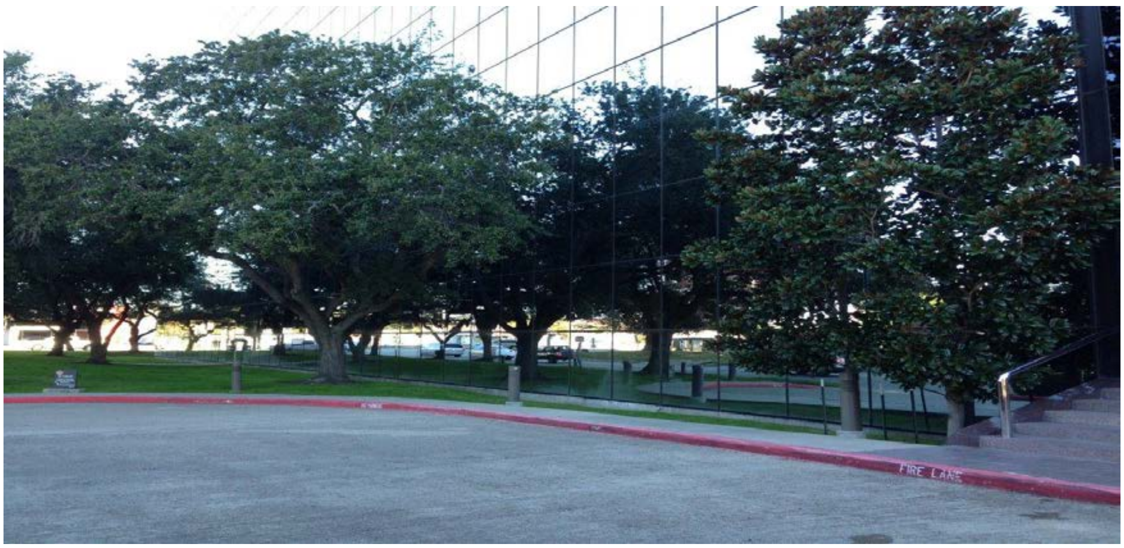
Effects of Vegetation on Foundations Bearing in Expansive Clays in Urban Environment

Kenneth E. Tand, P.E.

Practicing Geotechnical Engineer
Kenneth E. Tand & Associates
2817 Aldine Bender Rd,
Houston, Texas 77032



Expansive Clay Problems

Expansive clays are recognized by the National Science Foundation as one of nine hazards in North America causing building distress. It is estimated that the annual cost of damages due to expansive clay is in the order of $15 billion dollars (Cerato, 2016).

Expansive clays cover about one quarter of the surface area of the continental United States, which reasonably represents Texas as well. However, Texas' five largest cities are located in areas where highly expansive clays are present.

I have performed more than 50 geotechnical forensic studies for sites in Texas where damages have occurred due to expansive clays, with most in the greater Houston area. This paper is specific to commercial buildings in the greater Houston area supported on underreamed piers or spread footings. However, the conclusions will also be applicable to cities with similar geologic and environmental conditions. This paper excludes discussion of residential and light commercial buildings supported on stiffened slab on ground foundations.

What was found in my database was that pre-existing or planting of new trees next to buildings was the major contributing factor at more than one half of the Houston sites.

Removal of pre-existing trees or thick underbrush prior to construction occurred at another one quarter of the sites. The presence of trees, or impact of their removal, was the primary cause of distress to most of the buildings that I have investigated.

Trees and Suction

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. Carbon dioxide, water, and sunlight are used to produce glucose, oxygen, and water. The chemical equation for this process is: $6CO_2 + 6H_2O + light = C_6H_{12}O_6 + 6O_2$.

Chloroplasts are the site within the leaves where photosynthesis actually occurs. The leaves have inner and outer membrane protective covers that keep the chloroplast structures enclosed. The conversion of carbon dioxide to sugar occurs in a dense fluid known as stroma within the chloroplast. Chlorophyll is a green pigment within the chloroplast that absorbs light energy. Layered stacks of thylakoid sacs convert light energy to chemical energy.

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. Nature did not provide a pump below the tree that pumps the water up to the leaves. What happens is that moisture losses at the surface of the leaves, termed transpiration, cause 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 living pipeline for the upward flow of water from the ground (Biddle, 2001).

The bulk of the root system for most trees, not all, is located within the upper 3 feet of the ground surface. I have personally examined samples where scattered roots have been found at depths of 15 to 18 feet. These are exceptions, and the depth of the roots is more often 10 to 15 feet. The underlying root system subdivides into fine roots that connect to fine feeder roots. 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 density of clay soils tends to restrict the growth of the fine feeder roots. However, as the clays desiccate macropores and fissures open up allowing penetration of the roots. I have often found roots in fissures and slickensides. Extraction of water from the soil causes suction, which in turn causes the soil particles to be pulled closer together. Some soils, such as sand and gravel, have strong contacts and resist collapse of the soil structure. However, most clays are somewhat compressible, and the volume change can be appreciable. This process is commonly referred to as shrinkage.

In general, the larger the leaf area of the tree the more water is needed. Once the feeder roots have more or less extracted the available water near their tips, then they must extend their root system to draw more water. It should be noted that most, not all, trees are dormant during part of the year. Rains allow recharging of the groundwater taken by the trees during the active season. The trees at the sites in this report are primarily live oaks which do not go completely dormant during the winter.

Urban development is often detrimental to the growth and survival of trees. In general, there is 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. A substantial portion of the rain runoff that occurs today historically infiltrated into the subsoils to maintain a high water level. Often, small trees are planted in small landscape areas between the buildings and paving for landscaping purposes. When the trees get too large to survive on the groundwater in the 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 complete barrier to recharge from rainfall in the rainy seasons. Thus, the root system must grow laterally and downward in search of new water sources once they are below the buildings and paving.

Area Geology

Most of Houston, excluding the northwest quadrant, is located on the Beaumont formation. The soils were deposited in Pleistocene times in shallow coastal river channels and flood plains which generated a complex stratification of sand, silt and clay. The clay portion is composed of montmorillonite, kaolinite, illite and fine ground quartz (Vipulanandan, 2007). The normally consolidated clays became overconsolidated due to desiccation that occurred during cyclical drying periods. The increase in density resulted in weak bonding between the clay particles that caused the clays to have a shrink/swell behavior. Also, desiccation produced a network of fissures and slickensides in the clay that increased the mass permeability of the geologic formation.

About one-quarter of the clays in the Beaumont formation in Houston have a moderate to high shrink/swell potential (PI of 20 to 40), and about one half have a high potential (PI of 40 to 60). Most of the remaining one quarter have a very high potential (PI>60), but pockets of clay with low potential (PI<20) exist. The four sites discussed in this report are located on sites where clays with a high to very high shrink/swell potential exist.

The Thornthwaite Moisture Index (TMI) is about 18 which would categorize Houston as having a humid climate. The TMI is an average value and does not reflect extreme conditions between years, concentrations of rainfall, or varying site conditions due to vegetation and irrigation. The TMI may not be an appropriate index for urban areas where mankind has dramatically changed environmental conditions.

Trees and Foundation Performance

I first became aware of settlement of underreamed piers due to moisture demand of trees in the early 1980s at three schools in Spring Branch. The piers were bearing at depths of 8 feet, which was below the commonly accepted 6 foot depth of the active zone in the 1960s and 1970s. The piers at each school were close to large oak trees, and they had settled about 1½ to 2 inches due to moisture demand of the trees.

