Use of Dual Tube Nuclear Gauge for Crack Detection in Expansive Clay Soils

JUDITH B. CORLEY AND MARY ANNE RODRIGUEZ

Dual tube instrumentation was installed at vertical barrier projects in Texas to determine the spacing of horizontal cracks that transmit water through expansive clay soils. Site selection was contingent on roadway rehabilitation that included installation of a vertical moisture barrier. To date, six dual tube sites in Texas have been instrumented and readings taken. Field problems encountered were manufacturing defects with the sensor probe, moisture damage to the scintillation probe, and difficulty in extending readings to required depths due to poor design of the extension rods. The scaler ratemeter is susceptible to damage during normal transport. Data obtained in the field consisted of depths and count ratios for the source and sensor in the field-installed dual tubes. Density was determined using calibration curves of density versus count ratio supplied by the manufacturer. Plots of the density versus depth for each location were prepared and were studied to determine the crack pattern. Crack spacings of between 4 and 5 in. were obtained for four sites in climatic zones III-C and II-C, while spacings of 7 in. were obtained for two sites in or near climatic zone III-B.

Two types of pavement damage are commonly noted in pavements founded on expansive clay soils: pavement undulations, and longitudinal edge cracks. Pavement undulations consist of periodic areas of heave that normally extend across the pavement width and result in pavement roughness and concomitant decline in ride quality (*1*). Longitudinal edge cracks extend along the edge of pavement and result in a decrease in lateral support and an increase in evaporation at the pavement edge. Often the cracking phenomenon develops progressively, with a series of "parallel" cracks extending inward from the edge of pavement. This type of damage often results in a subsidence of the edge of pavement from the initial cross section.

The type and severity of pavement damage are affected by the subgrade moisture conditions. Site moisture conditions can vary from very dry conditions to wet conditions. When the subgrade is very dry prior to construction, the soil will have a fully developed array of horizontal and vertical cracks that divide the soil mass into blocks. Water may flow in the cracks as free water at a rate that is several orders of magnitude higher than that indicated by the low permeability of the intact clay. Thus the sides of the blocks are exposed to free water and are able to swell, while the centers of the blocks are not exposed to free water and remain very dry due to the low permeability of the clay within the block (*2*).

At the opposite end of the moisture spectrum, the subgrade could be initially in the wet condition, where the soil is "swelled" and the crack structure is closed. When the wet subgrade is covered with a pavement, evaporation occurs at the edge of pavement but cannot now occur from the covered soil. Shrinkage occurs at the pavement edge, and the marked difference in moisture conditions results in the development of a longitudinal crack. Once the longitudinal crack develops, it allows increased and deeper evaporation to occur, exacerbating the situation.

A wide variety of treatments have been used in efforts to control one or both of these classical damage mechanisms. One such method is to remove the expansive clay soil to a calculated depth and replace it with a compacted select fill. In addition to being expensive, the method had a tendency to result in rapid moisture availability to the subgrade through the select fill. Reed (*3*) reported that the method was unsuccessful in preventing pavement undulations.

A variation of the "remove and replace" method is the construction of a compacted fill of in situ soils. This approach has several positive aspects. There is no significant permeability difference between the subgrade and the compacted fill, so that no water source is created. In addition, the process of removing the soil, breaking it up into workable form, and recompacting in lifts destroys the crack structure. Time would be required for a new crack structure to reform, and the pavement would prevent drying. This approach is consistent with the observation that severe undulations are most often observed in cut sections and only after many moisture cycles in fill sections. A combination of both select fill and a layer of recompacted site clays was utilized on reconstruction of 131 miles of I-90 in South Dakota. Improved pavement performance with reduced maintenance expense was noted over a 13-year period (*4*).

An extension of the idea of compacting in situ soil above optimum moisture content is to prewet or preswell the subgrade without removal or recompaction. This technique may be carried out by ponding water at the surface or by multiple pass water injection (*3,5,6*). The soil is wetted using the existing crack structure, which is not affected by this process. These techniques are time consuming, create a difficult working environment, and do not prevent longitudinal edge cracking.

