Settlement of Foundations on Expansive Clays Due to Moisture Demand of Trees

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FRIEND OR FOE

Trees are our friends. They extract carbon dioxide from the air, and release back oxygen for us to breathe. They provide us with beauty, and give us shade. Some trees provide us with fruits and nuts, and they provide a home and food for animals and birds.

We humans are the foe. We harvest the forests for lumber, and clear the land for farming or residential developments. Historically, we have not replenished what we have taken.

Expansive clays comprise most, not all, of the near surface soils in the greater Houston area. Shallow foundations have often suffered distress due to shrinkage of the clays resulting from moisture demand of trees. We humans have caused the problems because we don't understand the basic needs of the trees.

TREES AND SUCTION

The following is a layman's discussion of the phenomenon of suction and the survival of trees and other vegetation. To begin, it is an obvious fact that all trees need water to survive. Almost all trees, with a few exceptions, obtain water from the ground. It has been reported that large oak trees can suck more than 55 gallons of water a day from the subsoils during the dry summer months. The tree leaves process carbon dioxide by a phenomenon known as photosynthesis to produce sugar which provides energy needed for growth and survival, and water is needed for this process.

Nature did not provide a pump below the tree that pumps the water up to the leaves. What happens is that moisture loss at the surface of the leaves causes a suction that draws water up from the roots, through the trunk, and then through the branches to the leaves. Thus, the tree system is a pipeline for the upward flow of water from the ground. This process is similar to a person sucking liquid through a straw.

The feeder roots extract water from the subsoils by suction. The suction in turn sets up extraction of water from the soil beyond the root system. The pipeline for flow of water through the soil is the pores between the soil particles.

The extraction of water causes suction in the soils which in turn causes the soil particles to be pulled closer together. This phenomenon can be visualized by putting one finger at the end of a flexible straw and then sucking on the other end causing the straw to collapse. Some soils, such as sand and gravel, have strong contacts and resist collapse of the soil structure. However, most clays are compressible and the volume change is appreciable. This process is commonly referred to as shrinkage.

In general, the larger the tree the more water is needed for survival. Once the feeder roots have more or less extracted the available water near the tip, they must extend their root system to draw more water. It should be noted that most hardwood trees, not all, are dormant during part of the year. Rains allow recharging of the groundwater taken by the trees during the active season. Live oaks are an exception because they do not become dormant during the winter months.

Urban development is often detrimental to the growth and survival of trees. There is generally good site drainage which minimizes infiltration of rain water into the ground, and the presence of buildings and paving are a complete barrier to water infiltration. However, locating a tree in a large landscape area and watering it can actually be beneficial to its growth and survival.

Trees are often planted in small landscape areas between buildings and paving for landscaping purposes. The thought is that trees are good for the ecology and aesthetically pleasing. However, many landscape architects do not completely understand the impact that trees can have on the future performance of buildings.

When trees get too large to survive on the groundwater in a small landscape area, they will send their roots beneath building slabs and paving to find a new source of water to survive. There is generally an abundant source of water under covered areas in the summer when water is needed the most because the building slabs and paving act as a barrier to drying from the sun. However, the buildings and paving are a barrier to recharge from rainfall in the rainy seasons. The root system must grow laterally and downward in search of new water sources once they are below the buildings and paving.

EXPANSIVE CLAYS

The greater part of Houston is situated on a geologic formation known as the Beaumont Clay (see Fig. 1). However, the Montgomery formation is located in the northern and western areas of Houston. Both geologic formations were deposited in Pleistocene times in shallow coastal river channels and flood plains. The courses of river channels changed frequently during the period of deposition generating a complex stratification of sand, silt, and clay.

The clays and plastic silts were overconsolidated to significant depths due to desiccation that resulted when the water table was lowered during the Second Wisconsin Ice Age. The clay portion is composed of montmorillonite, kaolinite, illite, and fine ground quartz. The presence of montmorillonite results in a moderate to high shrink/swell potential.

