Time Related Heave Observations and Implications on Current Heave Prediction Models

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Abstract: Current methods of estimating potential surface movement of an expansive soil profile generally use effective stress concepts to weigh the relative contribution to the observed or potential surface movement of each sub layer of soil at a given depth. These models provide results showing that the relative contribution to the overall surface heave is reduced with depth. For a uniform, top-down wetting front migrating through the soil profile, the rate of heave observed at the surface should slow with time. However, time related heave data from several sites in North Texas overlying residual soil and weathered shale of the Upper Cretaceous Eagle Ford Formation indicate that the rate of observed heave is not reduced with time. This paper provides a discussion of these findings and the implications on current heave prediction models.

Introduction

Heave of deep deposits of expansive soil and weathered clay shale present numerous challenges in the North Texas region. Surface heave due to expansion of clay soils can be divided into two types: Seasonal movement related to the natural wetting and drying cycle and deep-seated movement related to a increase in moisture content of the deeper soils.

Expansion of clay soil occurs as the effective stress is reduced as a result of an increase in moisture content which subsequently reduces the negative pore water pressure or soil suction of an unsaturated soil. For a soil to swell, moisture must be made available to the potentially expansive soil profile. In areas with a climate that produces a distinct wet and dry season, the moisture profile of the upper soils will seasonally fluctuate to a certain depth. This depth is referred to as the "zone of seasonal activity" in which clay soils will expand and contract as the moisture content (and effective stress) fluctuate.

The second type of heave of expansive soils is a result of "deep-seated" movement. This occurs when moisture is made available to soils below the zone of seasonal activity. Moisture is typically made available to theses deeper soils through irrigation, leakage of utility lines, or a natural increase in soil moisture below a floor slab or paving.

Considering a relatively uniform soil profile, the relative contribution to the overall surface movement for each sublayer of soil should decrease with depth due to increased effective stress. This behavior should be observed for both seasonal and deep-seated heave. If the expansion of the soil profile is due to an increase in moisture content from a top-down wetting front migrating through the soil profile, the rate of movement observed at the surface should decrease with time. This paper provides a discussion of the time rate of heave observed at two sites in North Texas and implications on heave prediction models.

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Heave Prediction Models

Two types of heave-prediction methods are typically used in practice to estimate the potential surface heave. The first type is a purely empirical model, which relates the predicted heave to some easily measured soil parameter. The second model is based on site specific swell testing and calculating changes in effective stress and its effect on potential heave.

Empirical Methods - Potential movements are estimated through empirical methods such as proposed by McDowell (1959) or the TxDOT Method 124-E. These two approaches require that an initial moisture condition and correlations with the soil properties of the soil be used to evaluate the magnitude of potential movement associated with seasonal wetting and drying of the soil.

Effective Stress Methods - This method is based on the swell index and void volume considerations. Active soils expand or contract as a result of changes in stress or loading. The magnitude of heave is proportional to the logarithm of the change in stress in accordance with the formula shown below. The rate of change is referred to as the swelling index, C_s. The value of C_s is obtained directly from swell tests.

The magnitude of movement is calculated using the equation provided below, derived from standard consolidation theory.

$$\Delta h = [C_s/(1 + e_o)] \cdot h \cdot \log(P_f/P_o)$$

where: Δh = heave of the layer;
C_s = swelling coefficient;
e_o = initial void ratio;
P_o = initial stress state;
and P_f = final stress state.

Once the void volume characteristics of the soil are determined from a swell test, an estimate of the change in effective stress is required. Changes in stress are due to loading changes or changes of the matric soil suction. The initial stress state is taken to be equal to the maximum laboratory swell pressure. The final stress state is taken to equal the overburden pressure at the point where the volume change is calculated plus an equilibrium value of soil suction. A discussion of the effects of soil suction is beyond the scope of this paper, however a reasonable estimate of equilibrium soil suction may be obtained based on the Russam-Coleman (1961) correlation between equilibrium soil suction and the Thornthwaite Index. Lower values of soil suction than the equilibrium value may occur if the soil is allowed to become fully saturated due to point sources of water. Note that in the equation positive volume change (heave) will be calculated as a negative number. It should also be noted that this method does not account for lateral stress relief due to closure of dessication cracks within the seasonal zone.