Horizontal barriers have been used and will continue to be used, both to improve highway safety and to control moisture stability in the driving lanes. The common horizontal barrier consists of the paved and sealed shoulder, which reduces evaporation from the edges of the driving lanes, thereby reducing longitudinal cracking within the lanes of traffic. Use of impermeable membranes below unpaved shoulders is an alternative to the paved shoulder horizontal barrier (*5*).

Texas Transportation Institute, Texas A&M University, College Station, Tex. 77843.

To achieve pavement stability on expansive clay subgrade, it is necessary to control both edge evaporation and water movement through the crack structure. Use of vertical moisture barriers offers promise to achieve control over both types of pavement distress (*1*). Providing that the barrier extends below the depth of the crack structure, free water flow will be controlled from entering or leaving the soil mass beneath the pavement. Evaporation will still occur beyond the vertical barrier, but the flow path for the soil beneath the pavement will be lengthened so that change in soil volume will be minimized. Unlike prewetting and horizontal barriers that are used in new construction, the vertical moisture barrier can be installed in existing distressed pavements as part of pavement rehabilitation efforts (*6*).

VERTICAL MOISTURE BARRIER PROJECTS

The Texas State Department of Highways and Public Transportation (DHPT) has a considerable history of installing and evaluating vertical moisture barriers for pavements founded on expansive clay. One of the early efforts was I-410 in San Antonio. This pavement had required repeated levelling efforts from the time of construction in 1960 until installation of the vertical barrier in 1978 (*6*). Additional moisture barriers were placed at I-37 and U.S. 90 in order to improve construction techniques and to decrease damage due to expansive clay subgrade. In all cases, the installation of the vertical barrier was part of a pavement rehabilitation project on a pavement already known to exhibit significant distress due to expansive clays. Favorable results were obtained for the early San Antonio projects, with maintenance costs for the barrier sections reduced from a minimum of $50,000 per year to zero (*7*).

Following the beneficial installations in San Antonio, a research project was undertaken by DHPT and the Texas Transportation Institute to consider several different types and depths of vertical barriers. This project was installed on I-30 in Greenville, Texas. Barrier tests included 8 ft deep fabric, 6 ft deep fabric, 8 ft deep pressure-injected lime slurry, and 8 ft deep pressure-injected lime/flyash slurry. Results of this project showed that test sections with the vertical moisture barrier deformed more than the control sections. The difference between the initial and the equilibrium suction conditions were considered to be the cause of the difference in performance of the Greenville sections. The more effective barriers permitted the equilibrium suction condition to be approached more rapidly (*8*).

An additional site has been installed and monitored in Sierra Blanca, in far west Texas. This site has demonstrated the effects of highly variable subgrade conditions, with surficial sands being underlain by expansive clays at depths ranging from 2.5 ft to 20.0 ft.

With succeeding efforts at installing and monitoring vertical moisture barriers in Texas, the level of understanding has improved. Efforts are now aimed at maximizing performance and predicting the behavior of installed barriers.

CURRENT PROJECT DESCRIPTION

Installation of dual tubes and monitoring of vertical density variations was performed as part of a project to control moisture variations under pavement sections founded on expansive clay soils using vertical moisture barriers. The project, which is still in progress, is funded by the DHPT and involves test sites throughout Texas. The project team consists of researchers from the Materials Division of the Texas Transportation Institute, Texas Tech University, and the University of Texas at El Paso. The project consists of several distinct phases:

- Coordination with highway engineers to select suitable sites;
- Instrumentation of sites and control sections wherr possible during installation of vertical barrier;
- Monitoring of pavement performance and subgrade suction conditions to evaluate effectiveness of vertical barriers;
- Preparation of a computer model to allow evaluation of sites for use of vertical barriers;
- Recommendations regarding suitability of vertical barriers for various regions in Texas and rational sizing methods to assure adequate performance; and
- Recommendations of construction improvements to facilitate installation of the barriers and minimize deterioration of pavement conditions due to construction.