Settlement resulting from moisture demand of vegetation was known by other engineers prior to this time period. Felt (1953) reported damages to Texas roads due to vegetation. Castleberry (1974) discussed damages to residential dwelling in Texas. Eastwood (1997) discussed case histories of residential foundations in Houston damaged due to trees. Houston's citizens were publically notified about problems with trees and settlement of residences in Houston Post article the “Foundation problems preventable” (1988). Tand (2001) discussed case histories of commercial foundations damaged due to trees. There are many more geotechnical engineering papers discussing this subject, and a few are listed in the references.

I have found 8 inches of ground settlement below floor slabs at several sites in Houston. The largest settlement of an underreamed pier due to moisture demand of trees that I have observed was 5¾ inches at a site near NASA. The pier was bearing at 9 feet below top of slab. An underreamed pier bearing at a depth of 13 feet settled 3 inches at another site close to the medical center due to moisture demand of trees. The most heave of an underreamed pier due to removal of pre-existing trees is 1½ inches at a site in the Bellaire area. It was a lightly loaded interior pier bearing at a depth of 10 feet below finished floor. These large magnitudes of foundation movement are exceptions, not common occurrences.

Most commercial buildings in Houston were historically supported on spread footings bearing at depths of 6 ± 2 feet or underreamed piers bearing at depths of 8 ± 2 feet, and most have performed good. For example, the author performed forensic geotechnical studies at an elementary school in the Galleria area that was constructed in the late 1950s where performance of 6 feet deep underreamed piers was good at more than three quarters of the building. However, 5 inches of settlement of the piers occurred in areas close to trees.

One might ask, was situating the piers at 6 feet good structural design from the standpoint of foundation costs, or was planting trees for aesthetics next to the school bad architectural design? The reality is that most engineers and architects practicing at that time period simply did not understand that moisture demand from trees could cause large magnitudes of settlement to occur.

Some practicing geotechnical engineers today are situating underreamed piers deeper because of poor foundation performance that infrequently occurs. Engineering is a balance between performance and cost. It is my opinion that the threat of litigation is causing us to become more conservative driving up the cost of foundation construction. I believe that more effort should be directed at finding what is causing the problems, and then making changes to correct them.

Much of Houston was farm land from the late 1800s to mid 1900s before suburban spread started to occur. The farm land was often terraced to hold water which recharged the groundwater lost during the dry summer months. The water level was commonly found at 10 ± 5 feet in the 1970s and 1980s. The water level is now more commonly 20 ± 5 feet today because the farm land and low areas were drained, and the land surface has been covered with streets and buildings with good drainage to remove rain water that previously recharged the groundwater. There were always problems with foundations on expansive clay in Houston, but they are more prevalent today. Also, expectations regarding foundation performance are higher today.

The redevelopment of older properties occurring in Houston today presents challenges when removal of trees is necessary. The trees often have desiccated the clays to deep depths, and significant heaving occurs after their removal. Developers also have to consider the impact of existing trees located within the street right of ways because cities often restrict their removal.

Practicing geotechnical engineers mostly concern themselves with bearing capacity, and limiting settlement due to structural loads to 1 inch or less. Obviously, we must expand our thinking to include the effects that vegetation has on performance of foundations. We must be trained to recognize potential hazards so that we can provide our clients with a safe and economical foundation system.

CASE HISTORY 1

The site is located in the Upper Kirby district. The building is a 2-story concrete frame structure constructed in the early 1980's. The foundation system is spread footings bearing at depths of 10 feet below top of slab (±8½ feet below natural grade).

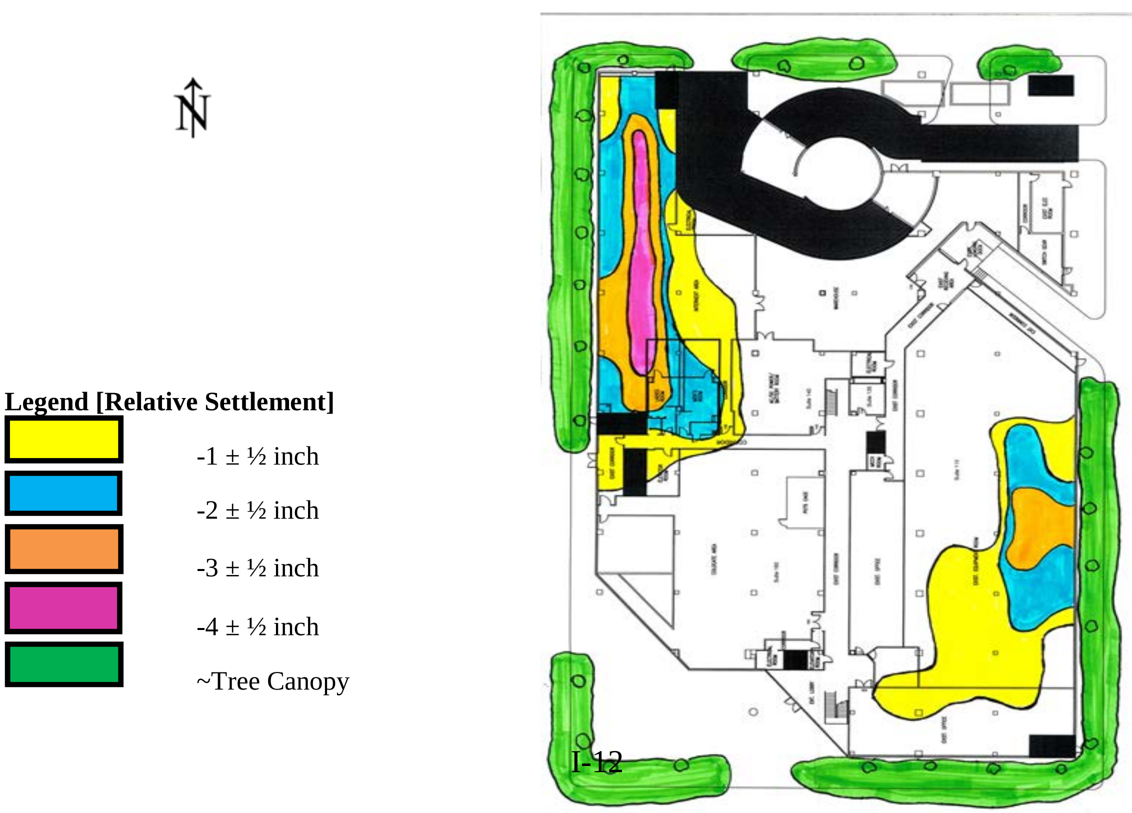
Differential movement caused cracks in the dry wall, gaps along baseboards, and unlevel floors. There were openings in the joints of the concrete spandrel panels, and a ½ inch separation in one glass window wall connection at the northwest corner. The floor slab had been raised with urethane foam in the restroom on the north side in 2012, but sticking doors indicating that additional movements were still occurring in 2013.

An elevation survey was performed in November 2013, and the contours of relative floor slab movements are shown on Fig. 1. The contours of slab movement are based on a benchmark located in the center of the building next to a column where the elevation survey shows that little floor movement had occurred. Construction tolerances are generally ±½ inch when floor slabs are poured, but could be 1 inch or more if poor quality control occurs. Elevation measurements were made with a digital water level with an accuracy of 0.1 inch. I have also found 0.2 inches of elevation variations within a 3 foot square due to floor slab imperfections. There are also issues regarding total and differential settlement of the footings that occurred. Thus, the contour lines are not entirely accurate, but are certainly within the accuracy needed when performing forensic studies.

About 4 ± ½ inches of settlement of the floor slab was found along the easterly half of the north wall, and 3 ± ½ inches along the westerly half of the south wall. The elevation survey on the 2nd floor indicated that 3 ± ½ inches of settlement occurred at one footings on the north , one on west, and one on south walls. The maximum differential settlement of the footings between adjacent exterior columns was 2½ ± ½ inches. Also, 2 ± ½ inch of differential settlement occurred between interior columns and exterior columns.