Evaluation of Time-Dependent Heave

By assuming that surface heave occurs due to reduced effective stress in the soil profile related to a reduction in the negative pore pressure resulting from a uniform top-down wetting front, the soils near the surface should contribute to the observed surface heave before the deeper soils. Considering a relatively uniform soil profile, the initial effective stress will increase with depth, resulting in a decrease in potential heave related movements. Therefore, by assuming a constant rate, downward migrating wetting front, the rate of heave observed at the surface should decrease with time as the contribution of the deeper layers to the magnitude of surface heave should be less than the shallower layers. However, as can be seen in Figure 1, the time rate of heave appears to be relatively constant for the South African sites evaluated by Blight (1994). A careful inspection of Figure 1 indicates that for the pattern of heave with time is most closely modeled with a linear model rather than a decreasing slope which would be expected if the rate of heave was decreasing with time.

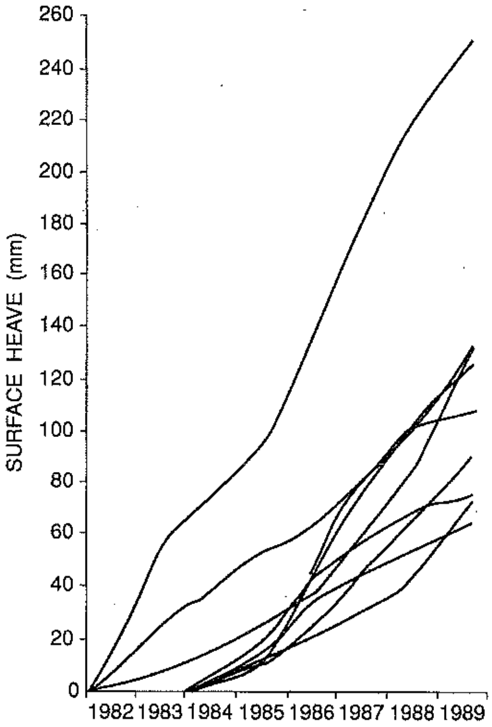

Figure 1, Heave of Various South African Sites (Blight, 1994)

Case Studies in North Texas

Site 1, Office Warehouse Structure

This site consists of an office/warehouse structure constructed in 1978. The structure was originally constructed with a ground-supported floor slab in conjunction with a pier-and-beam foundation. The floor slab was constructed over approximately 4-1/2 to 5 feet of "select" clayey sand fill. The original ground-supported floor slab experienced significant distress due to heave of the underlying expansive soils and was demolished and replaced in June 1993.

Subsurface conditions at this site consist of surficial fill overlying severely weathered grading to unweathered clay shale of the Upper Cretaceous Eagle Ford Formation. Unweathered shale of the Eagle Ford Formation is typically dark gray, soft (rock classification), montmorillonitic clay shale, which weathers to a yellowish-brown to brownish-gray material possessing the engineering properties of a CH clay.

At Site 1, the weathered shale extends to approximate depths of 29 to 33 feet, with the degree of weathering decreasing with depth. Significant quantities of free ground water were not encountered during a field investigation conducted in February, 1993. Soil properties for each of the soil types encountered are summarized in Table 1.

TABLE 1
SUMMARY OF SOIL PROPERTIES, OFFICE/WAREHOUSE

Soil Description	Depth, ft.	Liquid Limit	Plasticity Index	Cs
Sandy clay and clayey sand "select" fill	0 to 7	20 to 30	10 to 15	N.A.
Grayish-brown and brownish-yellow, weathered shale	3 to 33	60 to 75	45 to 50	0.06 to 0.10

At the time of the field investigation, no ground water table was present. An analysis of the soil-moisture profile of the three deep borings at the site indicates that the moisture content decreases with depth and the soil suction increases with depth (Figure 2). This observation suggests that a top-down wetting front is responsible for the moisture variation and subsequent heave below the floor slab at this site.