Each dual tube installation is a permanent part of the pavement instrumentation and is generally located adjacent to the holes in which suction and temperature sensors were installed outside the vertical barriers. A schematic of a typical site installation is shown in Figure 1.

Installation of the dual tubes and monitoring of density with depth was conducted in order to provide input for the computer model. The computer model considers moisture flow in expansive clay soils to consist of free flow in vertical and horizontal cracks, followed by gradual infiltration of the water into the clay clods. Determination of the size of the clay clods and the depth of cracking of the expansive clay is necessary in order to utilize the computer model. The model also is capable of handling multiple soil layers that may be present in some locations.

Figure 2 shows the types of elements used in the computer model, with each element consisting of a relatively homogeneous soil clod. Horizontal lines on Figure 2 may indicate changes in geometry, changes in material characteristics, or locations of horizontal cracks. Vertical lines indicate changes in geometry, locations of vertical cracks, physical barriers, or convenient locations to obtain rectangular elements of reasonable size. The purpose of using the dual tube system was to define the crack spacing.

The presence of either shrinkage cracks or thin layers of different material will result in changes in density with depth. It was believed that these changes would be detectable using

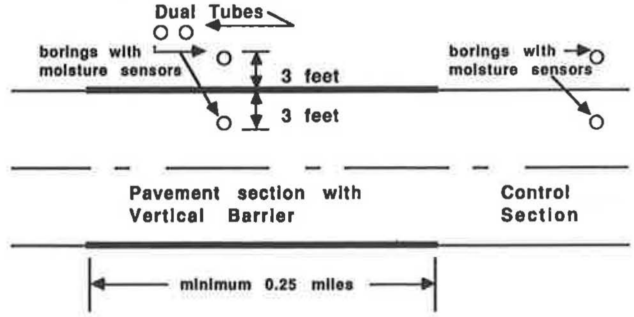

FIGURE 1 Schematic of field instrumentation.

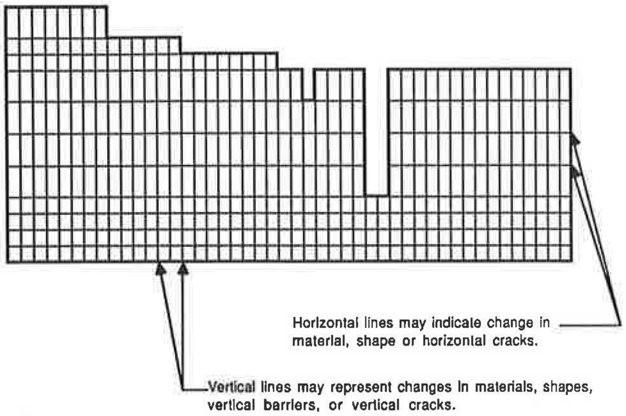

FIGURE 2 One possible configuration of computer model of moisture flow through cracked clay.

the dual tube nuclear gauge. The purpose of the installation was to allow determination of density at frequent depth intervals, in order to determine the size of the clods formed by shrinkage of the expansive clay soils. This information is required so that a vertical barrier is extended to a sufficient depth to prevent moisture flow in horizontal cracks, which would result in significant moisture variation beneath the pavement.

SITE SELECTION

Instrumentation of any site for this project was contingent on installation of the vertical barrier by a local highway district. Site selection thus required coordination of efforts with local maintenance engineers so that desirable sites were considered for rehabilitation. Local district personnel were asked to submit candidate sites having the following characteristics:

- Site should be founded on expansive clay soil. Sites that have interbedded layers of sand, silt, gravel or shale are included in this group.
- Site should have a history of repeated maintenance requirements. These pavements may have sagging shoulders, extensive cracking, or a "roller coaster" ride.
- Roadway must be in cut, at natural grade, or in a minimal fill. Roadways that are placed on extensive clay fill do not exhibit the same degree of moisture movement through a developed crack system and were therefore excluded.
- Distressed length of the pavement section must be at least 0.25 miles.
- Site may have either high or low groundwater conditions. Moisture conditions beneath a pavement with a vertical barrier will stabilize more rapidly for a high groundwater table.
- Maintenance or pavement rehabilitation must be planned within the duration of the project.

