Spatial Characterization of Expansive Clays

COSTAS GEORGHIOU, MICHAEL W. O'NEILL, and OSMAN I. GHAZZALY

ABSTRACT

A site on which a building was to be constructed was studied by conducting a large number of pH and Atterberg limit tests on grab samples of soil and in situ resistivity tests on a grid pattern. Contour plots were then made of these indicator properties to attempt to identify zones of high and low potential expansion and horizontal expansion potential gradients. Characteristic surface waveforms were also studied at the site by time-delayed differential surveys of two lines of 128 surface markers, the Fourier transforms of which provided signatures of ground surface movements. Surveys of the soil-supported first floor slab made after construction suggest that the strongest correlation of floor movement was with plasticity index gradient.

Expansive clay problems are well known throughout the world. They are of particular importance to transportation engineers who deal with large-scale projects such as highways and airfields, which are vulnerable to differential soil movements that are the result of water movements through expansive clays. As the use of shallow abutment and pier foundations increases, bridge engineers are also becoming concerned with expansive clays.

Several general procedures exist for the identification of potentially expansive soils (1). For purposes of this paper these procedures can be classified into two groups: (a) traditional methods, and (b) spatial methods.

Traditional methods rely on tests on samples from a limited number of undisturbed sample borings; for example, the widely spaced borings used in the development of bearing capacity parameters for a building, bridge, or culvert. Traditional methods use a variety of indicators to establish the expansive potential. These indicators include liquid limit, plasticity index, a combination of liquid limit and natural water content, soil suction, and one-dimensional swell or zero swell pressure.

A typical example is the procedure by Vijayvergiya and Ghazzaly (2). This method correlates a swell index (ratio of natural water content to the liquid limit) with one-dimensional swell test results and zero swell pressure data. From these correlations a tabulation was developed between the swell index and ranges of probable swell. A similar traditional method, widely used by transportation engineers, is McDowell's method (3), which provides a technique for computing the potential vertical rise (PVR) from classification tests and a family of curves of stress versus volumetric swell. The method applies only to natural soils. A comparable method for compacted soils was proposed by Seed et al. (4).

Some traditional methods rely on direct measurements for the determination of swell potential. Jennings and Knight (5) proposed a method for the determination of potential soil heave from a double oedometer test. Snethen and Johnson (6) proposed a methodology for characterization of expansive soils using measured or estimated changes in soil suction.

Traditional methods suffer from the problem that, because so few sampling points exist, only a general qualitative picture (e.g., "moderate" swell potential) or at best a single quantitative parameter (e.g., 4-in. swell potential) is developed for a site. However, swell potential gradients, particularly in the horizontal direction, are more important than average magnitudes in forecasting distress in pavements and structures. Mound-depression (gilgai) structure and other swell anomalies are not usually identified by traditional methods.

Spatial methods, on the other hand, allow for the assessment of the variation of swell indicators in three dimensions and thereby permit the construction of indicator gradients. Spatial methods (involving gradients) are more relevant for assessing possible structural distress because they may lead to correlations with differential movements. Pioneering work has been done in spatial characterization by Lytton (7) and McKeen Nielson (8), among others.

McKeen and Nielson (8) proposed a spatial methodology whereby soil suction is measured on a large number of soil clods (directly or indirectly), recovered at shallow depths over a large area (e.g., an airfield site), permitting swell potential contour maps to be drawn and swell potential gradients to be established. They also describe a method to evaluate differential swell potential across a site by making accurate level readings on lines of equally spaced markers (stakes) at different times. Variations between readings at each stake at different times are converted into Fourier transforms to obtain wavelength and amplitude characteristics of the site.

APPLICATION OF THE SPATIAL METHOD

A variation of McKeen's spatial method was applied to a specific site in Houston, Texas, on which a building ("new engineering building," Figure 1), whose structural frame was supported on shallow drilled footings and whose first floor slab was supported on soil, was to be constructed. The site, which was essentially flat, had no vegetation but grasses except along the eastern and northeastern portions of the building line, where several small groves of oak, pine, and mimosa trees with trunk diameters of up to 14 in. existed, as shown in Figure 1. The site is situated on the Beaumont clay formation, which is a stratified deltaic deposit composed of preconsolidated clays and occasional fine sands and silts (9). A general profile of the site is shown in Figure 2.

Undeveloped areas of the Beaumont formation present gilgai features on aerial photographs, according to Dawson (9). Because the soils were deposited

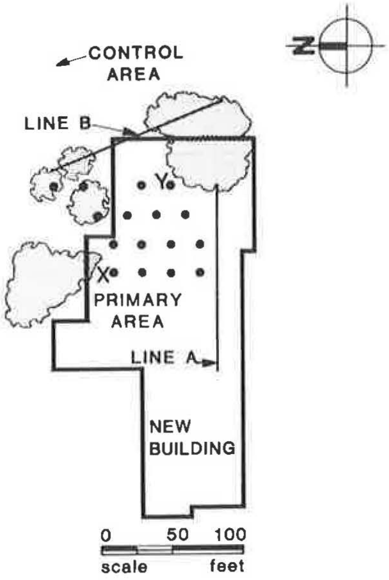


FIGURE 1 Area map.

intermittently over a long period of geological time, the possibility exists that immature gilgai have been buried beneath the surface. According to O'Neill and Ghazzaly (10), buried gilgai fields may result in movements of footings if buried gilgai are exposed during construction.