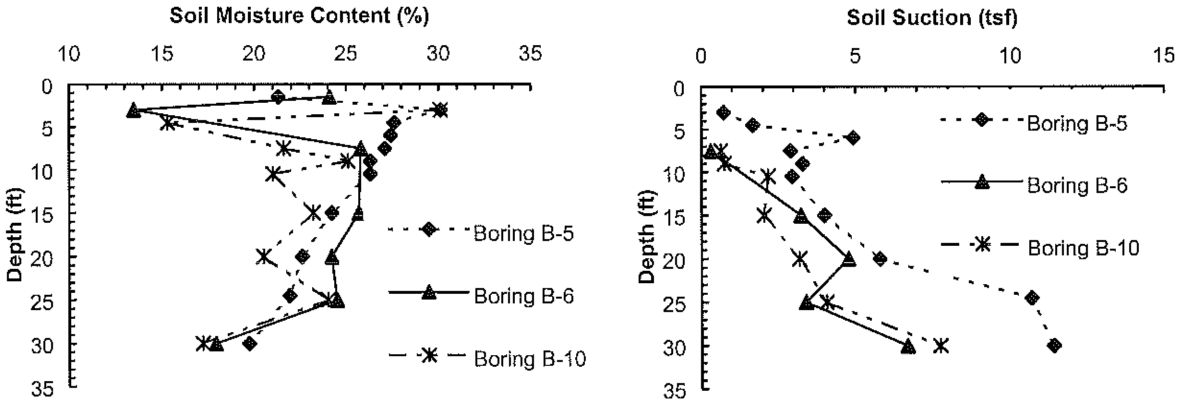

Figure 2, Soil Moisture and Suction Profiles for Site 1.

At the time of the field investigation, (February, 1993), two previous elevation surveys of the floor slab conducted in 1989 and 1993 indicate that the magnitude of surface heave as observed by relative elevation surveys varied from eight to nine inches. The magnitude of heave of the floor slab between the two surveys was compared at 17 locations, with the points of highest differential movement plotted in Figure 3a. Although the data is limited, the heave appears to have occurred in a relatively linear fashion from 1978 to 1993 with differential movements ranging from 1.5 to 7.0 inches higher than the post-construction elevation in 1989 and approximately 1.9 to 8.0 inches at the time of the 1993 survey. Therefore, over the 15 year period following the original construction, the movements of the floor slab occurred in a relatively linear fashion. The potential for additional heave was estimated to be up to approximately 14 inches prior to replacement of the floor slab in 1993.

The floor slab was replaced in June, 1993 with other improvements to the structure. The economic lifespan of the improvements was estimated to be approximately five years, and differential movement was monitored after replacement of the slab. Within approximately 14 months after placement of the new floor slab, significant differential movements were noted. The movement of the slab was monitored over the next 29 months with nine periodic floor elevation surveys. After a total period of approximately 43 months after replacement of the floor slab, observed heave varied from approximately zero to a maximum of 4-1/2 inches. A graph showing average slab rise vs. time is presented in Figure 3.

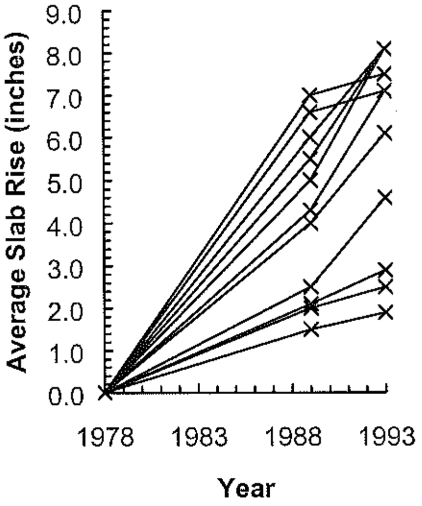

Figure 3a, Slab rise vs. time following original construction.

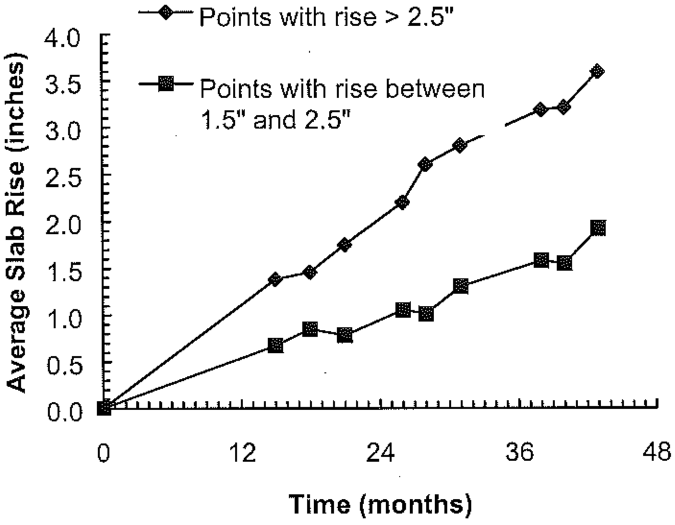

Figure 3b, Slab rise vs. time following slab replacement (June, 1993).