Based on these characteristics, highway personnel suggested a total of 48 sites. Each of these sites was visited by a research project engineer, and a list of "most suitable" sites was prepared. In addition to the characteristics above, the research team was also interested in having sites present in a variety of climatic zones and geographic areas within the State.

To date, six dual tube sites have been instrumented and readings taken. These sites are located in College Station, Seguin, Converse, Irving, Wichita Falls, and Snyder, Texas, as shown on the map in Figure 3. Also shown in Figure 3 are the climatic zones in the State of Texas. Results of the project in Greenville have suggested that climatic conditions are an important variable to barrier performance, so it was desirable in the current project to test the barriers for a variety of climate types. The variability of the size and spacing of soil cracks, or the degree to which the cracks are open for water flow at the time of construction, may also be a function of climatic zone. Additional sites are anticipated, and additional readings will be taken at existing sites where the dual tubes are not damaged during construction.

All of the sites listed above are located either at natural grade or in cut sections. The site in Seguin, part of a major rehabilitation project of I-10, is a roadway section subjected to heavy traffic loads and a particularly high percentage of truck traffic. The site located near Converse is a pavement improvement and capacity enlargement project of a farm-to-market (FM) road that previously consisted of two lanes with no shoulders. The site for the dual tube installation in College Station is the soils research area at the research annex at Texas A&M University.

The site in Wichita Falls is on I-44 and is unusual in that the barrier has been installed at the inclination of the slopes past the shoulder. This resulted in ease and economy of installation but significantly less vertical penetration of the barrier. The Irving site is located on the outer urban traffic loop of the Dallas metropolitan area in a soil formation that is extremely expansive. The dual tube is installed at MacArthur Boulevard, where Loop 635 is located approximately 25 feet below natural grade and the exit roadway rises to the level of the uncut soil. The Snyder site is a four-lane divided highway located approximately 18 miles north of Snyder. The dual tubes are installed at natural grade in what appears to be undisturbed clay soils.

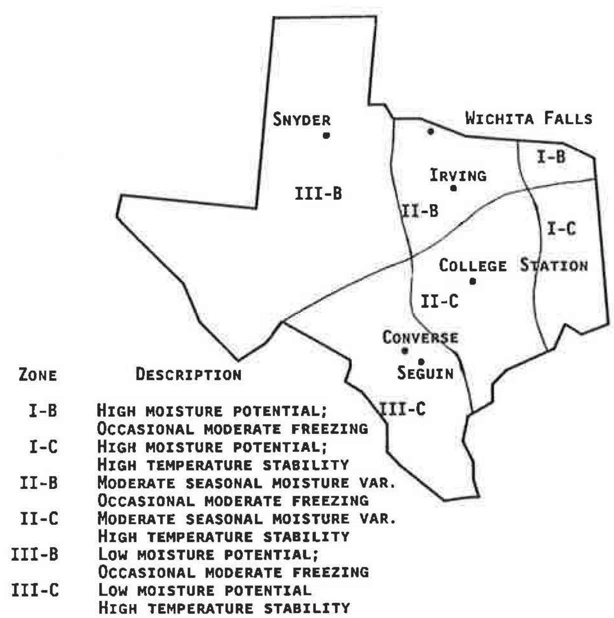

FIGURE 3 Site locations and climatic zones for highway technology.

DESCRIPTION OF INSTRUMENTS

The dual tube nuclear system consists of two parallel aluminum tubes, a nuclear source and sensor, and a scaler ratemeter. The field installation consists of drilling and placing the aluminum tubes, and the field monitoring involves inserting the source and sensor and obtaining the resultant readings on the scaler ratemeter.

The dual tubes used for this project are 10 ft aluminum tubes having an outside diameter of 2 in. Borings for placement of the tubes were made using a truck-mounted probe with a 2 in. diameter auger. A template is used during drilling to ensure that the two holes are parallel and are separated by a distance of 12 in. Prior to insertion, a rubber plug was placed into the lower end of each aluminum tube. Each tube was sealed at the surface with a steel banded rubber cap to minimize water entrance into the tube. Following the installation process, a minimum of two days was allowed prior to taking readings, in order to allow the soil to achieve good contact with the installed tubes.