The Thornthwaite Moisture Index (TMI) is about 18 which would categorize Houston as having a humid climate. The TMI is the difference in mean annual rainfall and the amount of water that would be normally returned to the air in inches by evaporation of moisture from the ground surface and transpiration by plants assuming that an unlimited supply of water is available in the soil for transpiration. O'Neill and Poormoayed indicate that the most problematic conditions occur when the TMI is between +20 and -20.

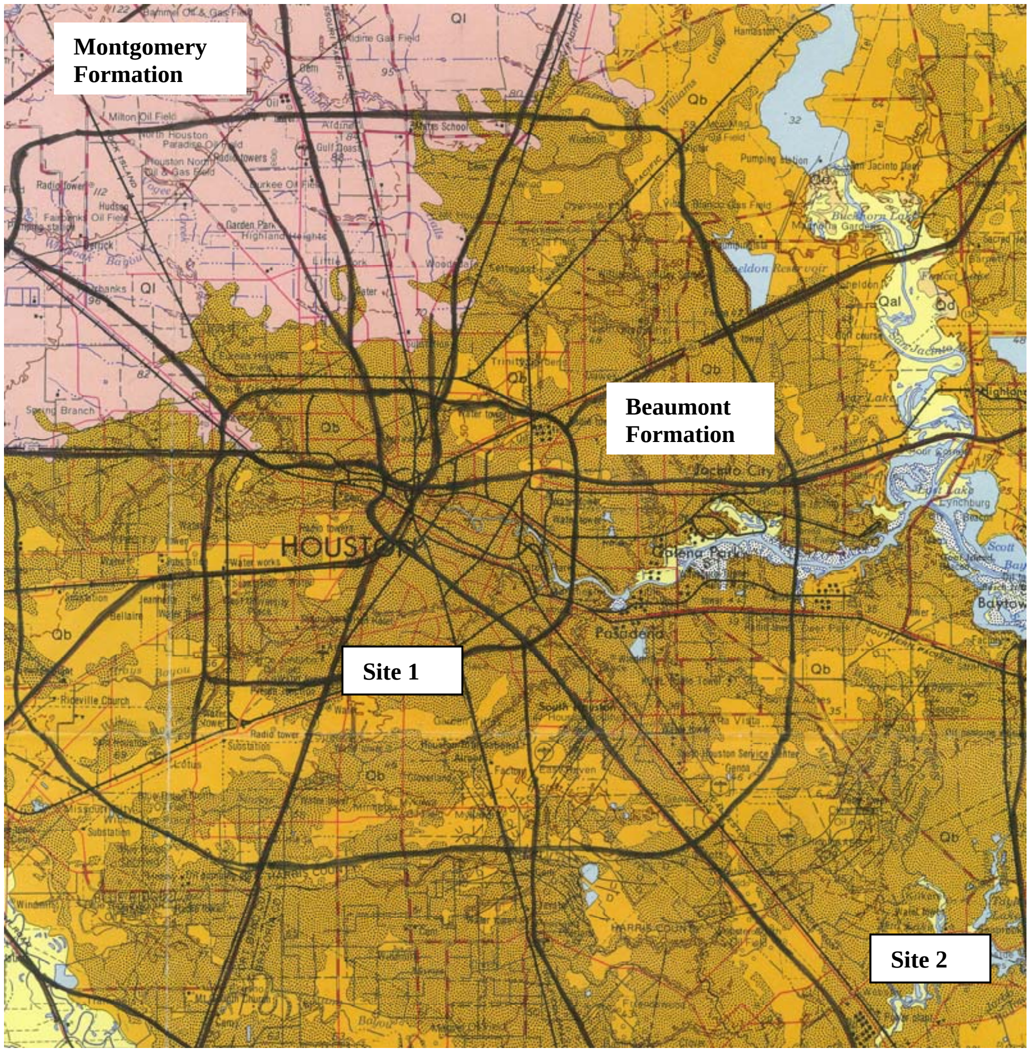

Fig. 1: Houston Geological Formations

The TMI is an average index value and does not reflect extreme conditions between years, concentration of rainfall, i.e. intensive rainfall that mostly runs off and/or the bulk of the rainfall occurring within several months (winter), or varying site conditions due to vegetation and irrigation. The TMI may not be an appropriate index for urban areas where man has dramatically changed environmental conditions.

