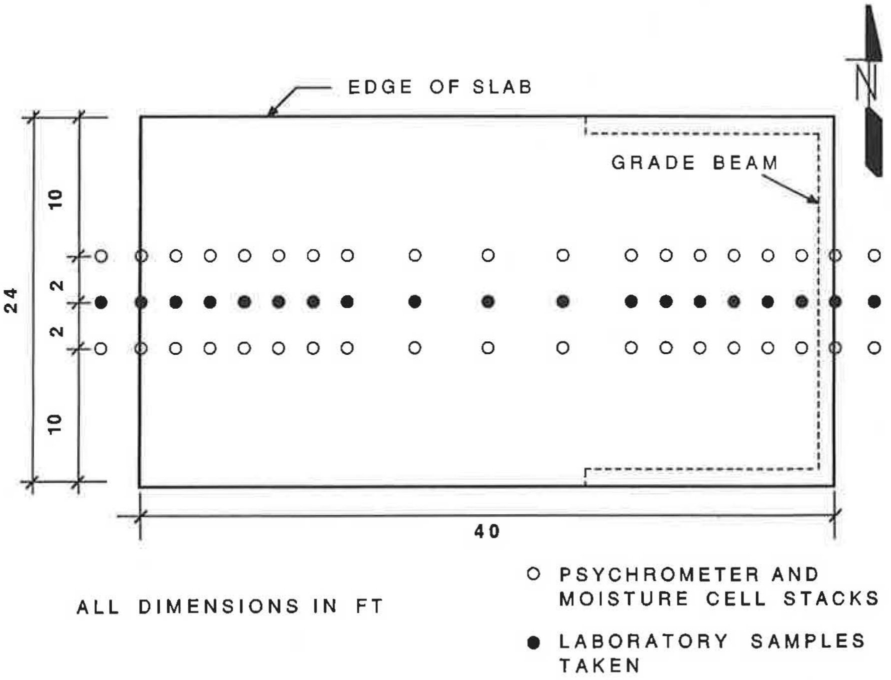

FIGURE 3 Test site layout showing dimensions of the test slab model, instrumentation stacks, and sampling locations.

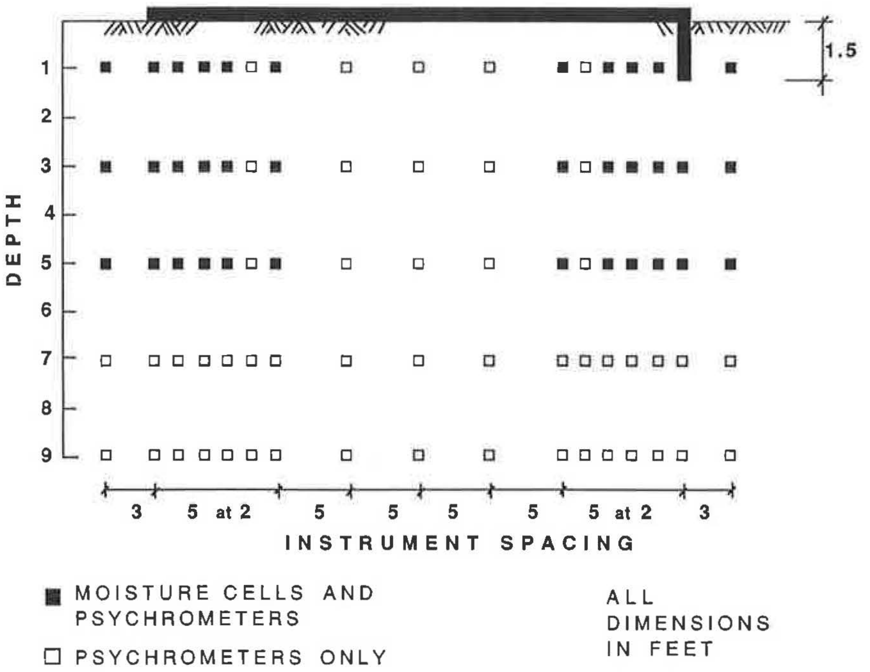

FIGURE 4 Vertical location and distribution of the instrumentation installed at the Amarillo site.

corded daily temperature and precipitation values for the period of this study. Thus, the climatological data was considered to be site specific.