The instruments used on this project consisted of Model 2376 two-probe density gauge, Model 2651 scaler ratemeter, and extension rods, all manufactured by Troxler Electronic Laboratories. The scaler ratemeter consists of three portions: a timer/counter for taking readings; a ratemeter module used to calibrate the unit; and a power supply module. The source consisted of a 5 mCi unit of cesium 137, which screwed onto the source probe from its lead-encased travel container. The source produces gamma photons of 662 KeV energy by radioactive decay. The sensor consists of a scintillation probe, which produces pulses proportional to the energy of the gamma radiation striking it.

Field readings were obtained at each of the six installations to within six in. of the termination depth of the tubes by research engineers from the Texas Transportation Institute. The scaler ratemeter was calibrated at each location by placing the source probe and the sensor probe into a calibration frame and obtaining readings. Following calibration, the source was inserted into one aluminum tube and the sensor was inserted into the other. A bubble level was used to ensure that both source and sensor were at the same elevation prior to each reading. A reading was taken over a period of one minute. The various components of the field instrumentation are shown in Figure 4. The arrangement between the source and sensor probes while taking readings is shown in Figure 5. Readings, in the form of a count, were taken at 1 in. intervals by carefully lowering both source and sensor in the dual tubes.

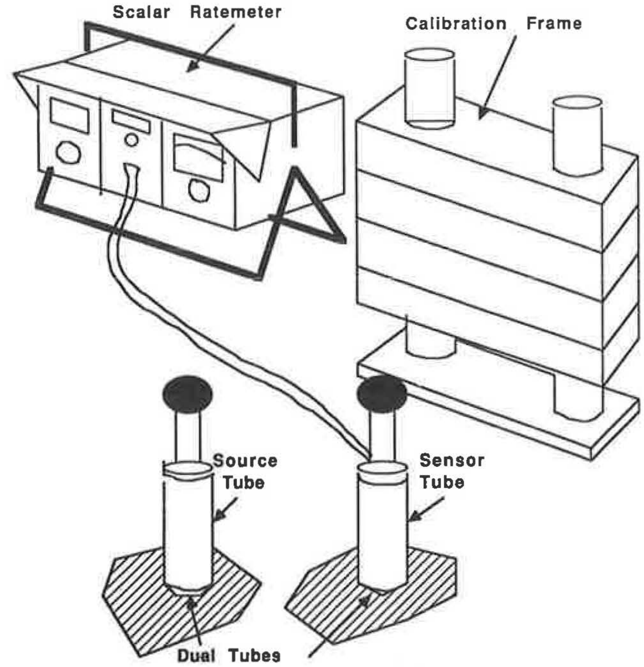

FIGURE 4 Field instruments for dual tube operations.

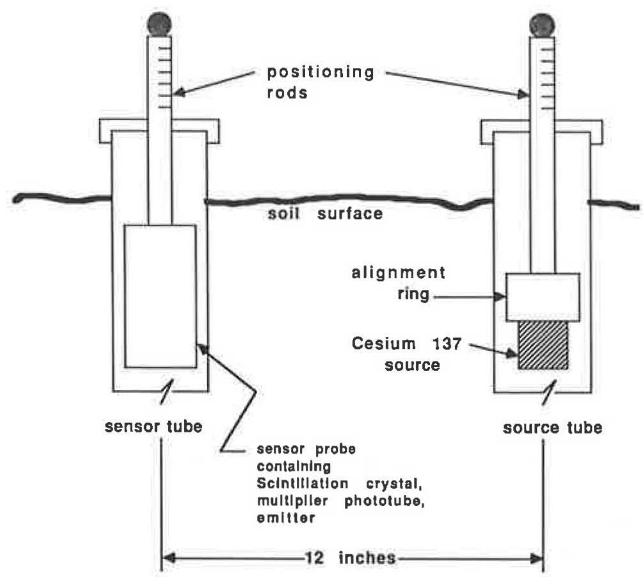

FIGURE 5 Source and sensor probes during field readings.