As can be seen from the preceding figures, the observed heave in the floor slab increases in an approximate linear fashion considering both the original floor slab as well as the replacement floor slab, with significant heave related movement still occurring approximately 19 years after the original construction.

Site 2, Two Story Classroom Building

The second site considered for this paper is a classroom building constructed in Irving, Texas. This structure consists of a two-story classroom building with a pier and beam foundation and a suspended floor slab. The building was constructed in 1956 with underreamed piers founded at approximately six feet and a suspended floor slab. At the time of a detailed investigation in 1992, the structure had experienced differential movement and distress since construction.

This site is located within fill and terraced alluvial soils overlying weathered and unweathered shale of the Upper Cretaceous Eagle Ford Formation. Fill consisting of dark gray to light olive-brown CH clay was encountered to depths of four feet during the field investigation in 1992. Alluvial soils consisting of dark brown to olive-brown sandy clays with some coarse sand and fine gravel extend to depths of 8 to 14-1/2 feet below the existing grade. Underlying the alluvial soils is weathered grading to unweathered shale of the Eagle Ford Formation. The weathered shale is similar to that within Site 1, and extends to depths of 26-1/2 to 31 feet below present grade. Below these depths, the weathered shale grades into dark gray, unweathered shale. Limited ground water was encountered within the upper alluvial soils and is attributed to surface infiltration and migration along preferential flow paths including utility excavations. A summary of the soil properties is presented in Table 2.

TABLE 2
SUMMARY OF SOIL PROPERTIES, CLASSROOM BUILDING

Soil Description	Depth, ft.	Liquid Limit	Plasticity Index	Cs
Dark gray to light olive- brown clay fill	0 to 4	~70	~45	N.A.
Dark brown to olive-brown CH/CL clay and sandy clay	0 to 15	20 to 65	10 to 45	~0.12.
Medium gray and brownish-yellow, weathered shale	8 to 31	70 to 105	50 to 75	0.04 to 0.12

Movement of the suspended first floor level slab has occurred since construction. A floor elevation survey conducted in 1960, four years after construction was complete, indicated that the majority of the structure was within approximately one inch of the original elevation of the floor slab, however, the central portion of the slab had experienced significant uplift. Elevations in this area indicate that up to approximately 4-1/2 inches of differential movement had occurred by 1960. This movement documented in 1960 is attributed to movement of the underreamed piers at relatively isolated locations due to point sources of water.

A second floor elevation study conducted in 1992 indicates that differential movement of the floor slab, as measured at column locations, is in excess of 12 inches. The area of highest movement at the time of this survey is the southwestern portion of the building and an isolated area in the northern portion of the building near an existing water line. The expansion near the water line is in the same vicinity as the area of largest movement in the 1960 survey, and is associated with a point source of water from the existing utility line. The movement in the southwestern portion of the building is consistent with expansion of the weathered shale as a result of migration of water along the contact between the weathered shale and overlying alluvial soils.

Although not enough data are present at this site to make any specific conclusions about the pattern of heave with respect to time, considering the continued distress more than 30 years after the original construction, the assumption that significant heave occurs long after construction appears to be valid. An examination of the soil-moisture profile indicates that, across most of the site, the weathered shale and upper alluvial soils were found to be in a relatively moist condition in 1992. The potential for additional heave in varied from approximately ½ to 11 inches at the time of the field investigation in 1992. The areas of increased potential heave are associated with the lower moisture content and increased soil suction observed throughout the soil profile. As can be seen in Figure 4, the soils in the vicinity of Boring B-3 are significantly drier and more expansive than the soils encountered in Borings B-1 and B-2. Review of boring logs obtained prior to construction of several other buildings in the vicinity of the classroom building indicate that the weathered shale was drier and more expansive at the time of construction.