More than 20 oak trees ranging from 14 to 24 inches in diameter were planted around the perimeter of the building. The canopies of the trees were located close to the exterior walls, and most had to be pruned to keep branches from rubbing against the exterior walls and window glass. I found that very little settlement occurred in areas not close to trees.

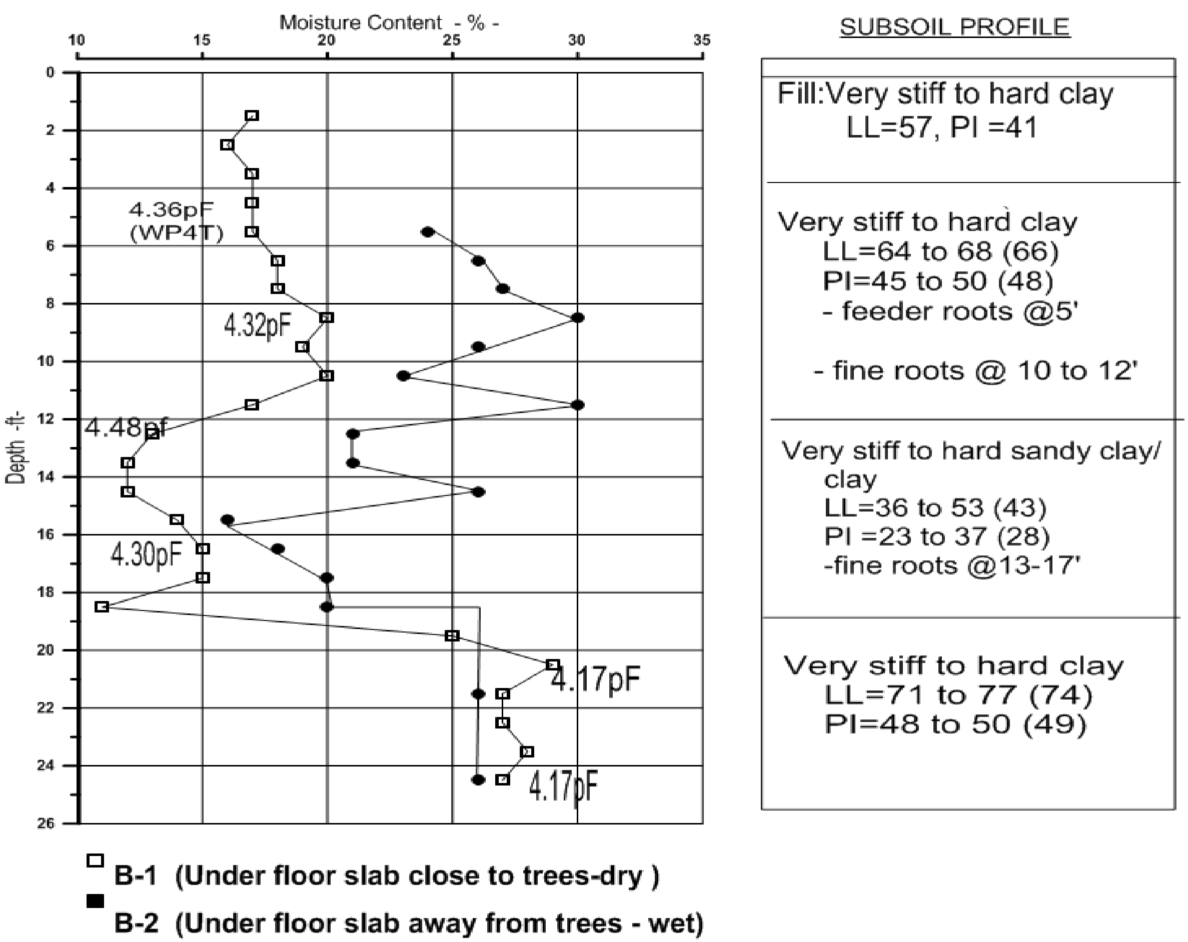
Figure 1
Contours of Elevation/Ground Floor



Two soil borings were drilled to depths of 25 feet inside the building using hand auger equipment. Also, one boring was drilled in a landscape area under the 2nd floor overhang where the separation in the window wall occurred. Disturbed soil samples were taken from the bucket auger on 1 foot centers, and relatively undisturbed samples were taken every 3 feet by driving a 3-inch O.D. Shelby tube into the soils using a sliding hammer.

Laboratory testing included determining the moisture content of each sample. The Atterberg limits properties, swell in an oedometer cell, and soil suction (WP4T instrument) were determined on each Shelby tube sample. On Fig. 2 a graph of the moisture content with depth is shown. The soil suction tests performed on the samples from the boring closest to the trees are recorded next to the moisture profile. The subsoil profile that describes the soil layers, and summarizes the Atterberg limit tests is also shown on Fig. 2. The average values of the liquid limit (LL), and plasticity index (PI) are enclosed in parenthesis i.e. (66).

Figure 2
Subsoil Moisture/Depth Profile
Case History 1



Feeder and fine roots were found between the depths of 5 to 17 feet in boring B-1 under the floor slab. The boring was beyond the drip line of the tree which is commonly, not correctly, assumed to be the extent of the root system. Free water was not encountered when drilling boring B-1 close to trees, but was encountered at a depth of 19 feet below top of slab in an area away from trees. The preconstruction depth of the groundwater level was probably higher.

The survey data indicates that the elevation of the floor slab at boring B-1 was ±3½ inches below what existed at the time of initial construction. This implies that total settlement of the original ground surface below the floor slab was ±6 inches when considering that a 2½ inch void was found below the settled slab.

The lateral extent of root growth is unknown. However, there was a noticeable change of the elevation of the floor slab about 50 feet south of the north wall in the middle of the building, and 50 feet north of the south wall near the southwest corner of the building. What is not known is what portion of the settlement is due to soil suction occurring beyond the tips of the feeder roots.

A comparison of the moisture content profile at boring B-1 near the trees, and at boring B-2 in the truck dock away from trees, suggests that the depth of moisture loss due to the trees is about 20 feet below top of the slab. However, I generally find soil suction values of 3.6pF to 3.8pF at similar depths when trees are not present. Thus, the high 4.2 pF soil suction below 20 feet suggests that the depth of moisture loss was probably deeper. The results of the swell test at 24 feet indicate that 0.4 percent volumetric swell of the clay sample occurred at this depth. No swell would have been measured if the clay sample had been saturated. This opinion is further substantiated by the high pocket penetrometer value of 4.2 tsf at 24 feet in boring B-1, compared to the 2.2 tsf value at B-2 away from the trees. High pocket penetrometer values are typically due to high soil suction. The geotechnical engineer must examine all the different tests when conducting engineering analysis in order to render credible opinions.

The structural engineer concluded that a life safety issue did not currently exist. However, continued settlement would probably increase the differential settlement potentially causing structural damage to the concrete frame. Also, frequent cosmetic repairs were being made due to settlement. Procedures had to be found to stop the settlement. The cost to underpin the footings with deep piles, and structurally suspend the floor slab was prohibitive, not to mention that it would be disruptive to the tenant leasing the ground level floor. There were numerous underground utilities around the building, and the trees were so close to the perimeter that installation of a vertical barrier was impractical.

Remedial action included removal of all the trees in the fall of 2014, and installation of a horizontal moisture barrier to slow the rate of rehydration of the clays. An elevation survey performed in February 2017 indicates that the footings along the north and south wall have rebounded about 1½ inches, which reduced the differential settlement. However, the footing at the northwest corner of the building that had settled 3 inches rebounded entirely in a 2 year time period.