DATA ANALYSIS AND RESULTS

Data obtained in the field consisted of the count for the source and sensor placed in the magnesium standard and depths and counts for the source and sensor in the field-installed dual tubes. The standard count was taken four times using a one minute reading for each count, and the average of the standard count was used in data analysis.

Following completion of field work at each site, count ratios were obtained for each field reading by dividing the field reading by the average standard count. The density was determined using calibration curves of density versus count ratio that were supplied by the manufacturer.

Plots of the density versus depth for each location are prepared. A typical plot is shown in Figure 6 for the density versus depth results at Converse, Texas. Several things can be observed in this plot. First, there is a significant increase in density at a depth of 28 in. This change in density corresponds almost exactly to the depth of material added at the pavement shoulder in order to widen FM 1516 from a two-lane to a four-lane roadway. It is important to note that fill is present even at a site that is essentially at natural grade due to the change in section geometry. The dual tube system is sensitive to these density changes and shows a dramatic

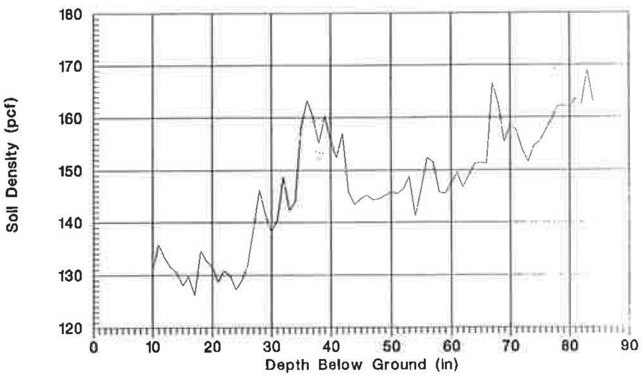

FIGURE 6 Soil density vs. depth below ground, FM 1516, Converse, Texas.

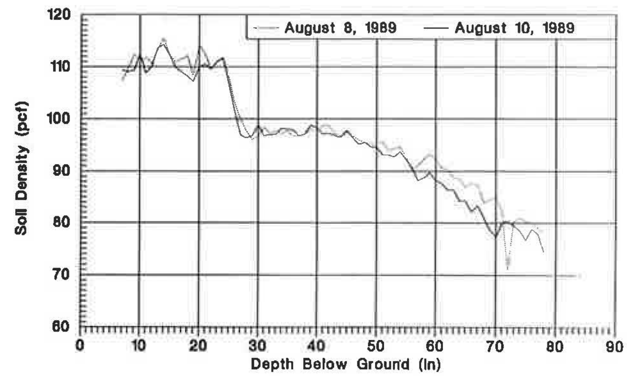

FIGURE 7 Soil density vs. depth below ground, Texas A&M research annex, College Station, Texas.

response in cases where the compaction specification results in a significantly different density condition.

Peak densities are observed in the fill material at about 5 in. increments and undoubtedly reflect both the quality assurance increment and the finished lift increment at the site. Several relatively low densities are observed in the fill material and show the ability of the dual tube system to detect densities that are below specifications. The feasibility of using the system for construction quality assurance is limited, however, due to the fixed location of the tubes and expense of the installation.

The purpose of the dual tube installation on this project was to determine the spacing of horizontal cracks that transmit water in expansive clay soils. To determine this crack spacing, the plot of density versus depth is observed for the subgrade below the fill. Depths associated with low density are listed and are combined into a single low point in cases where a trend toward lower density occurs. For example, two low points are observed on the Converse plot at depths of 15 and 17 in. These were combined into a single low point at 17 in. for the purpose of evaluating clod size. All significant low points were listed and included depths of 10, 17, 21, 24, 30, 33, 38, 41, 44, 54, 59, 63, 69, and 74 in. The difference between successive low points represents a soil clod, so clod sizes of 7, 4, 3, 6, 3, 5, 3, 3, 10, 5, 4, 6, and 5 in. were obtained. The average clod size for the Converse site was 5.3 in. Clod sizes of 4.7 in. appear to be suitable for modelling of the overlying fill material as previously described.