Much of the greater Houston area was farm land until the mid 50's when the city started to grow out into the suburbs. There were scattered trees mostly around the farm houses and along roads and creeks. The farm land was often terraced to slow down drainage during rains so the ground could absorb the moisture. In the late 70's, it was not uncommon to find the water table at depths of 5 to 15 feet.

Urbanization of the farm land resulted in covering great parts of the surface with concrete slabs, and asphalt/concrete paving. Also, the ground surface around residential and commercial tracts was sloped to provide maximum drainage away from the buildings. Along with urbanization came landscape improvements to include trees and shrubs planted around the buildings and along the streets for aesthetic purposes. The vegetation sucks water from the subsoils to survive. These factors have resulted in a gradual lowering of the water table, and it is now common to find the water table at depths of 15 to 25 feet. Thus, the availability of groundwater for transpiration has been greatly reduced.

CASE HISTORIES

This paper discusses two case histories where moisture demand on the clay subsoils caused significant settlement of the floor slabs and foundations. Both sites are located on the Beaumont formation, but in different parts of Houston.

Site 1 – This site is located in the greater Clear Lake area. The building is a 4-story steel frame office building. The exterior finish is window walls, and precast spandrel panels. The building was constructed in the period between 1984 and 1985 (~23 years old).

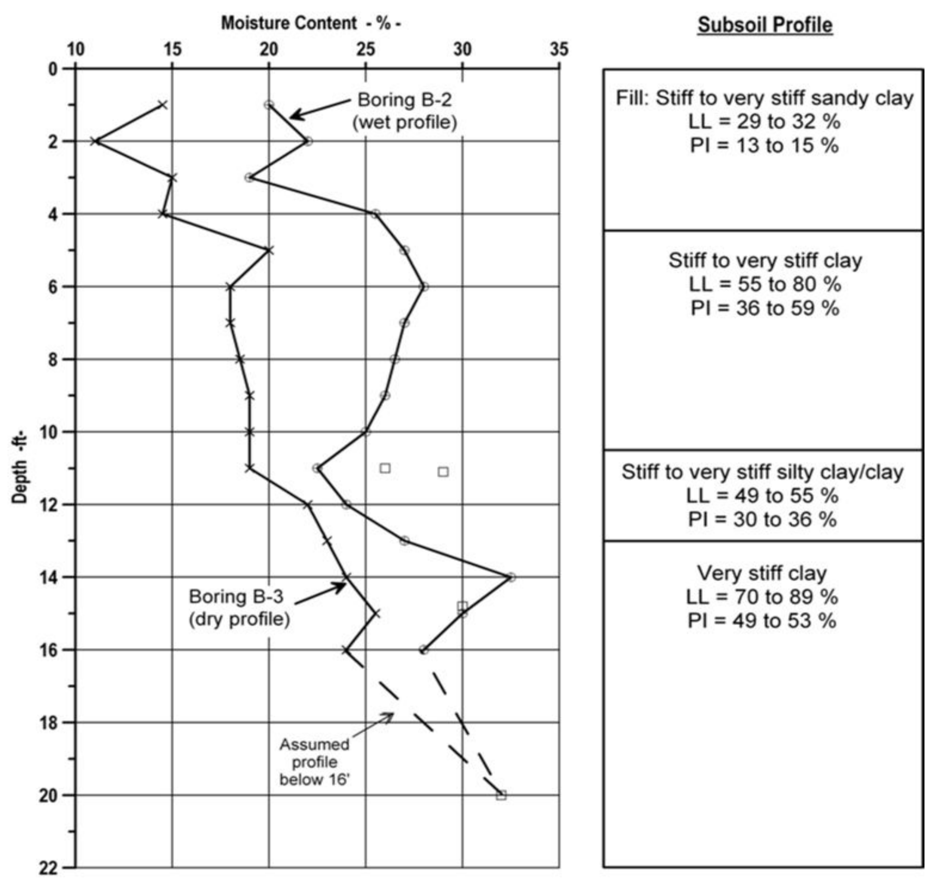

Figure 2: Moisture Profile with Depth (Site 1)

The foundation system is underreamed footings, sometimes referred to as belled piers, bearing at a depth of 8 feet below natural grade (~10 feet below exterior perimeter grade). The footings were sized for a net allowable bearing pressure of 4,500 psf.

The floor slab is 5 ± 1 inch thick, and it bears on 3½ feet of sandy clay fill. The fill is underlain by stiff to very stiff clay to a depth of 25 feet. The moisture profile along with a summary of the index tests is shown on Fig. 2.

Two 16 to 18 inch diameter oak trees had been planted 16 feet from the edge of the building in a small landscape area at this location (see photo 1). The drip line of the trees had reached the perimeter of the building, and the branches had to be pruned back to keep them from rubbing against the building.

Photo 1: Oak Trees Causing Settlement

An elevation contour profile of the ground supported slab is shown on Fig. 3. It clearly shows that 5 inches of settlement of the floor slab occurred along the south wall just west of the SE corner. This settlement reflected up into the elevated floors indicating that the footings also settled 5 inches. The soil boring drilled in this area revealed the presence of a 2¼ inch void below the slab. Thus, total settlement of the ground surface below the slab was 7¼ inches (5 + 2¼ = 7¼ inches). The contour profile indicates that the zone of settlement extends about 40 feet beyond the drip line of the trees located at the edge of the building.