The horizontal barrier had been recommended thinking that the time for rehydration of the clays would be in the order of 10 years so that slow and more uniform rebound would occur. Such action had been successful at another site in southwest Houston using a vertical barrier. However, it is my opinion that the barrier was only partially effective because it may not have been installed properly due to the many underground utilities, and that there was probably a water leak somewhere causing rapid rehydration of the clays.

The lessons learned are not to plant trees close to buildings, and that it is very difficult to install a vertical or horizontal barrier that will slow rapid rehydration of the clays. A deep foundation system with a structurally suspended slab will be required if trees are to be planted next to buildings.

CASE HISTORY 2

The site is located in the Westchase district on the west side of Houston. The building is a 12-story concrete frame structure constructed in the early 1980s. The foundation system is spread footings bearing at depths of 14 feet below top of slab (±10½ feet below natural grade).

Differential movement caused cracks in the dry wall, severe slab cracking, sticking doors, unlevel floors, and vertical offsets in the ceiling tiles. The floor slab had been raised with urethane foam in the tenant space on the north side in 2012, but movement of window walls indicated that additional movement was still occurring in 2013.

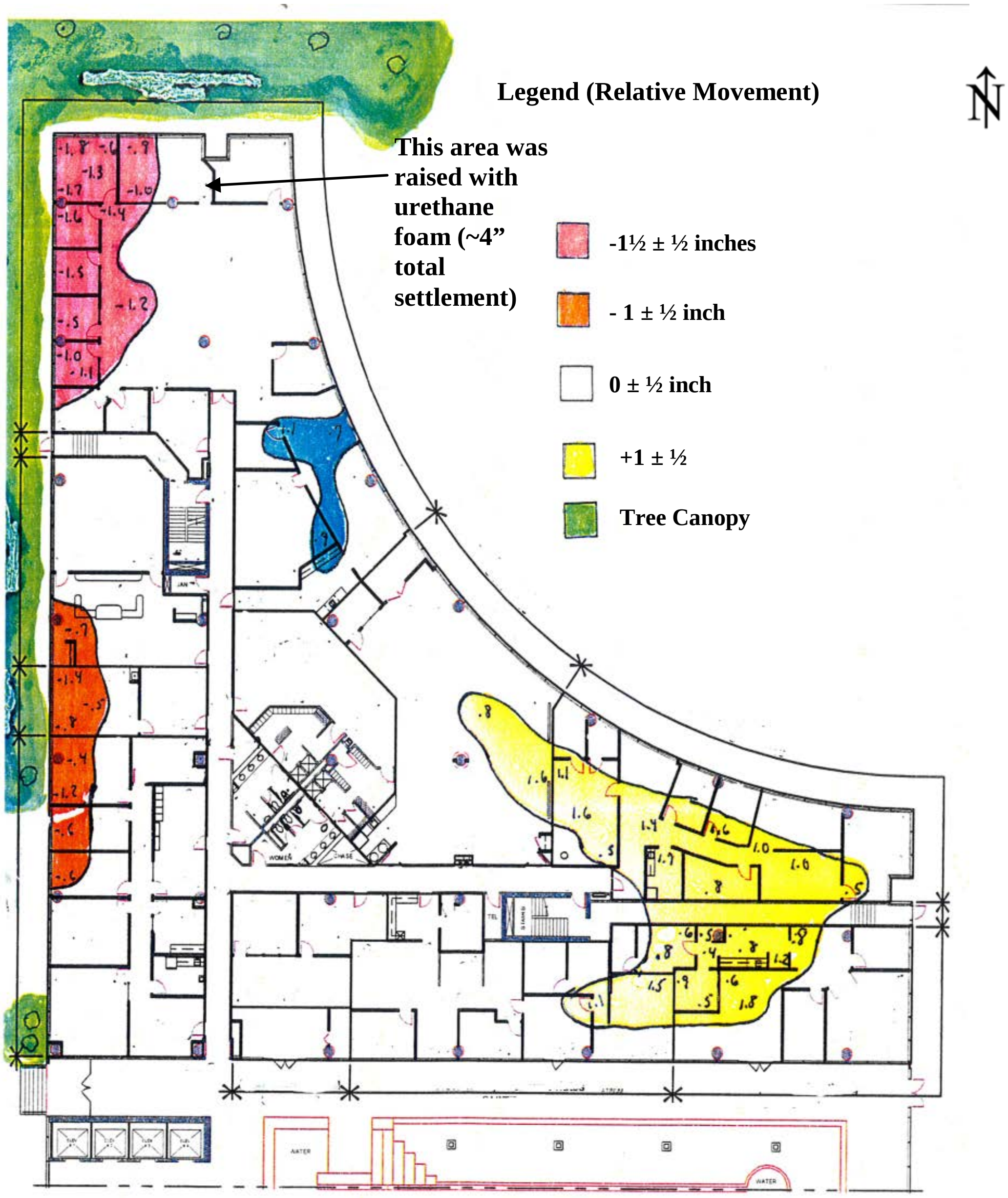
A cursory elevation survey had been performed by a contractor in January 2012 prior to injection of urethane foam to level the slab. The elevation survey after injection shows that the slab was raised 2 ± 1 inches. I performed an elevation survey in January 2014, and found that another ±1½ inches of additional settlement of the floor slab had occurred at the northwest corner of the building in a 2 year period. Also, ±1 inch of settlement was found along the west wall south of this area. The contours of relative floor slab movements are shown on Fig. 3.

The elevation survey on the 4th floor indicated that about 1½ ± ½ inch of settlement occurred at one footing at the northwest corner. The maximum differential settlement of the footings between adjacent interior and exterior columns was about 1 inch.

I often find that both heave and settlement have occurred in different locations in large commercial buildings. I found that 1 ± ½ inches of heave had occurred in the southeast corner of the building.