College Station Test Site

College Station has a warm-temperate, humid, continental climate that is modified by breezes from the Gulf of Mexico. The summers are long, warm, and dry. The winters are short and mild and characterized by short periods of clear cold weather that is freezing at times. The average temperature during the summer months is 83°F, and during the winter months it is 52°F. The annual precipitation averages approximately 38.8 in. Droughts of varying duration and severity occur during the months of July, August, September, and October. Although the rainfall averages more than 2.4 in./month during these months, it may fall in only one or two events and with such intensity that a large part of it runs off before it has an opportunity to infiltrate the soil. The greatest rainfall historically occurs in May, but during January, February, and sometimes December, when the humidity is high and the rate of evaporation low, the ground becomes saturated and remains so for several days. Rain usually falls more slowly in winter than at other times of the year.

College Station was under drier than normal conditions in the months immediately preceding site construction. Subsequent to site installation, the climate became wetter than normal for the first 2 years. The final year experienced drought conditions. The 74 year mean TMI for College Station is a nearly neutral −0.5 in./yr. The TMIs for the three 12 month periods of this study were +5.3, +28.1, and −19.5 in./yr. The Texas A&M College of Agriculture weather station, located approximately 100 yd southeast of the research site, recorded daily temperature and precipitation data. Thus, the climatological data used in this study was considered to be site specific.

MEASUREMENTS AND RESULTS

Moisture Cell Measurements

Amarillo Site

The soil moisture content change measurements obtained during the period of this study were disappointing. The moisture cell measurements failed to provide any significant contribution to the study, apparently because of the extreme weather conditions experienced at each site. The in situ soil moisture content exceeded the range of the sensors, apparently as a result of the extended rainy period at the beginning of the study. Brief drought periods experienced later at the site also made the instruments fail to function when the soil dried out and lost contact with the moisture cells.

College Station Site

As with the moisture cell readings obtained at the Amarillo site, the College Station site also initially encountered soil moisture conditions that were beyond the wet end of the cells' sensitivity. Then came the drought period, during which some moisture cells reactivated and began to give readings. Because of the sporadic nature of the results obtained during each measurement visit, the moisture cell readings were judged to be of little assistance in understanding the changes that were observed to occur at the site.

Thermocouple Psychrometer Measurements

The soil suction data were collected by calibrated thermocouple psychrometers and, as one form of data presentation, plotted in the form of contour lines of constant suction value using units of pF. All measurements were taken by university personnel. A typical contoured suction value presentation is shown in Figure 5. Each psychrometer was read at least three times during each measurement visit; a consistency in readings was taken to be a valid reading. Each psychrometer reading was corrected for temperature. Two psychrometers were installed at each depth; thus, if both sensors were operating, one provided a check on the other. Typically, "sister" psychrometers yielded readings within ± 0.2 pF of each other. However, sister readings occasionally exceeded this differential range. In these instances, judgment had to be used to determine which reading was invalid

Another check on the data was available. Since theoretical wet and dry steady state soil suction conditions, based solely on changes in climate, could be developed for each site, any data falling outside this envelope could be considered to be either in error or influenced by factors other than only climate (e.g., trees at the College Station site during the hot, dry summer months) (*7,8*). The influence of surface cracks, particularly during periods of drought, can often influence a psychrometric reading, even if the sensor is several feet inside a covered surface. A precipitation event immediately preceding a measurement also was found to have a significant influence on the readings obtained from some psychrometers (*8,9*).

A comparison of rainfall versus the number of working psychrometers is shown in Figures 6 and 7. Although it is likely that more factors are involved in the failure of the TCPs than just rainfall, the figures show a definite correlation between long-term wet and drought conditions and the number of psychrometers yielding readings each month.