The structure is a four-story steel frame building with no basement. The frame is supported on drilled piers that extend approximately 10 ft below natural grade. The upper 4 ft of the soils at the site directly under the building were removed and replaced with a controlled fill having a plasticity index of less than 20 as a way of minimizing the effect of the expansive clay on the building. The fill was extended 3 ft above grade to accommodate placement of the first floor slab, which was constructed about 1 year after the surface soils were removed. The slab was supported directly on the fill without any dowels to grade beams or columns.

Construction took place from the summer of 1981 through the summer of 1983. Climatic conditions at the site, which is in a relatively humid area, during 1980-1984 are shown in terms of the monthly Thornthwaite moisture ratio (11) in Figure 3, which also indicates the timing of major events relative to this paper. The monthly moisture ratio is defined in Equation 1:

$$\text{Monthly moisture ratio} = (p - e)/e \qquad (1)$$

where p is monthly precipitation and e is evapotranspiration for the month computed in terms of average temperature for the month. Published 20-year rainfall and temperature averages, rather than specific measured values, were used for November and December of 1984. Relatively dry conditions (for the area) existed during construction of the fill and foundation.

The spatial characterization process consisted of three simple steps. First, two lines of 128 (2^7) wooden stakes located 1 ft apart were driven 6 in. into the soil. The locations of these two lines are shown in Figure 1. The purpose of locating the stakes along those specific lines was to study the difference in surface movement patterns between an area free from substantial vegetation and an area where trees were prevalent. The level readings were taken on the stakes from September to December 1980, which was during a period of increasing moisture ratio. The second step involved establishment of a grid on the site as shown by the heavy dots in Figure 1. X and Y are reference markers used to relate grid locations and orientations in Figure 1 with those in later figures. Grab samples were taken at depths of 0 to 1, 3 to 4, and 6 to 7 ft at the grid points, and Atterberg limits and pore water extract pH tests were conducted on the samples. Wenner bridge resistivity tests were also conducted at the grid points with electrodes spaced so as to provide soil resistivity values at the average depth intervals described earlier. [The use of Atterberg limits, pH, and resistivity as indicators of expan-

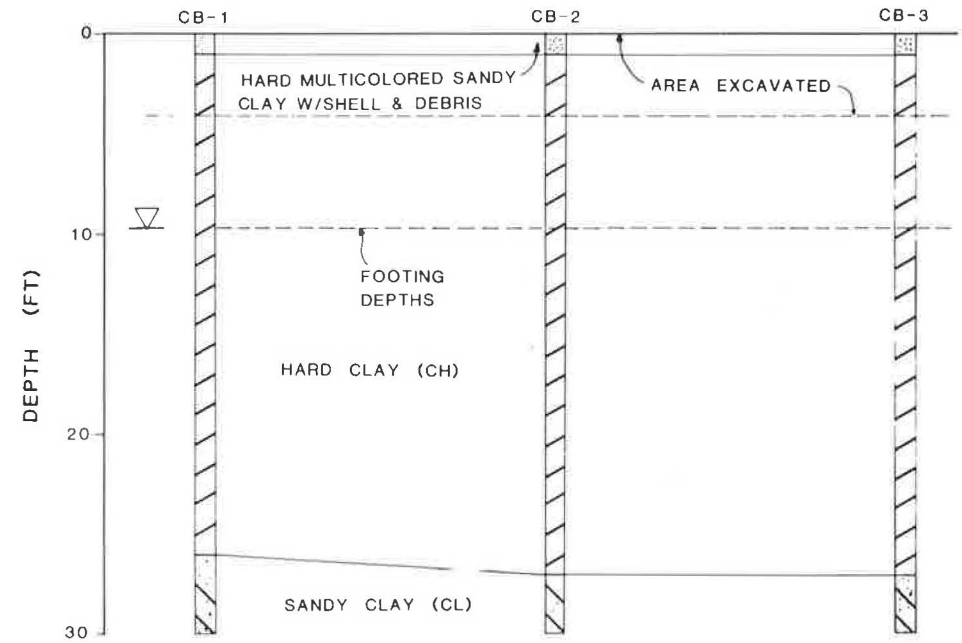


FIGURE 2 Soil profile.