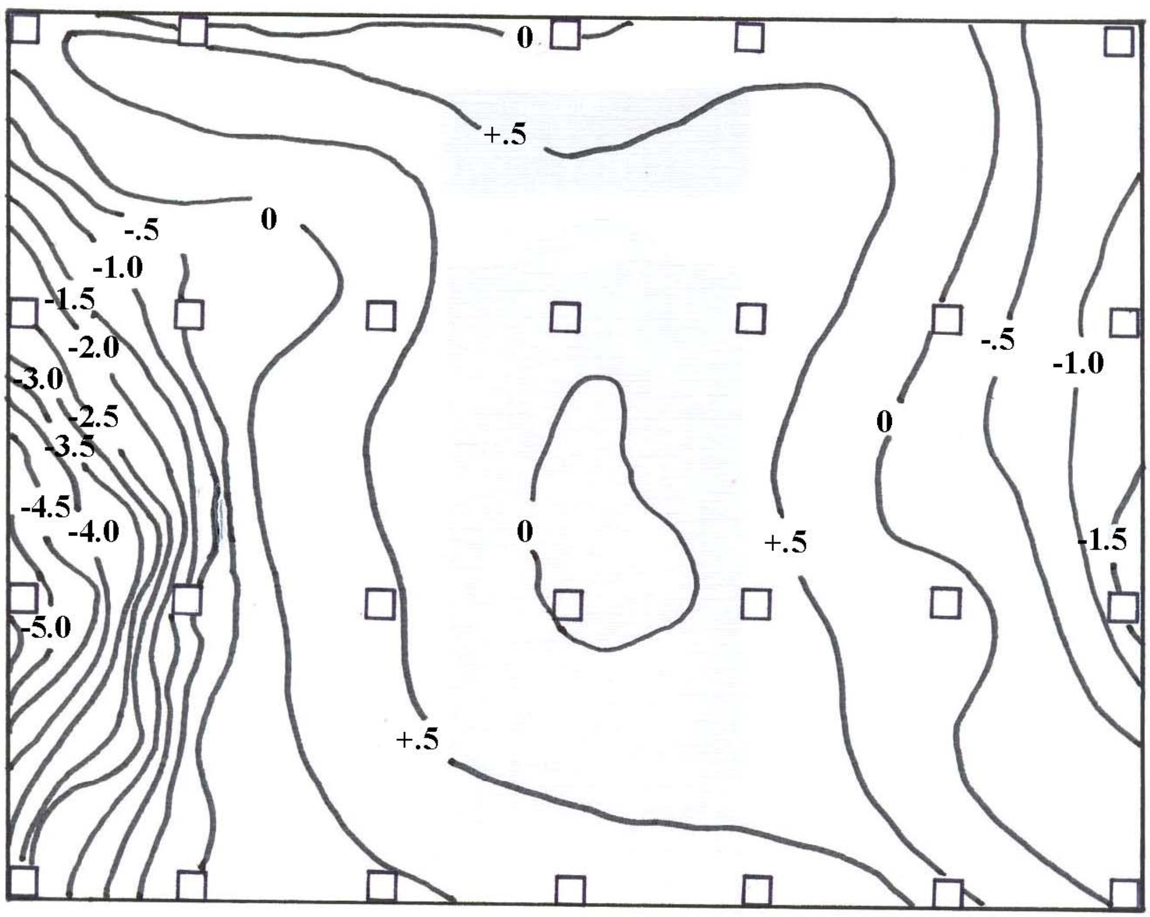

Fig. 3: Site 1 Elevation Contours

About 1½ inches of settlement of the floor slab occurred along the north wall west of the NE corner. The soil boring drilled in this area revealed the presence of a 1½ inch void below the slab. Thus, total settlement of the ground surface below the slab was 3 inches (1½ + 1½ = 3 inches).

Two 10 to 12 inch oak trees had been planted next to the building in this area. The trees had been planted so close to the building that extreme pruning had to be performed to keep the branches away.

The floor slab was relatively level in the interior portions of the building, and along the east and west walls where no trees had been planted. The old saying applies "where there is smoke, there is fire". Moisture demand from the trees has caused deep seated shrinkage of the clays resulting in settlement of the footings and floor slab in areas close to the trees.

The moisture profile with depth for boring B-3 near the area of maximum settlement is shown on Fig. 2. The moisture profile for boring B-2 located about 50 feet north of boring B-3 in an area not affected by the trees is also shown for comparison purposes. The □s shown in the figure were moisture data taken from the original geotechnical report performed by others. Note that the depth of moisture variation is below the depth of 15 feet, and it may be 20 feet or deeper.

Site 2 – This site is an office/warehouse park located on Loop 610 S near the Astrodome. There were four buildings, and each had experienced appreciable foundation settlement. The buildings are 1-story tilt wall structures, and they had been constructed in the late '70's (~30 years old).

The foundation system is underreamed footings, sometimes referred to as belled piers, bearing at a depth of 8 feet. However, straight shaft piers bearing at a depth of 5 feet were used to support the lightly loaded architectural columns along the office frontage. The original geotechnical investigation report could not be found, and thus the bearing pressures are unknown.