Amarillo Site

The soil at the site was very dry and nearly desiccated at the time of site installation. This condition was indicated by the in situ soil suction values ranging from a very dry 5.3 pF at a depth of 0 to 1 ft to a still quite dry reading of 4.3 pF at a depth of approximately 9 ft.

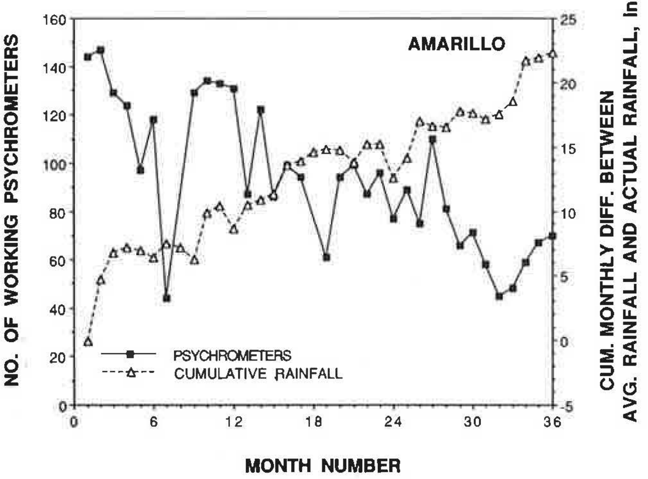

FIGURE 6 A comparison between the number of thermocouple psychrometers yielding readings during each monthly measurement visit to the Amarillo site and the surplus or deficit of precipitation each month with respect to the average precipitation for that month.

Two observations can be made from Figure 5, which depicts soil suction variations beneath the slab model one month after site installation. First, the soil immediately beneath the cover has become slightly wetter than the soil at a greater depth. This increase in moisture is attributed to the suction gradient continuing to draw moisture from depth as it was doing before installation of the impervious cover interrupted the moisture transfer to the atmosphere at the surface. Second, the essentially horizontal contour lines have been disturbed outside the cover by moisture entering the soil as a result of the rainfall occurring immediately after the site construction.

For most of the first 30 months of the study, the soil suction remained a fairly constant 4.2 to 4.4 pF at the soil surface

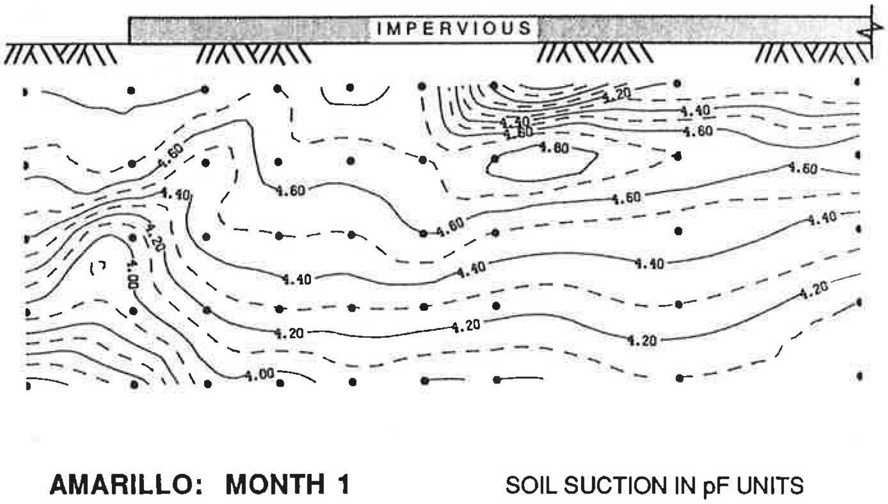

FIGURE 5 Lines of constant soil suction occurring beneath the west half of the slab model, as measured during the first measurement visit to the Amarillo site following test site construction.