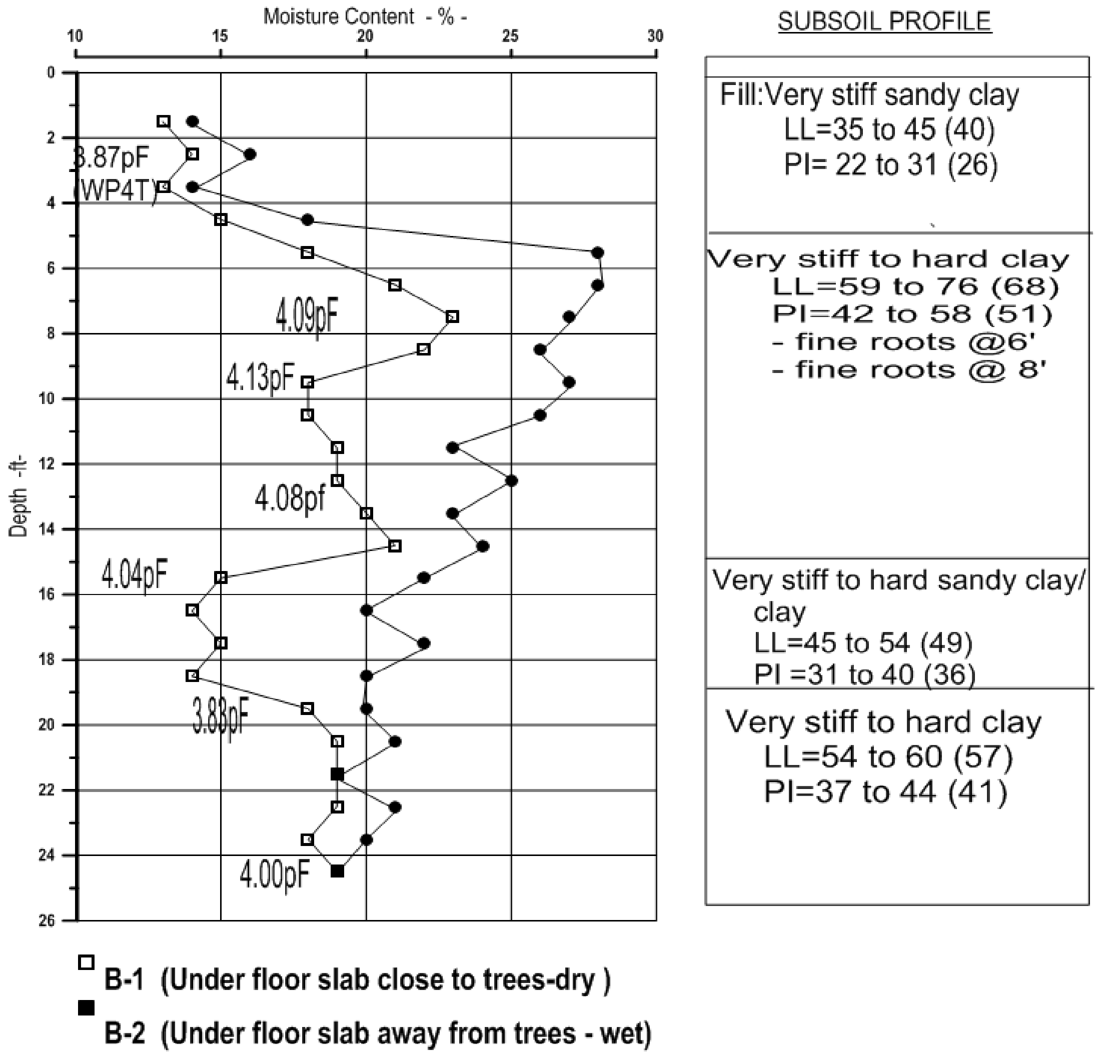
Two oak trees ranging from 20 to 26 inches in diameter had been planted 18 feet from the building at the northwest corner. Also, two 20 to 28 inch oaks were planted about 35 feet west of the building, and another three 20 inch oaks about 35 feet north of the building at the northwest corner. The canopies of the two trees nearest the building were close to the exterior walls, and they had to be pruned to keep branches from rubbing against the window glass. I found that very little settlement of footings occurred in areas not close to trees.

Fig. 3
Contours of Elevation Ground Floor



Two hand auger borings were drilled to depths of 25 feet inside the building. Boring B-1 was located in the northwest corner of the building where settlement had occurred, and B-2 was located in an area where little floor slab movements had occurred. The same procedures for field sampling and laboratory testing as discussed for Case History 1 were performed. The subsoil and moisture profiles are shown in Fig. 4.

Figure 4
Subsoil Moisture/Depth Profile
Case History 2



A 2¾ inch thick layer of urethane foam was found under the floor slab at boring B-1. Free water was not encountered when drilling the borings. However, the pocket penetrometer value of 1.4 tsf at 9 feet in boring B-2 suggests that the water table which existed when the building was constructed was close to this level (unknown fact).

Feeder and fine roots were found at depths of 6 to 8 feet at boring B-1 under the floor slab about 12 feet from the exterior wall. The boring was beyond the drip line of the tree which was close to the perimeter wall. The lateral extent of root growth is unknown. However, there was a noticeable change of the elevation of the floor slab level about 38 feet south of the north wall, and 48 feet east of the west wall prior to injection of the urethane foam in 2012.

A comparison of the moisture content profiles at boring B-1 near the trees, and at boring B-2 in an area not close to trees, suggests that the depth of moisture loss due to the trees is about 25 feet below top of the slab. The same comments made for Case History 1 also apply to the 4.0pF soil suction found at 24 feet.

The 2014 elevation survey found that the elevation of floor slab at boring B-1 was about ±1½ inches below the initial construction level. Thus, total settlement of the ground surface at this location was about 4½ inches considering that a 2¾ inch layer of urethane foam had been found below the floor slab.

The cost to underpin the footings, and structurally suspend the floor slab was prohibitive, not to mention that it would be disruptive to the tenants leasing the ground level floor. Remedial action included installation of an 8 foot deep vertical moisture barrier to slow the rate of rehydration of the clays. Additional injections of urethane foam to level the floor slab were not performed.

The lessons learned are not to plant trees close to buildings, and not to level floor slabs using foam thinking that this is a permanent fix. It is simply a temporary cosmetic fix, and will have to be performed again after additional settlement occurs. However, injection of foam is often selected by owners due to the high cost for permanent repairs.

CASE HISTORY 3

The site is located in the City of Nassau Bay close to NASA. The building is a 4-story steel frame structure constructed in the mid 1980s. The foundation system is underreamed piers bearing at depths of 9 feet below top of slab (±8½ feet below natural grade).

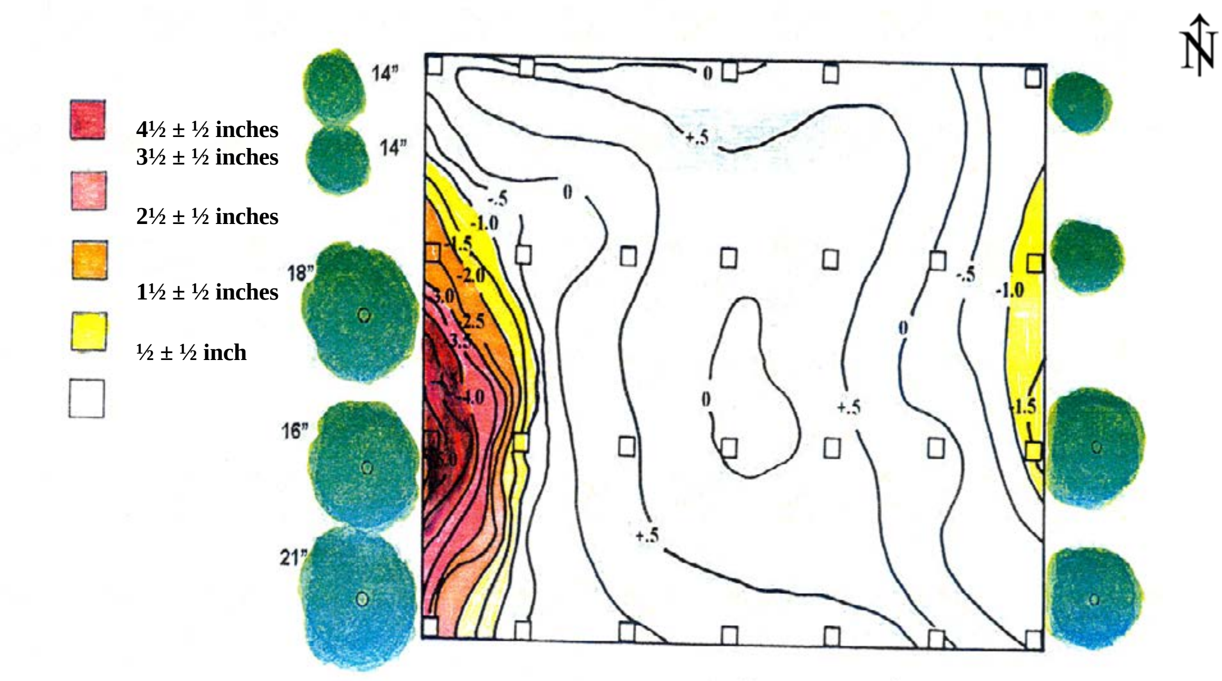
During a tenant buildout in 2006, the contractor expressed concerns about cracks in the dry wall, unlevel cracked floors, cracked windows, sticking doors, and cracks in exterior masonry walls. There were openings in the joints of the concrete spandrel panels and separations in glass window walls at different floor levels. The maintenance staff described a long history of cosmetic repairs.