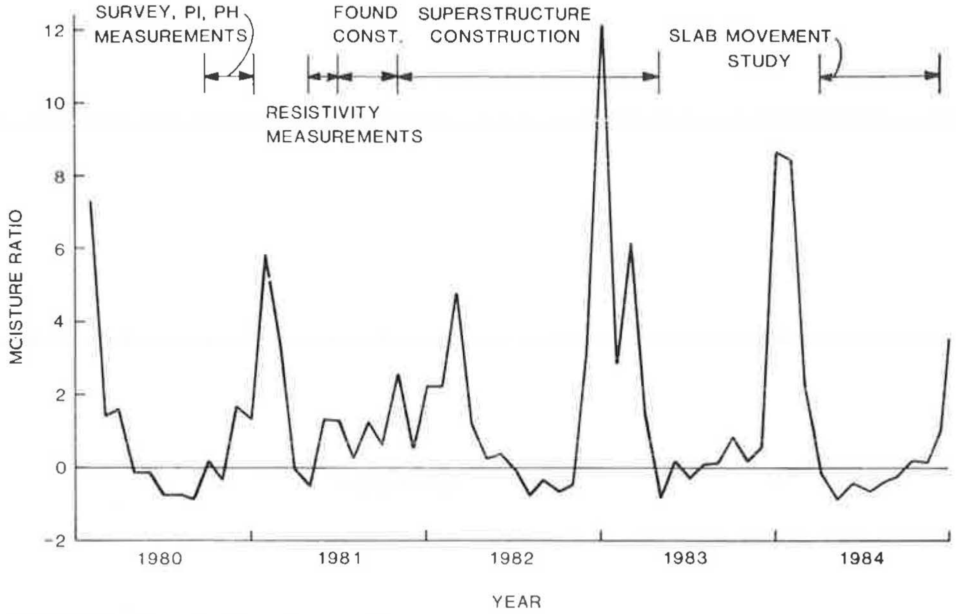


FIGURE 3 Thornthwaite moisture ratio versus time.

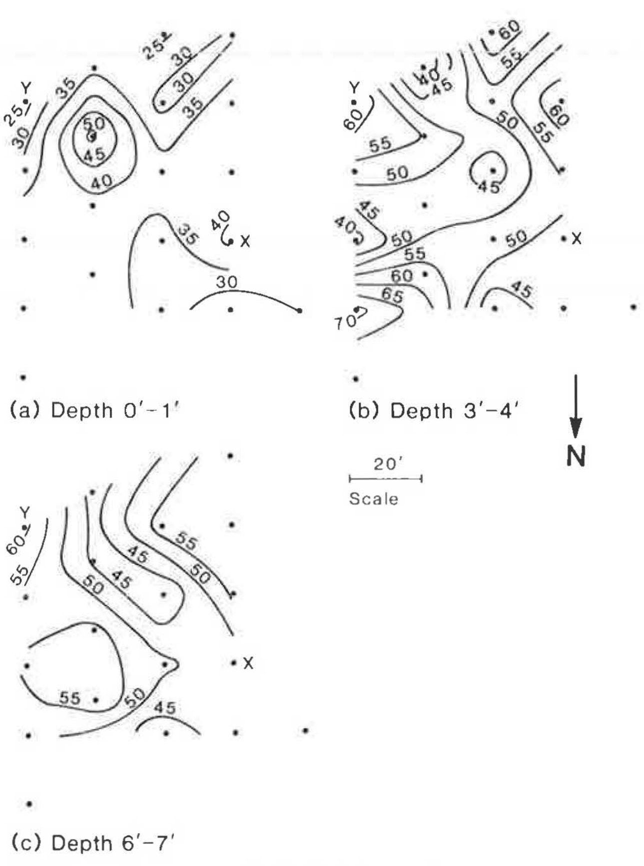
sion (or shrinkage) was considered appropriate because the value of each factor reflects, to some degree, pore fluid electrolyte concentration. In turn, electrolyte concentration is related to osmotic suction, which is a relatively important component of total soil suction in a "wet" climate, such as exists in Houston. In addition, resistivity is affected by pore air content and thus is hypothetically an indirect indicator of matrix suction.] Twenty of the grid points were located beneath the eastern half of the building (near the trees) and nine were located in a separate control area outside of the building (primary) area away from any trees. The second step operations (except for the resistivity tests) occurred during a period of increasing moisture ratio, shown in Figure 3.

The third step consisted of the instrumentation of three footings with electronic resistance strain gauges (mounted as full bridges at several levels on the longitudinal reinforcing steel in the plinths) as a means of directly measuring the effects of expansive soil movements. During the ensuing 3 years the measured strains were very small, so that it was not possible to separate strains produced by vertical soil straining from those due to electrical drift and other factors. This suggests that shear stresses on the plinths were small, probably owing to the existence of the 7 ft of controlled fill. No further observations concerning this step are given.

An additional post-construction phase of the study was added in 1984 after a crack was observed in the interior of the building. This phase involved taking measurements of the grade-supported first floor slab to determine if differential soil movement was taking place. Three sets of measurements were taken, one in March 1984, one in May 1984, and one in November 1984. The area of the slab that was accessible for this phase is shown in Figure 1.

RESULTS

Contour plots of plasticity index (PI), pH, and resistivity are presented in Figures 4-6 for the primary area. It is assumed that the contour patterns are later reflected in the pattern of movements in the completed structure; thus, high gradients in these indicators suggest potentially high rates of rotation in structures supported in the soil. Close examination of the PI contours shows no correlation of the contours at 0 to 1 ft depth with deeper contours. The maximum mean values of PI were observed at the 3 to 4-ft level, although general magnitudes appear to remain about constant with depth. At depths of 3 to 4 ft (shallowest depth