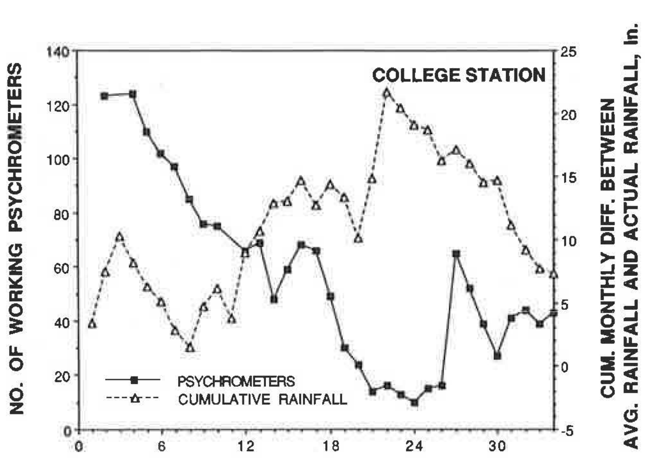

FIGURE 7 A comparison between the number of thermocouple psychrometers yielding readings during each monthly measurement visit to the College Station site and the surplus or deficit of precipitation each month with respect to the average precipitation for that month.

beneath the center region of the cover. Beginning at about Month 30, the soil suction data begins to indicate a wetting trend, with suction values trending to the 3.8–3.9 pF range. This wetting trend is consistent with the gradual development of a center lift mound at about this time (*8*).

College Station Site

The soil at the College Station site also was initially very dry. The soil suction near the surface was 4.9 pF, but the initial soil suction rapidly decreased to 4.3 pF at a depth of 2–3 ft and remained at this value until the average reduced slightly to 4.2 pF at the 8–9 ft depth. The contour lines for the College Station site (Figure 8) are not nearly as well defined as those at the Amarillo site. The poorly defined soil suction changes beneath the slab model are attributed to the influence of three mature trees located some 25 ft away from the edge of the site. As both the period of the study lengthened and the extended period of wet climate continued, more and more psychrometers failed to respond during measurement visits (Figure 8). During the Month 24 readings, as few as 10 of the 160 psychrometers yielded readings. However, drought conditions returned at about Month 25, and the number of working psychrometers subsequently began to increase, especially those located outside and near the edge of the slab model. These TCPs continued to report drying soil moisture conditions as the drought persisted. As many as 50 TCPs "revived" to yield readings over the last 8 months of the study.

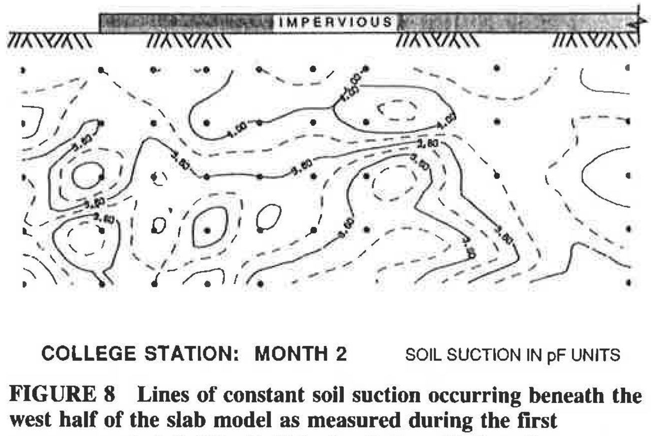

FIGURE 8 Lines of constant soil suction occurring beneath the west half of the slab model as measured during the first measurement visit (Month 2) to the College Station site following test site construction.

Surface Elevation Changes

All elevation points were determined and referenced to the 25-ft deep benchmark at each site of the time of site installation. The actual elevations of each site were then corrected to an assumed elevation of 10.00 ft in order to provide a horizontal reference plane. All subsequent elevation measurements were then referenced to this horizontal plane in order to better visualize the changes in the surface elevations as they occurred. Measurements were made using conventional engineering surveying techniques with an accuracy to the nearest 0.01 ft.