An elevation survey was performed in 2006, and the contours of relative floor slab movements are shown on Fig. 5. About 4½ ± ½ inches of settlement of the floor slab was found along the south wall, and 1 ± ½ inches along the north wall. The elevation survey on the 3rd floor indicated that about 5 inches of settlement occurred at the underreamed pier just west of the southeast corner. The maximum differential settlement of the underreamed piers between adjacent exterior columns was about 2½ ± ½ inches.

The elevation survey indicates that the elevation of the floor slab at boring B-3 was ±4 inches below what existed at the time of initial construction. This implies that total settlement of the original ground surface below the floor slab was ±6½ inches when considering that a 2½ inch void was found below the settled slab.

Five oak trees ranging from 14 to 21 inches in diameter were planted along the south perimeter of the building. The canopies of the three trees at the southwest corner had to be pruned to keep branches from rubbing against the exterior walls and window glass. Also, 4 oak trees were planted on the north side of the building. I found that very little settlement occurred in areas not close to trees.

Figure 5
Contours of Elevation/Ground Floor

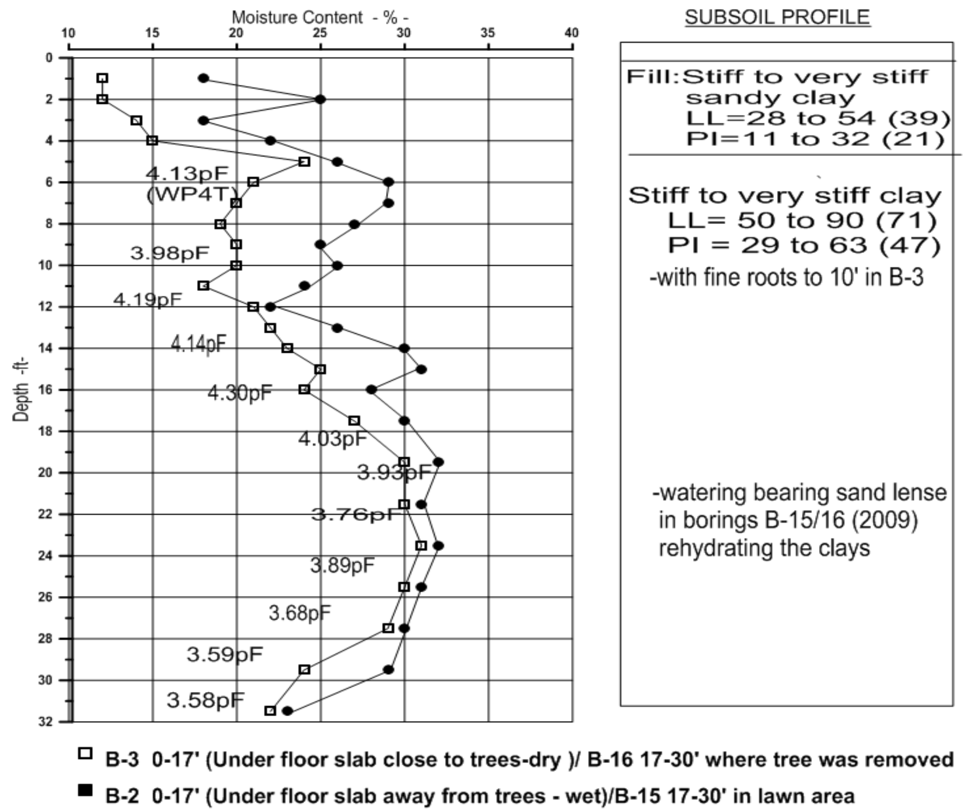


Five hand auger borings were drilled to depths of 17 feet inside the building in 2006. The same procedures for field sampling and laboratory testing as discussed for Case History 1 were performed, and the subsoil data is shown on Fig 6.

Feeder and fine roots were found at depths of 6 to 10 feet in boring B-3 under the floor slab about 8 feet from the exterior wall. Feeder roots were found at a depth of 5 feet in boring B-2 about 40 feet north of the south wall where a ½ inch void was found below the floor slab. The boring was well beyond the drip line of the tree which is commonly, not correctly, assumed to be the extent of the root system. The lateral extent of root growth is unknown. However, there was a noticeable change of the elevation of the floor slab about 60 feet north of the south wall.

The buildout was for a new tenant with a critical deadline for occupancy. Thus, there was no time to underpin the building and construct a new structurally suspended slab. The settlement was so severe at the southeast corner that the structural engineer directed that the floor slab be raised with urethane foam to level the floor as best as possible. The trees on the north side of the building were removed, but the trees on the south side were not removed for aesthetic purposes.

Figure 6
Subsoil Moisture/Depth Profile
Case History 3



The building was later sold to a real estate trust. Foundation movements continued causing cracking of window panes, sticking doors, and cracks in interior dry wall. Another water level survey was performed in November 2008. It was found that the underreamed pier at the southeast corner had settled an additional 1 inch since March 2007, and the pier west of this location settled an additional ¾ inch. The owner had all the trees on the south side of the building removed in December 2008 to prevent further settlement of the building.

Three additional soil borings were drilled to depths of 25 to 75 feet to provide recommendations for design and construction of a deep foundation system to stabilize the building. However, the cost for the repairs was so high that independent structural and geotechnical engineers were retained to study how the building could be stabilized for less cost. They directed that another 2 borings be drilled to depths of 15 feet under the floor slab, and 5 borings to 30 feet at the south end of the building. Boring B-16 was drilled where the 2 oak trees near the southwest corner had been removed.

Heaving of the floor slab started shortly after removal of the trees causing sticking doors and cracks in the interior dry walls in the tenant spaces along the south wall, especially at the southeast corner. Another level survey was performed in May 2010 to check whether any naturally occurring rebound had occurred due to rehydration of the clays. It was discovered that the underreamed pier at the southeast corner had rebounded 1 inch, and that the pier where the maximum settlement had occurred rebounded 1¾ inches due to deep seated moisture changes. However, ±2¾ inches of heave of the floor slab was found in the southeast corner of the building due to a combination of shallow and deep seated moisture changes.

The cost for a permanent fix was so high that the building has been left to heave until it stabilizes. Remedial repairs have included patching cracks in the dry wall, and readjusting doors as additional heaving occurs. No additional elevation surveys have been made since 2010.

The lessons learned are not to plant trees close to buildings, and not to level floor slabs using foam thinking that this is a permanent fix. The installation of foam for repair was a detrimental act because when the clays under the floor slab heaved they did not have a void to fill. Heave will probably raise the level of the floor slab above its' initial construction level.

CASE HISTORY 4

The site is located in the northeast corner of the City of Bellaire. Building 1 is a 1-story steel frame structure, and Building 2 is a 2-story steel frame structure. Both were constructed in the early 2000s. The foundation system for both buildings is underreamed piers bearing at depths of 10 feet below top of slab (±8½ feet below natural grade).