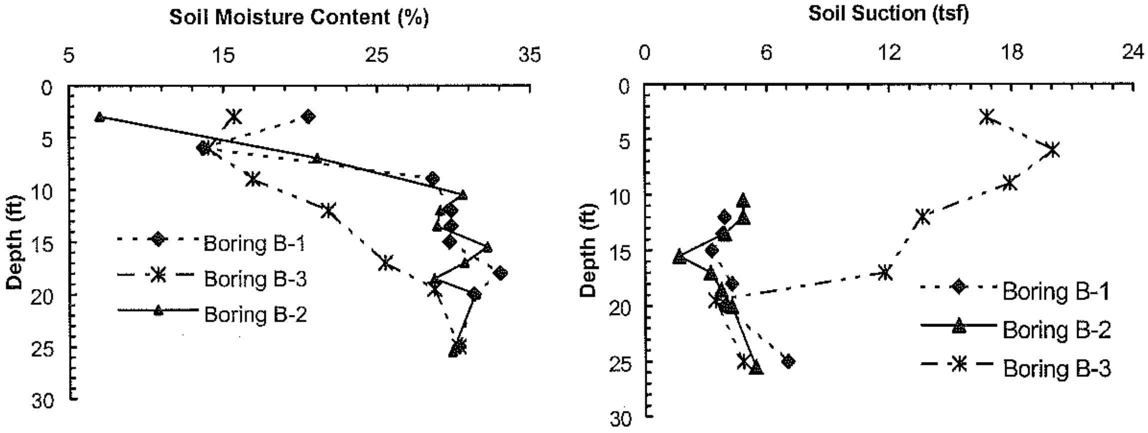

Figure 4, Soil moisture and suction profiles for Site 2.

Conclusions

As previously discussed for two case studies of sites in North Texas, as well as research by Blight (1994) in South Africa, the time rate of heave appears to be most closely modeled by a linear model. This seemingly conflicts with existing effective stress or empirical based heave prediction models. Two possible causes for this apparent discrepancy exist:

1. A nearly uniform top-down wetting front is not an appropriate soil moisture model, or
2. The deeper expansive soils contribute more to the observed surface heave than the shallower soils.

First, the top-down wetting front model may not be a true representation of the behavior of expansive clays. In arid to semi-arid climates with distinct wet and dry seasons, desiccation cracks will form in the upper soils during the dry season, providing direct conduits for water to migrate to the deeper soils during precipitation events in the wetter portion of the year. Therefore, in order to assume a true top-down, uniform wetting front, the effect of water migrating to deeper points in the soil profile via desiccation cracks must be neglected.

While this assumption does not necessarily reflect actual conditions, a top-down wetting front model will still be valid for most soil profiles in which a permanent water table is not present, particularly for the portion of the soil profile below the seasonally active zone. The effect of desiccation cracks will serve to essentially wet all portions of the active zone more or less simultaneously. Soils below the active zone will still be subject to downward migrating moisture, and therefore should contribute to the observed heave later than the surficial soils. An analysis of the moisture conditions of the two sites in North Texas support this assumption. At the time of sampling, the upper soils of Site 1 were relatively moist while the deeper soils were typically drier and more expansive. An analysis of Site 2, indicates that, with the exception of Boring B-3, both the upper seasonal soils and the underlying weathered shale was found to be relatively moist throughout the soil profile. This moisture is associated with the age of the structure and the soils were likely dry and expansive at the time of construction.

If a top-down wetting front is a valid assumption for most sites in which a permanent ground water system is not present, then in order for surface heave to occur in a relatively linear fashion, the deeper soils must contribute more to the surface movement than the shallow soils. To consider this further, it should be noted that in the North Texas area the zone of seasonal activity varies from 8 to 15+ feet, dependent upon geologic conditions. Therefore heave can be divided into two components, heave related to the seasonal wetting and drying cycle and deep-seated heave of soils below the seasonally active zone. The deep-seated heave will only occur if moisture is provided to the deeper soils. This moisture may be provided by leaking utilities, surface infiltration, or by a general increase in moisture below a slab as predicted by Russam and Coleman (1961).

Regardless of the source of the moisture to the deeper soils, swelling of soils below the active zone must be treated differently than swelling of soils within the active zone. The presence of cracks within the active zone serves to reduce the lateral confinement of the upper soils. Soils within the active zone do not swell only in a vertical direction, but also laterally by an amount related to the volume of the voids in a soil mass attributed to the presence of desiccation cracks. This lateral movement tends to reduce the observed surface heave from what would be predicted using parameters obtained from a one-dimensional oedometer test in which the soil is confined laterally.