Amarillo Site

Four days after installation, 1.53 in. of rainfall fell on the site; a total of 5.31 in. fell on the site during the 39 days between installation completion and the first measurement. The dry soil had begun to respond to this rainfall by the time of the first measurement. Heave was being exhibited around the perimeter of the cover (edge lift distortion pattern). The greatest heave measured was 0.8 in., which occurred at the east end of the slab model, the end with the 18-in. deep perimeter grade beam. The climate continued to be wetter than normal over this period, resulting in a very definite edge lift. The heave at the east edge of the slab model reached 2.3 in., while the heave experienced by the west edge of the covered surface was 1.0 in. The large heave measured on the east end of the slab model stayed between 2.0 and 2.5 in. throughout the study period, although the actual heave did reflect slight seasonal changes. Beginning at about Month 24, a mound began to develop beneath the center of the cover (center lift distortion). This mound continued to grow both laterally and in height throughout the remainder of the study period, reaching a maximum heave of 1.8 in. (*8*).

College Station Site

The month in which the site was constructed (August 1985) was very dry. Twelve of the 17 months preceding the site installation had recorded a moisture deficit. However, the period September–November 1985 was very rainy. As a result of this wet period immediately following the site installation, the ground heaved and did so fairly uniformly. Heaves between 0.5 and 1.0 in. were prevalent beneath as well as outside the cover. By Month 11, a center lift distortion started to be exhibited, particularly on the west, south, and east sides of the cover. Maximum heave occurred in the southwest quadrant of the cover and was 1.7 in. The maximum heave recorded each month remained in the 1.9–2.3 in. range. The maximum heave recorded during the 36-month study period was 2.5 in. in Month 29. Beginning with Month 32, a gradual general reduction in surface elevations was noted through Month 36 when the study terminated and a definite center lift condition was present (*8*).

Predictions Based on Measurements

One of the principal objectives of the study was to determine if reasonable estimates of shrink or heave of expansive soils could be made using soil suction data. Using soil suction theory (*7,8*), an estimate of the maximum heave to be expected at each site was made. This estimate was predicted on soil properties at each site and the initial soil suction profile. An estimate of each month's shrink or heave was also made using the monthly psychrometer (soil suction) measurements. Figures 9 and 10 show a comparison between the theoretical predictions and the actual measurements using psychrometer measurements taken beneath the center of the covered surface at each test site. Each figure also indicates the estimated maximum heave to occur at each location; as can be seen, the theoretical maximum heave has been approached but not exceeded. The predicted monthly heaves for the College Station site (Figure 10) stop at Month 18. Subsequent to this date, soil moisture conditions became too wet for the instrumentation and no further readings were obtained from this instrumentation "stack." Nonetheless, both figures indicate good correlation between predicted and actual heaves.

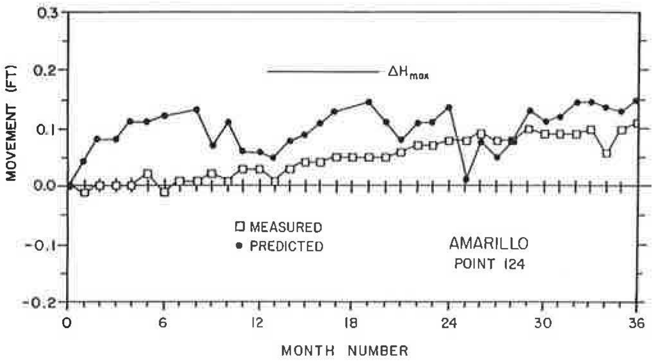

FIGURE 9 A comparison of the predicted month-by-month change in surface elevation with the measured surface elevation change at a point located at the intersection of the longitudinal and transverse centerlines of the Amarillo test site slab model [the maximum expected heave (ΔH_{max}) is also shown].