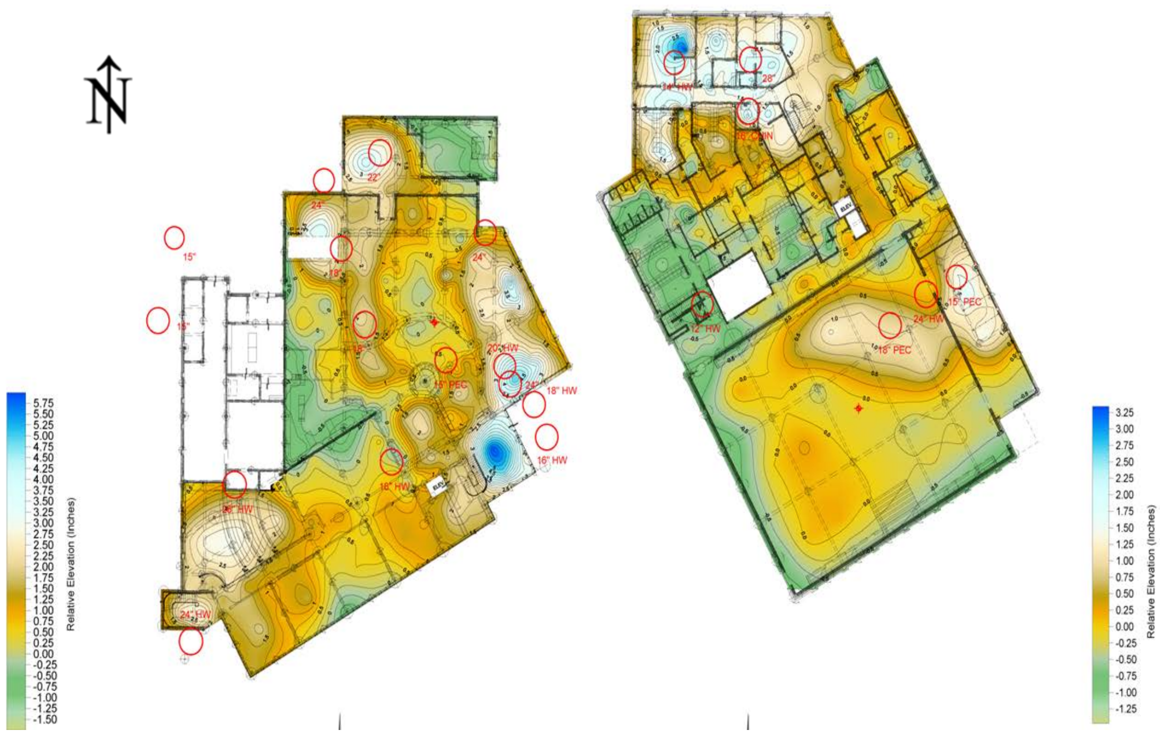
Differential movement caused cracks in the dry wall, severe slab cracking, sticking doors, unlevel floors, and cracking in CMU walls. Litigation ultimately occurred due to the severity of the distress.

An elevation survey was performed in 2009 by other consultants. Heave of the floor slab was found to be ±4 inches at Building 1 and ±6 inches at Building 2. One underreamed pier in Building 1, and four in Building 2 heaved ±1½. The contours of relative floor slab movements are shown on Fig. 7.

Five oak and pecan trees ranging from 14 to 28 inches in diameter were removed under Building 1 just prior to construction, and 13 under and very close to Building 2. The locations are shown on the contour plan, and there is a good correlation of heave and location of the trees.

The geotechnical engineer of record had drilled one boring to a depth of 25 feet under Building 1, and 2 borings under Building 2 in 1997. No groundwater had been encountered when drilling the borings. Minimal laboratory testing had been performed as was the standard of care at that time period, as well as today.

Figure 7
Contours of Elevation/Ground Floor

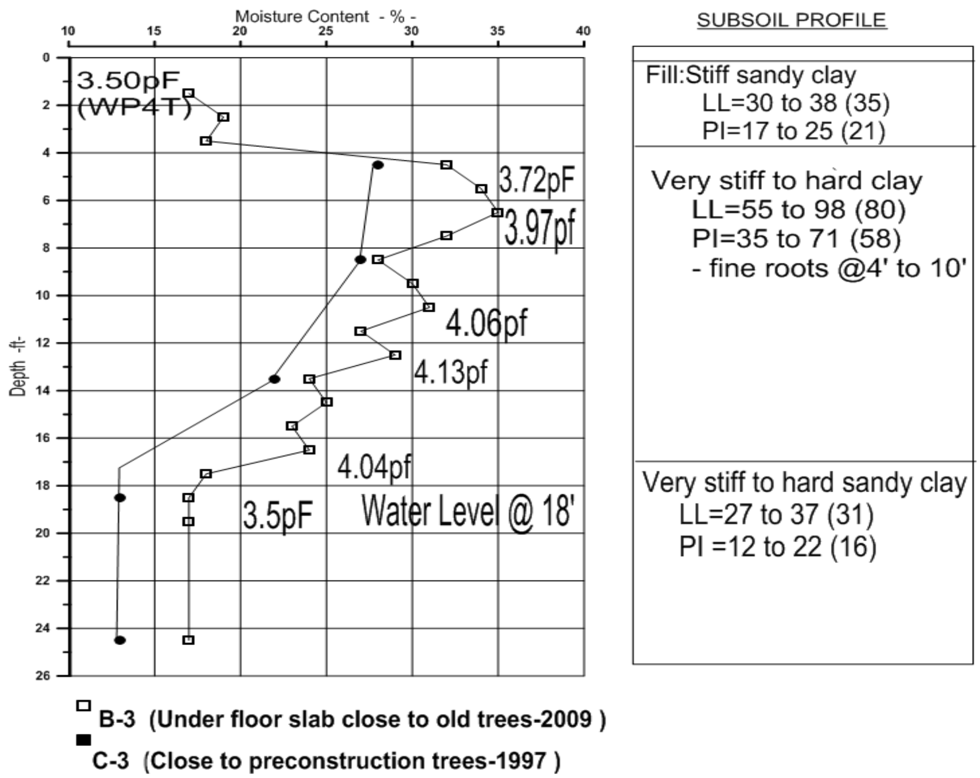


One hand auger boring was drilled to a depth of 20 feet in Building 1, and two borings in Building 2 by my geotechnical field crew in 2009. Sampling and laboratory testing were performed as discussed in Case History 1. The subsoil data at boring B-3, close to where trees had been removed, is shown on Fig. 8.

The moisture contents at boring B-3 (2009) are shown as dots "■" on the graph connected with a straight line. The soil suction tests are shown next to the moisture contents . The moisture profile at C-3 (1997) is shown as "●" connected together by lines. No suction tests had been performed in 1997 as suction tests were not standard practice in Houston at that time period, nor are they today. However, the pocket penetrometer tests values of 4.5+tsf from the depths of 4 to 25 feet indicate that the soil was dry and hard.

The moisture profiles indicate that the moisture content increased about 5 percent in a 12 year period. However, the values of soil suction were about 4.0 pF from 6 feet below the slab to the top of the sandy clay layer at 17 feet. This boring had been drilled about 25 feet from the exterior perimeter, and all the heave had not occurred in 2009.

Figure 8
Subsoil Moisture/Depth Profile
Case History 4



About 6 inches of heave was found in the southeast corner of Building 2 close to where three oak trees had been removed. This boring was located about 6 feet from the exterior wall, and the moisture contents were about 10 percent greater than at Building 1. Also, the value of soil suction was about 3.8 pF indicating moist clay. I believe that most of the heave, not all, had occurred at this location due to poor drainage around the building.

The lessons learned are to recognize the hazards of removal of trees from under buildings because a large amount of heave will probably occur. The fact that full rehydration of the clays at building 1 had not occurred in a 10 year period should be implemented into plans for future building construction at sites where trees will be removed. Another lesson for practicing engineers is that 4.5 tsf pocket penetrometer values imply dry soil, whether or not trees are present.

Depth of Active Zone

O'Neill and Poormoayed (1980) reported that the depth of active zone is in the range of 5 to 10 feet in the greater Houston area. They also discussed "Shallow root systems continuously remove moisture from near surface soil and desiccate expansive clays. When vegetation is removed and building floor slabs are placed on grade, the clays begin to regain moisture and structural distress even in soils that are relatively inert". However, there was no mention of the depth effect due to trees in their paper. Wray (1995) discusses "...another instance of when sites where vegetation was removed shortly before construction. If trees or large shrubs are removed at the end of the dry season or at the end of a drought during this construction operation, the ground beneath and around the trees and shrubs will most likely be very dry and desiccated. If the building is subsequently built over the desiccated site, the soil will subsequently swell up once the ground surface is covered".