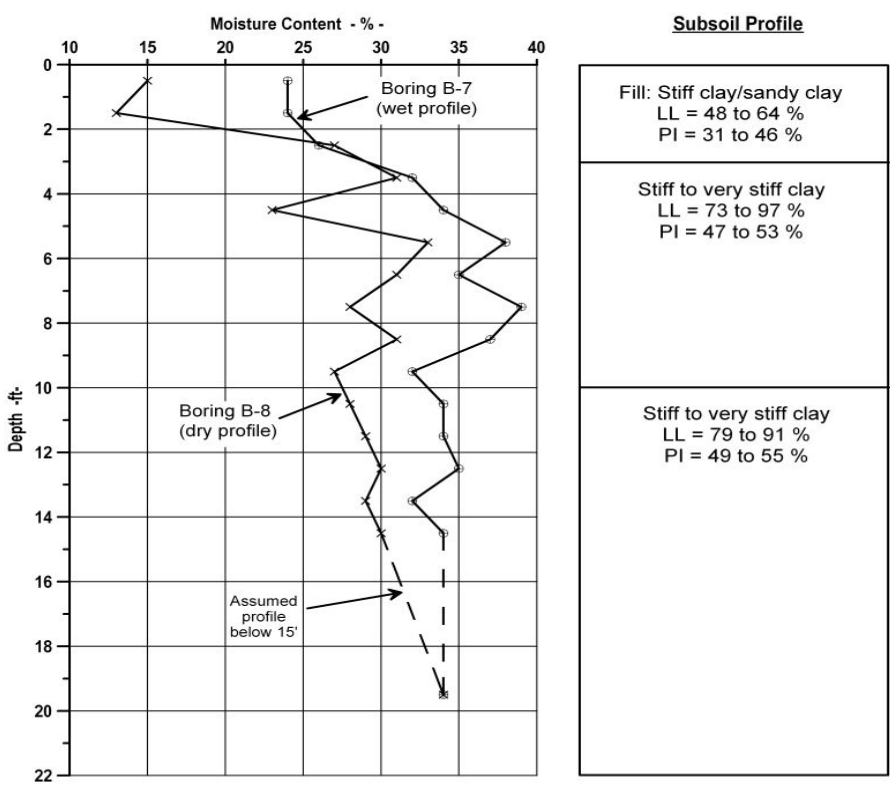

Figure 4: Moisture Profile with Depth (Site 2)

The maximum settlement occurred along the south wall of building C near the SW corner. The floor slab in this area was about 5¼ inches thick, and it was bearing on 2 feet of clay fill. The fill was underlain by clay to a depth of 55 feet. The moisture profile along with a summary of the index properties is shown on Fig. 4.

The elevation survey of the south half of the building is shown on Fig. 5. It clearly shows that about 8 inches of settlement of the ground supported floor slab occurred in this area. A void was not found below the floor slab at this location. Settlement had sheared off the rebar connecting the tilt panels to the floor slab in this area, and angle irons had been quick bolted to tie these two elements together. The contour profile indicated that the zone of settlement is about 25 feet beyond the drip line of the tree. There were openings at the top of the tilt panels indicating that settlement of the footings had occurred.