A similar evaluation of data was done for the site located at the Texas A&M research annex. The plot of density versus depth for this site is shown in Figure 7 and shows approximately 23 in. of dense material underlain by much less dense material. Readings at the site were repeated on two occasions to verify this finding, and the two plots show excellent repeatability. Density readings were evaluated to detect low-density locations, which were noted at depths of 11, 16, 19, 22, 28, 31, 36, 43, 51, 55, 63, 66, 70, and 77 in. Based on these depths to low-density areas, an average crack spacing of 5.1 in. is obtained. The average for the upper seven low-density peaks was 4.85 in., while the average for the seven deeper low-density peaks was 5.85 in.

The plot of density versus depth for the site on Loop 635 in Dallas indicates continued increase in density with depth. This site is located approximately midway in a 25 ft deep cut along an exit ramp from the loop onto MacArthur Boulevard. Dual tube readings were made on two site visits and resulted in average crack spacings of 4.8 and 5.0 in., respectively. Slightly higher average crack spacing was obtained when considering the upper low-density peaks as compared to the deeper peaks, with averages of 5.0 and 4.57 in., respectively. The range of crack spacings for the Dallas site was between 3 in. and 8 in.

Evaluation of the plots from Seguin resulted in an average crack spacing of 4.8 in., while those from Wichita Falls and Snyder yielded average crack spacings of 7.0 and 7.3 in., respectively. A significantly different crack spacing with depth was observed only for the Wichita Falls site, where the upper spacing was 6.6 in., while the deeper crack spacing was 9.0 in. The range of crack spacing values for the Seguin site was 3 to 10 in., while that for Snyder was 5 to 12 in. Crack spacings as low as 3 in. and as high as 14 in. were observed for the Wichita Falls site.

Based on results to date, it appears that crack spacings of between 4 and 5 in. apply to sites in the eastern and southern part of the State of Texas. Larger crack spacings of 7 in. or above are indicated for the two sites located in or near climatic zone III-B. The spacings may be related to the activity of the clay mineral as well as the climatic zone. Additional sites will be installed and monitored to test the validity of these conclusions.

FIELD DIFFICULTIES WITH DUAL TUBE SYSTEM

Several field problems have been encountered with use of the dual tube system. Among these problems are manufacturing defects in the sensor probe, susceptibility of the scintillation probe to moisture, and difficulty in extending readings to depths required for engineering applications.

Initial efforts at using the dual tube system met with severe difficulty in lowering the sensor probe into the installed dual tube. The sensor probe had been manufactured out-of-spec with regard to encasement diameter. Replacement of the sensor housing was required in order to correct the problem.

The high level of pressure initially required to lower the sensor probe into the dual tube resulted in damage to the housing seal. Moisture present in the tube entered the sensor and damaged the scintillation probe, despite the fact that the probe was not lowered below the level of the groundwater table. As a result of this costly damage, great care is now taken to ensure that the sensor probe is not exposed to water. As previously mentioned, both top and bottom caps are used during installation. Prior to taking any readings, each tube is checked for water. Water that is present is removed using a system of sponges on rope until a dry hole is achieved. No warning of water susceptibility was provided by the manufacturer. This problem may limit use of the dual tube system in very wet environments or will require redesign of the sensor probe with an improved water seal.

Transportation of the scaler ratemeter to take field readings has also been a problem. The instrument is very sensitive and must be transported in a level position. Despite considerable care to ensure that the equipment is not subject to jarring, the electronic boards in the ratemeter have loosened and required maintenance. It will be necessary to provide a less sensitive system before widespread use of the dual tube system will be feasible in civil engineering applications.