The case histories clearly show that trees can lower the moisture content of clay subsoils to depths of 25 ± 5 feet, and possibly greater. There will certainly be exceptions at sites where shallow deposits of water bearing sand exist to recharge the clay subsoils. The vast number of commercial buildings in Houston performing adequately support O'Neill's estimation of the depth of the active zone that exists at undeveloped sites without trees. Therefore, geotechnical engineers should be fully aware that assumptions regarding the depth of "seasonal moisture change" are not valid for sites where the moisture content has been depleted to deep depths due to moisture demand from trees. The soil borings for new construction must be deep enough that they extend below the active zone, and adequate laboratory testing must be performed to determine the depth of the active zone. The geotechnical consultant should perform swell tests to estimate the amount of heave (PVR) that can occur after removal of the trees.

Lateral Zone of Influence

A common question asked of me is "what distance do I plant trees away from the buildings?" There are commonly used "rules of thumb" such as a lateral distance equal to the height of the tree from the perimeter, or the crown (canopy) of a mature tree at the perimeter of the building. Another is to increase the ratio to 1½ times the height of the tree when a row of trees is present. However, it is obvious that one needs to plant oak trees much further from the building perimeter than pine trees, thus the rules of thumb do not always apply. Biddle (2001) states it clearly, "It can be very misleading to think that root spread will equate to canopy spread or to tree height or any other parameter of crown size. In some circumstances spread will be less, while in others active roots may be found far from their expected location". The tree will send its roots looking for a constant source of water….this is a matter that all mankind understands….SURVIVAL!

The case histories clearly show that trees can cause slab movements 50 feet or more from the drip line of a tree. What is not known is what part of this distance is due to soil suction occurring beyond the tips of the feeder roots. A plausible hypothesis can be deducted from the 4 case histories. Assuming that the common depth of the root zone is 10 feet and the depth of the active zone is 25 feet, then soil suction is depleting moisture from the remaining 15 feet. However, the horizontal distance could be greater (unknown fact). Soil suction has implications when designing a root barrier at the perimeter of a building because suction to depth of 25 feet at the edge of a ±8 foot deep root barrier will cause lateral movement of water from below the building. Thus, the root barrier will only minimize settlement of a building, not prevent it.

The landscape architect is a professional that understands the behavior of trees because they are educated and practice this discipline. He should decide what trees to plant, where to locate them, and what precautions to take if pre-existing trees are left close to buildings. Also, he must determine what size of landscape area is required for growth of the trees without its roots penetrating under the building looking for water. The geotechnical engineer is trained to understand the behavior of soil, such as shrink/swell of clays resulting from moisture changes. He is responsible for making recommendations for design of foundations for specific site conditions.

Conclusions

Foundations bearing in expansive clays in the urban environment often experience excessive settlement when trees are located close to buildings. This occurs because groundwater lost due to transpiration of trees in the dry summer months is typically not being replenished by infiltration during the wet winter months.

The case histories find that 4 to ±6½ inches of settlement had occurred under floor slabs due to moisture demand of trees. Also, 5¾ inches of settlement of an underreamed pier bearing at a depth of 10 feet had occurred. These are exceptions, not common occurrences.

The case histories clearly show that trees can lower the moisture content of clay subsoils to depths of 25 ± 5 feet, and possibly greater at other sites. Thus, practicing geotechnical engineers should be fully aware that assumptions regarding the depth of “seasonal moisture change” are not valid at sites where the moisture content has been depleted to deep depths resulting from moisture demand from trees.

The case histories clearly show that trees can cause slab movements 50 feet or more from the drip line of a tree. Thus, the rules of thumb for planting a tree one height of the diameter from the building for a single tree, or the canopy at the perimeter are not normally valid in the urban environment.

Careful landscaping design must be made by the landscape architect to protect buildings from settlement, as well as providing a sufficient landscape area for growth of the tree.

The redevelopment of older properties occurring in Houston today presents challenges when removal of trees is necessary. The trees often have desiccated the clays to deep depths, and significant heaving occurs after their removal. Developers also have to consider the impact of existing trees located within the street right of ways because municipalities often restrict their removal.

The geotechnical engineer must carefully evaluate the amount of heave that can occur after removal of trees, and make recommendations for a safe and economical foundation.

References

Biddle, G. (2001). *"Tree Root Damage to Buildings."* Expansive Clay Soils and Vegetative Influence on Shallow Foundations, ASCE Geotechnical Special Publication No. 115, pp. 1-23.

Castleberry, J.P. (1974), *"An Engineering Geology Analysis of Home Foundation on Expansive Clays"*, MS Thesis Texas A & M University.

Eastwood, D. and Peverley, R. (1997), *"Development of Design and Remedial Measures for Lightly-Loaded Structures Founded on Expansive Clays with Trees in Mind"*, Proceeding of ASCE Texas Section Meeting.

Farrow, M. and Roland, M., *"Factors Causing Ground Shrinkage From Tree Roots Well Beyond Drip Lines"*, Proceeding of ASCE Texas Section Meeting.

Felt, E.J. (1953), *"Influence of Vegetation on Soil Moisture Contents and Resulting Volume Change"*, Procedure 3rd International Conference of Soil Mechanics, Zurich 1, 24-27

Fisher, W. L. (1982), *"Geologic Atlas of Texas, Houston Sheet"*, Bureau of Economic Geology, the University of Texas as Austin.

Holtz, W.G. (1984), *"The Influence of Vegetation on the Swelling and Shrinking of Clays in the United States of America"*, Proceedings of Specialty Conference The Influence of Vegetation on Clays, pp. 69-72.

Nelson, J., Overton, D., and Durkee, D. (2001). *"Depth of Wetting and the Active Zone"*, Expansive Clay Soils and Vegetative Influence on Shallow Foundations, ASCE Geotechnical Special Publication No. 115, pp. 95-109.

O'Neill, M. W. and Poormoayed, N. (1980) "Methodology for Foundations on Expansive Soils", J. Geotechnical Engineering Division, *ASCE 106, G T 12*, December, pp. 1345-1367.

Richards, R. (2000), *"Tree Root Impact Distances for Slab on Ground Foundations"*, Proceeding of ASCE Texas Section Meeting.

Tand, K. E., (2001). *"Settlement of Foundations on Expansive Clays"*. Technical Presentation at Foundation Performance Association meeting in Houston, Texas, pp. 1-21.

Tand K. and Vipulanandan, C. (2011) *"Case Study on Settlement of a Foundation on Expansive Clay Due to Moisture Demand of Tree"* Proceedings, Geo-Institute, ASCE, CD, GSP 211, March 2011.

Tand K., Reed, R. and Vipulanandan, C. (2011) *"Effect of Geology on the Swelling of Expansive Clays in the Active Zone"* Proceedings, Geo-Institute, ASCE, CD, GSP 211, March 2011.

Tien, H. and Eastwood, D. (2004), *"Case Studies of Residential Foundation Movements in Southern Houston Area"*, Foundation Performance Meeting.

Vipulanandan, Ph.D., Kim, M. S., Harendra, S. (2007), *"Microstructural and Geotechnical Properties of Houston-Galveston Area Soft Clays"*, Proceedings (CD), Advances in Measurements and Modeling of Soil Behavior, GSP 173.

Wray, W. (1995), *"So Your Home is Built on Expansive Soils"*, ASCE Specialty Publication