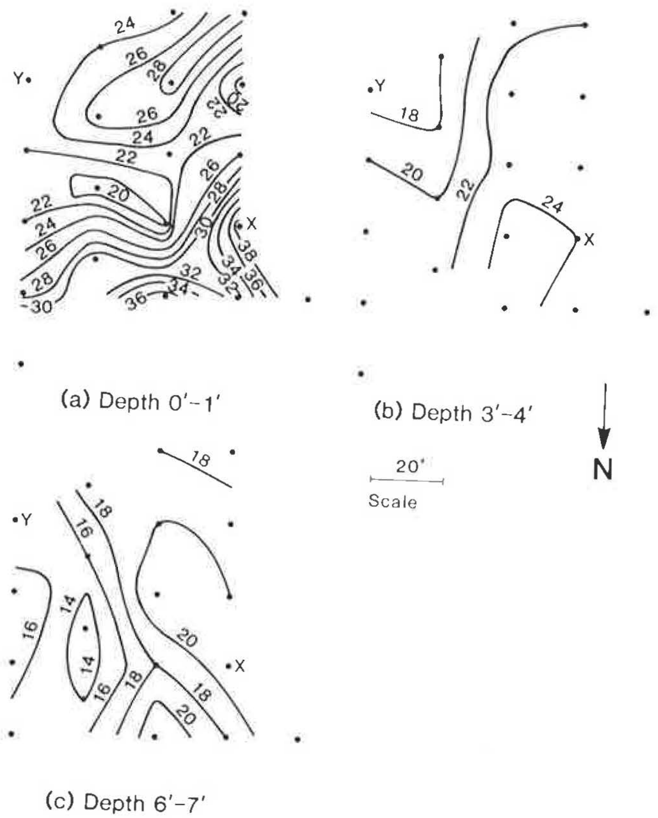


(a) Depth 0'-1'

(b) Depth 3'-4'

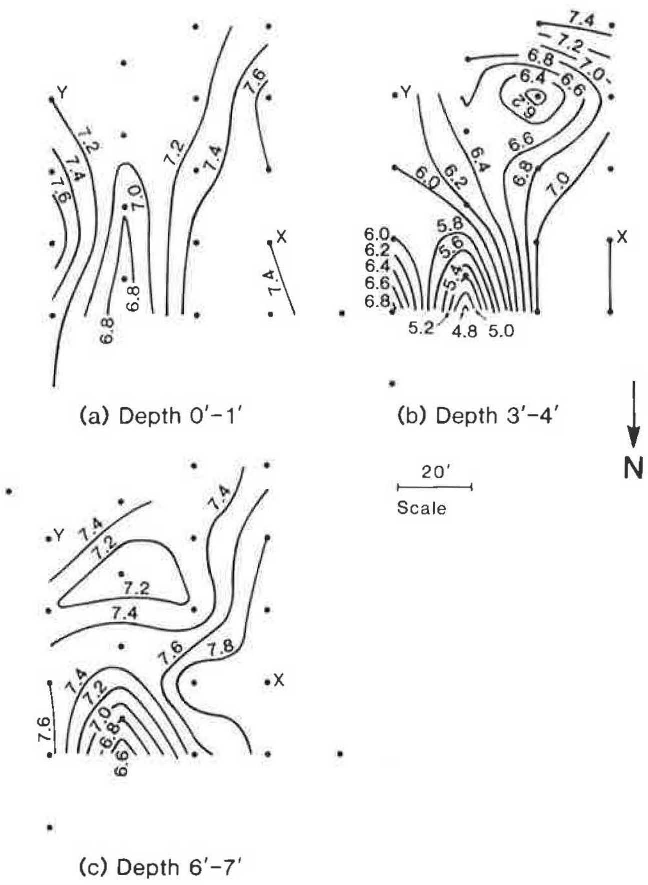
(c) Depth 6'-7'

FIGURE 4 Primary area plasticity index contours.



(a) Depth 0'–1'
(b) Depth 3'–4'
(c) Depth 6'–7'

FIGURE 5 Primary area resistivity contours.



(a) Depth 0'–1'
(b) Depth 3'–4'
(c) Depth 6'–7'

FIGURE 6 Primary area pH contours.

representing soil that was not excavated) and below, there appears to be a pattern of higher horizontal gradients than at the shallower depth (excavated soil). The gradients are highest in the north-east sector of the grid at a depth of 3 to 4 ft, near several trees.

The pattern of PI contours appears to be a complex one of ridges, troughs, mounds, and pits. PI maxima (peaks) are in the range of 60 to 70 at the lower two depths and minima (valleys) are in the range of 40 to 45. At the 6 to 7-ft depth there is a peak near marker point Y and one near the north arrow that correlate between the two depths. The shortest spans (wavelengths) between maxima at the 3 to 4 and 6 to 7 ft levels are 50 to 60 ft. This observation suggests that maximum differential movements in the structure due to free field expansion and contraction in the soil would develop (a) over a distance of 25 to 30 ft (one-half the wavelength) and (b) in areas where correlations in maxima and minima exist between depths of 3 to 4 and 6 to 7 ft. Condition (b) appears east-to-west over the top (south) part of the grid.