The dual tube system has been used up to the present time primarily by soil scientists in agricultural applications, which has limited its use to the upper 3 to 4 ft of soil. Engineering applications for pavements have required installations that have varied from 7 to 10 ft. The extension system for lowering the source probe and the sensor probe beyond the depth of 2 ft consists of multiple 2 ft rods that screw into the probe units. It was noted that rotation of the extensions during lowering loosened the connections between successive extensions and the weight of the extensions made it difficult to control lowering of the sensor probe beyond 9 ft. While these problems were overcome on this project by teamwork and care during connection of the extensions, greater difficulties may be encountered in applications requiring deeper tube installations.

As is the case with all instruments having radioactive elements, all personnel using the instrument must wear radiation badges to monitor exposure. In addition to normal training in the use of the typical density gauge, the dual tube system requires significantly more training and care in operation. The instrument must be field calibrated at each location, and the procedure to prepare the instrument prior to taking readings is detailed. Approximately 2.5 hours was required to set up and take readings at 1 in. intervals at each site.

CONCLUSIONS

Based on preliminary findings, it appears that the dual tube system can be used to characterize the clay clods and the locations of shrinkage cracks that determine moisture flow in the clay mass. This information has not been available previously due to the practical sample size required to obtain soil density in the laboratory. Location of the cracks requires obtaining density over short depth intervals so that changes are pinpointed.

Once installed, the dual tubes can be read repeatedly to observe seasonal variations. While limited data are available at this time, this may provide useful information for areas like Texas that have dramatic seasonal variations in moisture availability. Changes in the size of soil clods may also be an indicator of the depth of seasonal moisture variation. This depth is an important design parameter for a variety of transportation structures.

Problems associated with the dual tube system will limit its use for engineering applications until design changes are made. The most critical problem is the susceptibility of the scintillation probe to moisture, which limits use of the system to holes above the groundwater table. Improvement of the water seal in the sensor probe is necessary for most engineering projects where dry conditions cannot be guaranteed. An improved extension system should also be provided to facilitate use of the dual tube at depths greater than 9 ft. The development of a locking mechanism over the screw fitting and a lighter extension unit are also desirable.

Results have demonstrated that the dual tube system produces results that are consistent with the design and construction processes at a site. It is possible to detect weak layers, lift thicknesses, and fill thicknesses. In addition to this transportation application, the system may prove useful in solid waste management applications where detection of these items is essential and permanent monitoring systems are required.

REFERENCES

1. M. Picornell and R. L. Lytton. Behavior and Design of Vertical Moisture Barriers. In *Transportation Research Record 1137*, TRB, National Research Council, Washington, D.C., 1987, pp. 71–81.
2. R. L. Lytton, R. L. Boggess, and J. W. Spotts. Characteristics of Expansive Clay Roughness of Pavements. In *Transportation Research Record 568*, TRB, National Research Council, Washington, D.C., 1976, pp. 9–23.
3. R. F. Reed. Roadway Performance in an Expansive Clay. In *Transportation Research Record 1137*, TRB, National Research Council, Washington, D.C., 1987, pp. 36–41.
4. E. B. McDonald. Construction Methods to Control Expansive Soils in South Dakota. In *Transportation Research Record 1089*, TRB, National Research Council, Washington, D.C., 1986, pp. 57–62.
5. D. H. van der Merwe, F. Hugo, and A. P. Steyn. The Pretreatment of Clay Soils for Road Construction. *Proc., Fourth International Conference on Expansive Soils*, Vol. 1, ASCE, New York, 1980, pp. 361–382.
6. M. L. Steinberg. Deep Vertical Fabric Moisture Seals. *Proc., Fourth International Conference on Expansive Soils*, Vol. 1, ASCE, New York, 1980, pp. 383–399.
7. M. L. Steinberg. Controlling Expansive Soil Destructiveness by Deep Vertical Geomembranes on Four Highways. In *Transportation Research Record 1032*, TRB, National Research Council, Washington, D.C., 1985, pp. 48–53.
8. D. D. Gay and R. L. Lytton. Pavement Roughness on Expansive Clays Altered by Vertical Moisture Barriers. *Proc., Annual National Meeting*, ASCE, Memphis, Tenn., 1988.

Publication of this paper sponsored by Committee on Environmental Factors Except Frost.