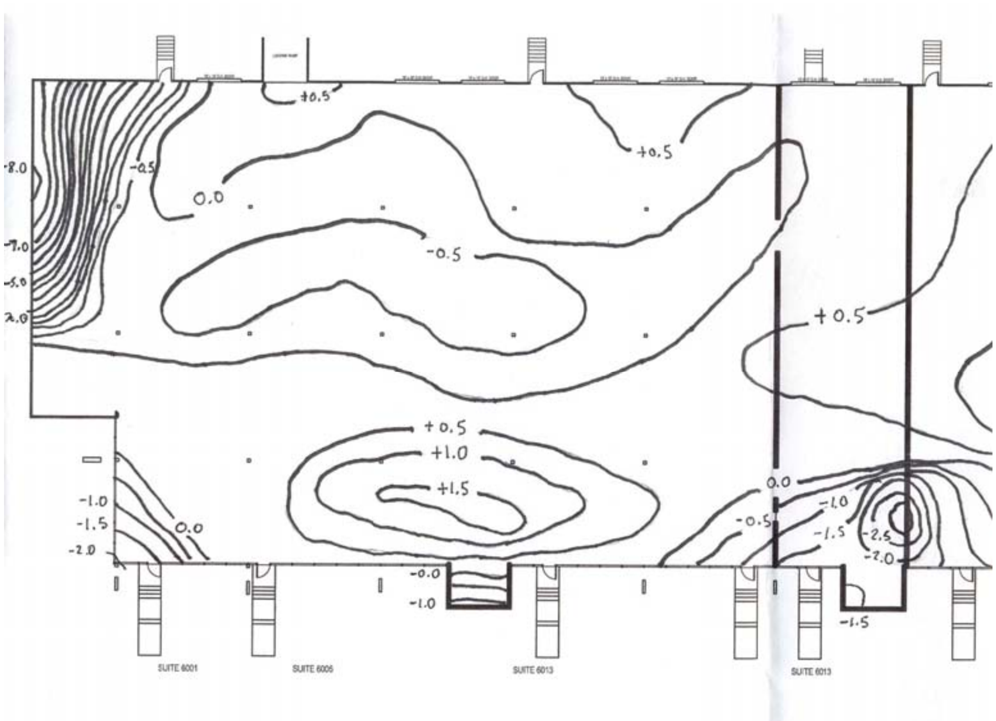

Fig. 5: Site 2 Elevation Contours

As shown in Photo 2, a 22 inch diameter oak tree had been planted close to this area. Also, two 10 to 14 inch diameter trees had been planted west of the SW corner of the building.

The floor slab was not level throughout this building. There were areas where ±1½ inches of heave occurred, as well as settlement at other locations near trees. It is readily apparent that moisture demand from the oak tree caused deep seated shrinkage of the clays resulting in settlement of the footings and floor slab.

Photo 2: Oak Tree Causing Settlement

The moisture profile with depth for boring B-8 near the area where maximum shrinkage occurred is shown on Fig. 4. The moisture profile for boring B-7 located about 125 feet northeast of this location in an area not affected by the trees is also shown for comparison purposes. Note that the depth of moisture variation is below the depth of 15 feet, and it may be 20 feet or deeper.

LESSONS LEARNED

Planting trees close to buildings on expansive clays will result in considerable settlement of floor slabs near the trees. About 7 to 8 inches of total settlement of the ground surface occurred below the floor slabs at both of the sites discussed in this paper.

Floor slabs designed to be ground supported can not tolerate such settlement without causing significant distress to the building. Situating a floor slab on a pad of select fill intended to minimize heaving of expansive clays is not effective in controlling deep seated settlement due to shrinkage of the clays.

About 5 inches of settlement of the underreamed footings bearing at a depth of 10 feet below exterior perimeter grade occurred at Site 1. This greatly exceeds the commonly accepted design criteria of 1 inch. The depth of moisture change at these two sites is at least 15 feet below grade, and it could be 20 feet or deeper.

Foundations for buildings next to trees can be designed for the magnitude of settlement observed. However, this would require the construction of a deep foundation to support the building frame, and the floor slab must be designed as a structural member due to loss of ground support. Proper consideration must be given to connection of the underground utilities to the slab so that differential movement between the "fixed" structure and settling ground surface does not rupture the pipes. While such a design would certainly be effective, it would be very costly. Many buildings might not be economically feasible due to the added cost of foundation construction.

A more economical approach would be to locate the trees far enough away from the building so that moisture demand of the trees on the clay subsoils does not cause settlement of the foundation. The zone of moisture influence was about 40 feet beyond the drip line at Site 1. However, this occurred because the floor slab restricted recharge of moisture. The lateral zone of influence would probably be much less if the tree was situated in a large landscape area to allow rainfall and irrigation water to recharge the clays. A deep impermeable root barrier at the perimeter of the building can be installed to minimize the potential for growth of roots below the floor slab.

What has been identified is a design issue to be addressed by the landscape architect. The landscape architect should be an educated professional that understands the water needs of the various species of trees, and has knowledge about the effects that moisture changes have on expansive clays. He must coordinate the location of landscape areas and types of trees and other vegetation to be planted with the architect of record and Owner. Failure to implement a proper design will ultimately result in poor foundation performance, and possibly a failure if the magnitude of settlement is too severe.