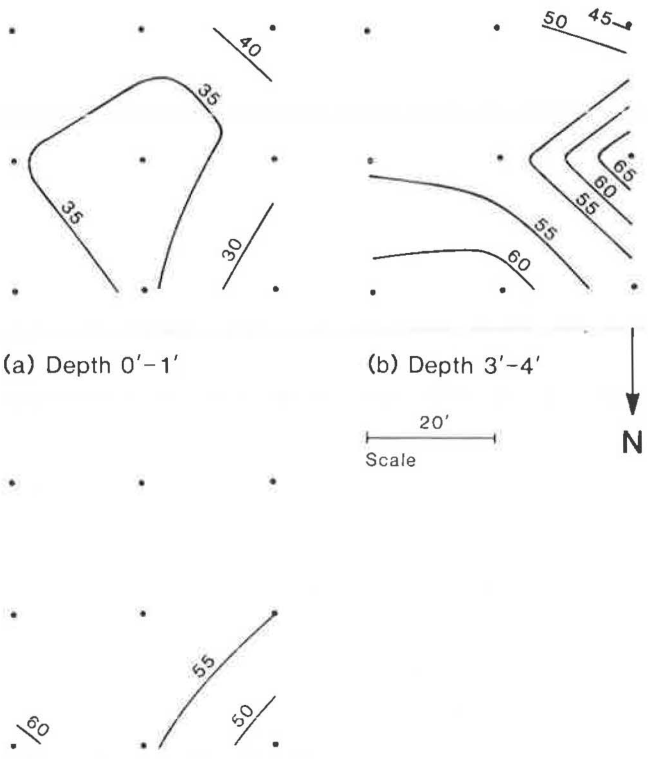
The resistivity contours in Figure 5 show a clear trend of lower general magnitude with increasing depth. A comparison of contours at the three different levels shows no clear correlation of results at different depths and no identifiable peak-to-valley distances at any depth. Another observation is the reduction of horizontal gradient of resistivity below 0 to 1 ft. This may be because resistivity was measured in situ with electrodes at spacings that increased with depth of resistivity value, which may have had an averaging effect over increasingly larger areas. It therefore appears that resistivity measured in the manner described was not a sensitive indicator of soil expansion potential variability at the depths at which soil was not excavated.

Figure 6 shows the pH contours. A comparison of the results at the three levels indicates a fairly close correlation depthwise of contours of high acidity and alkalinity. The extreme values of pH were 4.8 and 7.8. The pH contours are rather strongly influenced by the results at a single grid point near a tree, where the pH was very low at all depths. If the results of that point were to be ignored, a weaker correlation would be present among the three levels.

The soil is generally more acid at 3 to 4 ft than at 0 to 1 or 6 ft. Acid soils tend not to produce diffuse double layers that are as large as those in basic soils, which suggests that the soils at 6 to 7 ft may have more involvement in the development of expansion potential than those at 3 to 4 ft. The extreme acidity (pH < 6) at the 3 to 4-ft level, however, is physically associated with the presence of tree roots, which, when removed, could conceivably have resulted in the lowering of matrix suction in the soil, with resultant swelling. (No evidence of heave in the portion of the completed floor slab situated above the soil with pH < 6 was observed, which suggests that significant suction reduction either has not yet occurred or that it occurred rapidly, before the floor slab was placed.)

The pH contours have a topographic form similar to those for PI, although the extreme value-to-extreme value spacing below 0 to 1 ft is not well-defined within the grid that was used. The spacing (wavelength) appears to be slightly higher than that observed in the PI contours.

By comparing the three indicator contours at all levels, no evident correlation exists among the three indicators. The few depthwise correlations of the PI contours found in the primary area were absent in the control area (Figure 7), possibly because the control area was too small. At the 6 to 7-ft level



(a) Depth 0'-1'

(b) Depth 3'-4'

(c) Depth 6'-7'

FIGURE 7 Control area plasticity index contours.

there is very little variation in PI in the control area. The gradient variations between the control and primary areas may be due to the differences in vegetation in the two areas.

The observations made for the resistivity contours in the primary area apply to the control area. As shown in Figure 8, the horizontal resistivity gradients and the general magnitudes decreased with depth. At the 6 to 7-ft level, the resistivity was essentially uniform horizontally.

The pH contours in the control area, shown in Figure 9, indicate smaller horizontal gradients than in the primary area. The pH at 0 to 1 ft and 6 to 7 ft is essentially uniform over the area, with values near neutral. Only the layer from 3 to 4 ft showed pH variation.

Discrete Fourier transforms (12) of surface elevation changes along the lines of stakes also provided information on potential differential soil movements. Transforms of differences in elevation at each of a number of vertical movement markers over a fixed period of time provide descriptions of prominent wavelengths of surface deflection in the free-field (without structure) soil and their relative magnitudes. The appropriate transform equation is