However, soils deeper within the soil profile, within the zone of deep-seated movement, are laterally constrained since they are below the seasonally active zone, and no dessication cracks are present. Therefore, when the effective stress of these soils is reduced by a reduction in the soil suction due to the addition of moisture, the soils expand in the direction with the least resistance, which in this case is the vertical direction.

The amount of lateral expansion of the soils within the active zone is related to the void space produced by the dessication cracks. The cracks typically are not uniform throughout the soil profile, however, it is reasonable to assume that the overall void volume due to the presence of the cracks within a soil mass will decrease with depth, becoming essentially zero at the maximum depth of seasonal activity.

Implications on Current Methods of Heave Prediction

Based on the preceding discussion, the evaluation of potential heave of soils within the seasonally active zone and soils within the zone of deep-seated movement should be considered separately. The magnitude of heave due to expansion of soil within the seasonally active zone will be reduced by an amount related to the volume of the dessication cracks which form within the soil. Considering a soil mass which increases in volume due to expansion, the volume of a laterally confined soil will increase in the vertical direction only, while an unconfined soil mass will expand in three directions, with the magnitude of expansion in the vertical direction reduced by a factor of approximately three compared to the laterally confined soil mass.

The lateral stress relief due to cracks within the soil will result in a reduction in the amount of vertical heave within the seasonal zone compared to the zone of deep-seated movement, considering a soil with the same material properties. This reduction is equal to an approximate factor of three for the fully unconstrained case. While it may not be reasonable to assume that the presence of cracks is sufficient to cause the soil to behave as an entirely unconstrained material, some reduction of movement in this area seems reasonable.

Empirical methods of estimating heave, such as the TxDOT Method 124E, often account for the lateral stress relief associated with the seasonal zone.

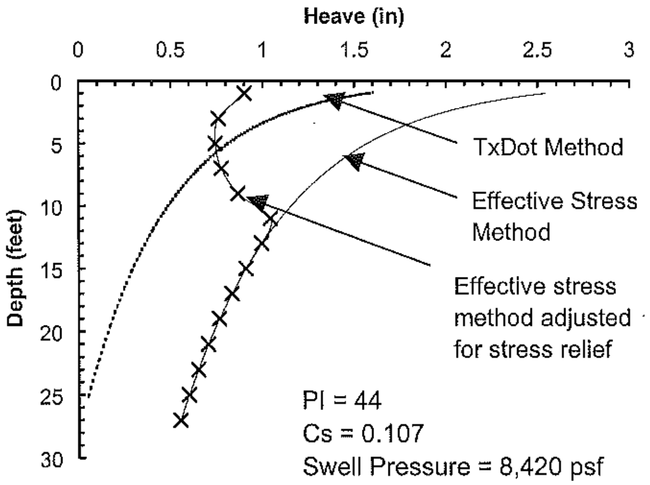

Figure 5: Relative contribution of subsurface soils to surface heave with depth

The relative contribution to the total surface heave of each two-foot thick soil layer in a uniform expansive soil profile is shown in Figure 5. The idealized soil profile in question consists of highly plastic, severely weathered clay shale of the Eagle Ford Formation. The parameters obtained from lab tests on the soil are shown on Figure 5. The contribution of each layer of soil was calculated at two-foot intervals using both the TxDOT Method 124E as well as effective stress calculations. As can be seen from Figure 5, the calculated heave is significantly greater when calculated using effective stress principles than the TxDOT empirical method. In addition, to account for the effect of stress relief due to dessication cracks, the depth of seasonal activity was assumed to be 12 feet, with the magnitude of heave reduced to reflect fully unconstrained behavior at the ground surface, varying linearly to the fully constrained behavior at a depth of 12 feet.

An analysis of the data presented in Figure 5 suggests that caution should be used when evaluating potential movements below the seasonally active zone using the TxDOT Method 124E or a similar method. It has been the experience of the authors that heave within the deep seated zone of movement is more closely estimated by an effective stress analysis using parameters obtained from swell tests. Therefore, while an empirical method such as the TxDOT Method 124E may be applicable within the seasonally active zone, the an effective stress model should be applied to soils below the zone of seasonal activity.

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