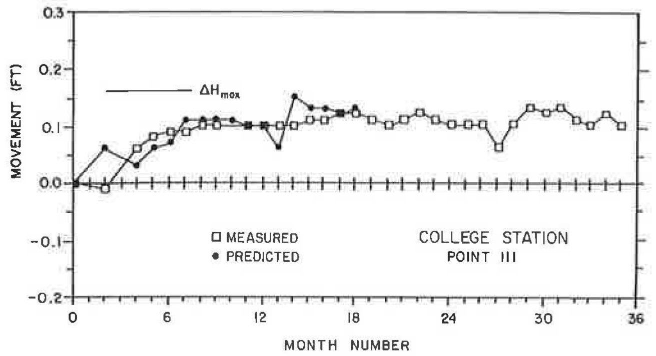

FIGURE 10 A comparison of the predicted month-by-month change in surface elevation with the measured surface elevation change at a point located 2 ft west of the transverse centerline and on the longitudinal centerline of the College Station test site slab model [the maximum expected heave (ΔH_{max}) is also shown].

CONCLUSIONS

Some conclusions can be made about the success of the instrumentation used on this study and the validity of the measurements obtained from these sensors.

1. Although the vendor of the fiberglass moisture cells has cited successful applications of this device in heavy clays, it appears that caution should be exercised when using this device in field applications in such clays unless soil moisture conditions are reasonably certain not to exceed the sensing bounds of the instrument. The use of this instrument in this field study must be considered to be a poor selection.
2. Use of thermocouple psychrometers on a study such as the one described above must be considered as being partially successful. The instrumentation provided monthly readings at the dry climate site without any significant problems under drought conditions. However, when saturation conditions were approached, the readings became either unobtainable or unreliable. Invariably, the sensors began functioning again or began to give reliable measurements once the wet conditions causing the loss of the instrument measurements began to become drier. Thus, the selection of thermocouple psychrometers for the dry climate site was, in retrospect, a good decision.
3. Use of thermocouple psychrometers proved to be a poor selection with respect to the wet climate site. Based on a review of prior year precipitation data, it appeared at the outset of the study that psychrometers would likely perform well over the duration of the measurement period. Although some localized or brief failure period due to excessively wet soil conditions was anticipated, it was expected that the sensor would soon recover and function once again when the wet conditions passed. Employing 100 percent redundancy in instrumentation was also thought to provide some hedge against any total loss in measurements. However, this was proven to be wrong when extremely wet weather persisting over a 2-year period plagued the site. It was also believed that the fiberglass moisture cell would provide some measure of the soil moisture conditions, should the soil approach saturation and become too wet for psychrometric readings. However, it was subsequently learned that the soil moisture conditions also exceeded the operating range of the moisture cell. Thus, the selection of the thermocouple psychrometer for the wet climate site proved to be a poor selection, although good data was obtained over approximately the first 18 months of the study.
4. Using the psychrometer measurements, converted to soil suction, to predict surface shrink and heave of the soil showed reasonably good comparisons between the predicted surface

elevation changes and the measured surface changes. Thus, it appears that reasonable predictions of the expected shrink and heave at an expansive soil site can be made if the proper soil characterization properties and if some knowledge of the in situ soil suction conditions are known.

At the time of instrumentation selection, a convenient device for making wet moisture condition measurements at depth was not commercially available. Thermal blocks, the precursor of the Moisture Control System (MCS) and Agwatronics sensors, were not considered to be practical for this installation. The MCS heat dissipation matrix soil sensor became commercially unavailable in 1979, and the Agwa-II heat dissipation matrix soil sensor was only introduced commercially at about the time of the site construction. The currently available Agwa-II sensor reportedly has a sensing range from approximately 0.1 bar to approximately 3 bars (higher potential sensors are reportedly available but require several months to acquire). Thus, were this study to be performed now it would be desirable to install both thermocouple psychrometers and heat dissipation sensors at the wet climate site to ensure that wet soil conditions are also captured.

SOIL SUCTION CONVERSION FACTORS

$$
\begin{aligned}
1{,}000\text{ cm } H_2O &= 0.9806 \text{ bars}\\
&= 0.9678 \text{ atm}\\
&= 14.2234 \text{ psi}\\
&= 98.0665 \text{ kPa}\\
&= 980.6650 \text{ dyne/cm}^2\\
&= 3.0000 \text{ pF}
\end{aligned}
$$

ACKNOWLEDGMENTS

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