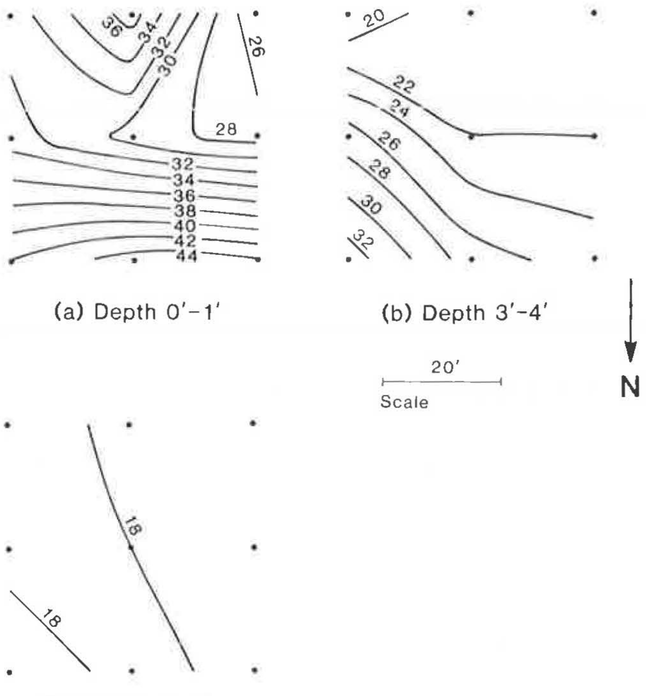
$$X_k(f) = \Delta h \sum_{n=1}^{N} x_n e^{-2\pi j(kn/N)} \quad (2)$$

where

Δh = stake spacing (1 ft);
n = stake number (1, 2, . . . , 128);
N = total number of stakes (128);
x_n = difference in elevations at stake n over the time period;
$j = (-1)^{0.5}$; and
X_k = Fourier amplitude.

The parameter k is defined by the wavelength λ_k for which X_k is computed by Equation 3, in which Δf is a numerical constant.

$$\lambda_k = (k\Delta f)^{-1} \quad (3)$$

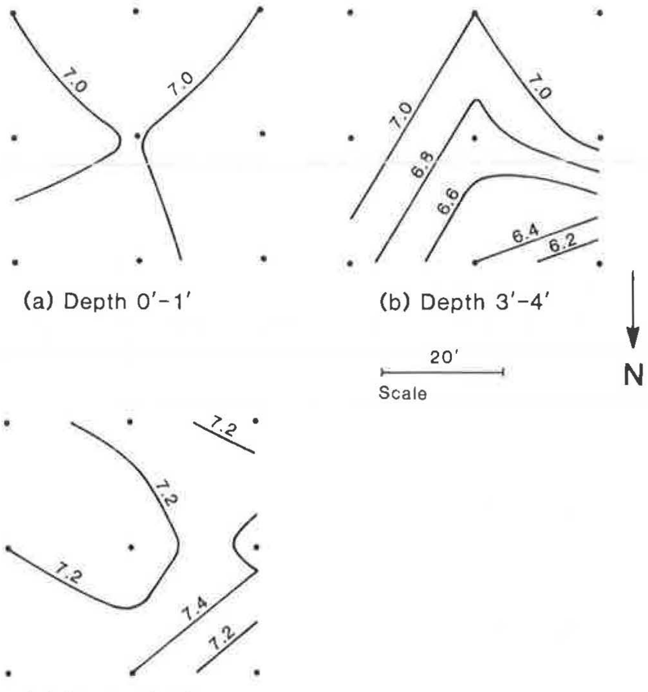


(a) Depth 0'-1'

(b) Depth 3'-4'

(c) Depth 6'-7'

FIGURE 8 Control area resistivity contours.



(a) Depth 0'-1'

(b) Depth 3'-4'

(c) Depth 6'-7'

FIGURE 9 Control area pH contours.

The Fourier transforms of the surface elevation studies are shown in Figures 10 and 11. Both figures are plots of Fourier amplitude versus n. The wavelength (λ_k) is 128 ft/n.

Only the first n/2 frequency components are unique in the transform and therefore have any physical significance. The second half is a mirror image of the first half.

The surface elevation studies were performed in the fall of 1980 during a period of increasing moisture ratio (Figure 3). The solid lines in Figures 10 and 11 are transforms of elevation differences taken during an initial 45-day interval; the dashed lines represent differences during a 45-day interval immediately following the first interval.

No discernible periodicity appears along Line A and no particular trend toward increasing amplitude with time is evident, except for one major peak at $n = 3$ ($\lambda_n = 42.7$ ft), which is interpreted as the potential fundamental wavelength for the portion of the site without trees. This is contrasted with 50 to 60 ft observed in the PI contours (Figure 4). The amplitudes and periodicity are much stronger along Line B (through the area with trees) than along Line A, especially for low values of n. Prominent peaks are observed at $n = 6, 9, 15, 21$ and 33 ($\lambda_n = 21.3, 14.2, 8.5, 6.1$, and 3.9 ft). They probably represent movements due to differential suction that is influenced by the presence of the three root systems. There is no clear trend of increasing or decreasing Fourier amplitude with time along Line B. Behavior of the type found along Line B suggests that differential free-field soil movements occur over short enough distances to cause potential harm to a light structure even if the trees are removed, since stabilization at reduced suction may require many years following tree removal.

Finally, the slab movement study results are shown in Figure 12 in which plus (+) values indicate heave and minus (-) values indicate settlement. These measurements were initiated after a crack developed in a corridor wall on the western edge of the study area. The period between the two sets of measurements in Figure 12a (March 1984 to May 1984) was very dry. Zones of heave and settlement correlate very generally at areas of high and low PI, respectively, although no complete wave pattern appeared in the slab. The general mode of movement of the slab during that period was settlement, with an average value of about 0.02 ft measured. Settlement reached as much as 0.05 ft, 20 ft south of Marker X (and 20 ft north of the crack), the reason for which is unknown. Heave up to 0.03 ft was detected just east of Marker Y, which was near a peak in the PI contours for the level of 6 to 7 ft and also in the former grove of trees, through which elevation Line B had been installed 3 1/2 years earlier. No distress was discernible in the building in the zone of heave at that time.

Figure 12b shows slab movement contours over a longer period of time (March-November) in which the short-term differential movements (Figure 12a) appear to continue but with a tendency toward further settlement. One additional wall crack 25 ft southeast of Marker X developed during May-November.

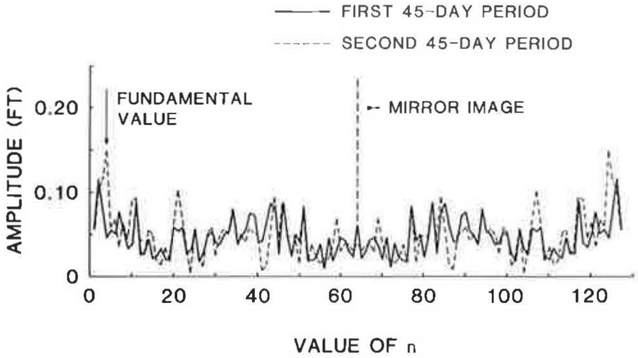


FIGURE 10 Line A Fourier transform.

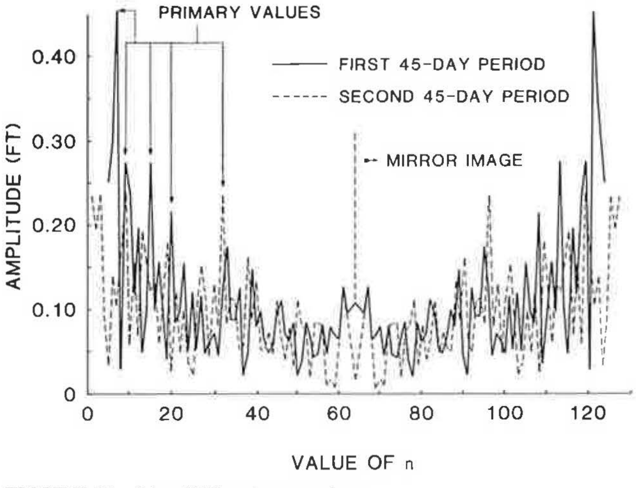


FIGURE 11 Line B Fourier transform.

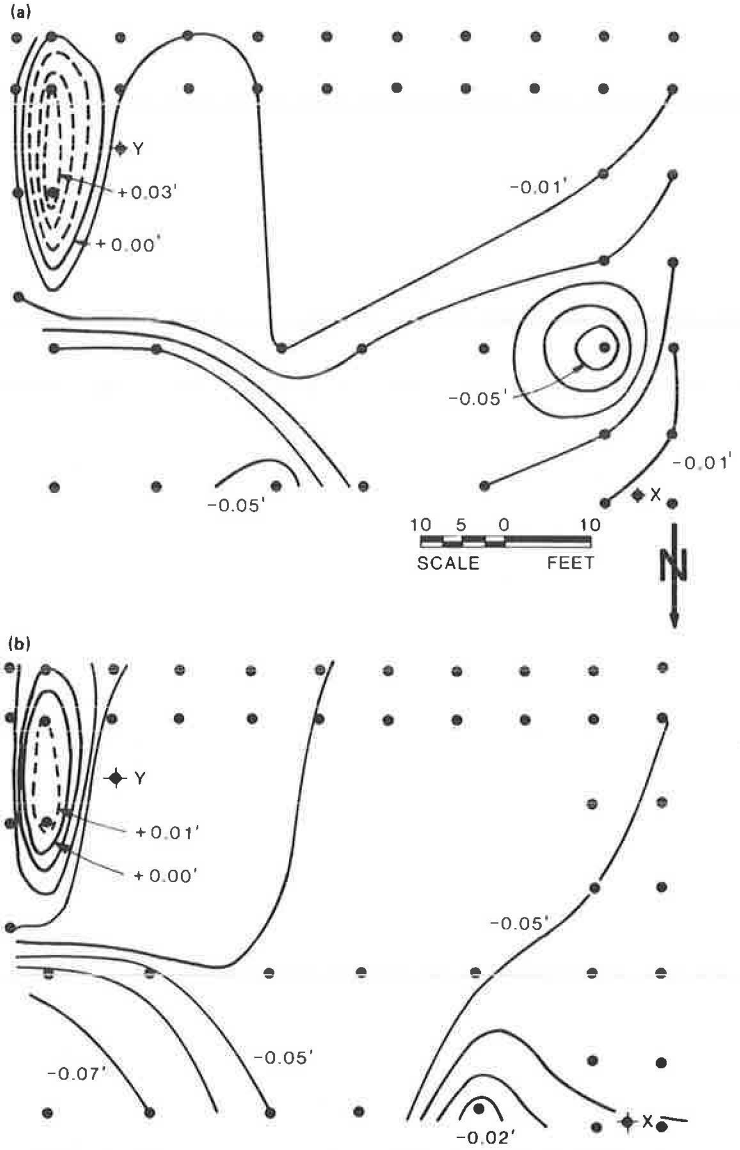


FIGURE 12 Slab movement contours: (a) March-May 1984; (b) March-November 1984.

CONCLUSIONS

The following conclusions are drawn from the study:

1. No obvious correlation could be found between PI, resistivity, and pH.
2. Resistivity was not a suitable indicator at the study site.
3. There appears to be a vague correlation between the slab movement contours and the PI contours at 6 to 7 ft.
4. The Fourier transforms appear to provide good indications of the relative expansive potential of the soil.
5. The spatial techniques described are relatively quick and inexpensive to perform. More studies of the type reported here are needed to establish their general reliability.

ACKNOWLEDGMENTS

The study reported in this paper represents the combined efforts of McBride Ratcliff and Associates, Inc., McClelland Engineers, Inc., F.E. Willcox, David Broussard, and the Office of Facilities Planning and Construction of the University of Houston. The authors are indebted to these organizations and individuals for their assistance and support. Appreciation is also extended to Le T. Pham for her help in preparing the figures.

REFERENCES

1. D.R. Snethen, L.D. Johnson, and D.M. Patrick. An Evaluation of Expedient Methodology for Identification of Expansive Soils. Report FHWA-RD-77-94. FHWA, U.S. Department of Transportation, Washington, D.C., 1977.
2. V.N. Vijayvergiya and O.I. Ghazzaly. Prediction of Swelling Potential for Natural Clays. Proc., 3rd International Research and Engineering Conference on Expansive Clay Soils, Haifa, Israel, Vol. 1, 1973, pp. 227-234.
3. C. McDowell. The Relation of Laboratory Testing to Design for Pavements and Structures on Ex-

pansive Soils. Colorado School of Mines Quarterly, Vol. 54, No. 4., 1959.

4. H.B. Seed, J.K. Mitchell, and K.C. Chan. Studies on Swell and Swell Pressure Characteristics of Compacted Clays. Bull. 313, HRB, National Research Council, Washington, D.C., 1961, pp. 12-39.
5. J.E. Jennings and K. Knight. The Prediction of Total Heave from the Double Oedometer Test. Symposium on Expansive Clays, Transactions, South African Institute of Civil Engineers, 1957.
6. D.R. Snethen and L.D. Johnson. Characterization of Expansive Soil Subgrades Using Soil Suction Data. Presented to Transportation Research Board Committee on Environmental Factors Except Frost, Washington, D.C., Jan. 1977.
7. R.L. Lytton, R.L. Boggess, and J.W. Spotts. Characteristics of Expansive Clay Roughness of Pavements. Transportation Research Record 568, TRB, National Research Council, Washington, D.C., 1976, pp. 9-23.
8. R.G. McKeen and J.P. Nielson. Characterizing Expansive Soils for Airport Pavement Design. Report FAA-RD-78-59. FAA, U.S. Department of Transportation, 1978.
9. R.F. Dawson. Land Subsidence Problems. Transactions, ASCE, Vol. 130, 1965, pp. 206-207.
10. M.W. O'Neill and O.I. Ghazzaly. Swell Potential Related to Building Performance. Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, No. GT12, Dec. 1977, pp. 1363-1379.
11. C.W. Thornthwaite. An Approach Towards a Rational Classification of Climate, Geographical Review, Vol. 38, 1948, pp. 55-94.
12. J.W. Cooley and J.W. Tukey. An Algorithm for the Machine Calculation of Complex Fourier Series. Mathematics of Computation, Vol. 19, No. 90, April, 1965, pp. 297-301.

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

Measurement of Swelling Pressure in the Laboratory and In Situ

Z. OFER and G. E. BLIGHT

ABSTRACT

During the past 30 years more than 25 methods for the determination of the engineering characteristics of expansive soils and the prediction of heave have been proposed in the western world. Many of the proposed methods relate to laboratory or index tests whereas in situ tests, being more complex, have received less attention. Some commonly used laboratory and in situ testing methods for the determination of heave and swelling pressure are reviewed. Two instruments developed in South Africa are described, and test results are presented and compared with field loading test results. It is concluded that if sampling disturbance, size effects, selectivity in soil sampling, and simulation of actual site conditions are accounted for, laboratory and in situ test results are in good agreement.

Expansive clays are soils that exhibit unusually large volume changes as a result of moisture variations and environmental changes. The behavior of expansive soils affects the performance of structures buried in and founded on these soils; therefore, the understanding of their properties and their engineering characterization is of great importance. Engineers are well aware of the distress that lightly loaded structures, roads, runways, and utilities buried at a shallow depth in a swelling soil can suffer. The damage caused to such structures may be considerable, and rehabilitation at an early stage of a structure's life may be required, which imposes a heavy economic burden on the owner or user.

During the past 30 years more than 25 methods for the determination of the characteristics of expansive soils and the prediction of heave have been proposed in the Western world (1). However, a universally accepted method has yet to be developed. Many of the proposed methods relate to laboratory or index tests whereas in situ tests, being more complex, have received less attention. The purpose of this paper is to review some commonly used laboratory and in situ methods for the measurement of swelling pressure and heave. Two instruments developed in South Africa are described, and test results are presented and compared with some field loading test results. The relationship between laboratory