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

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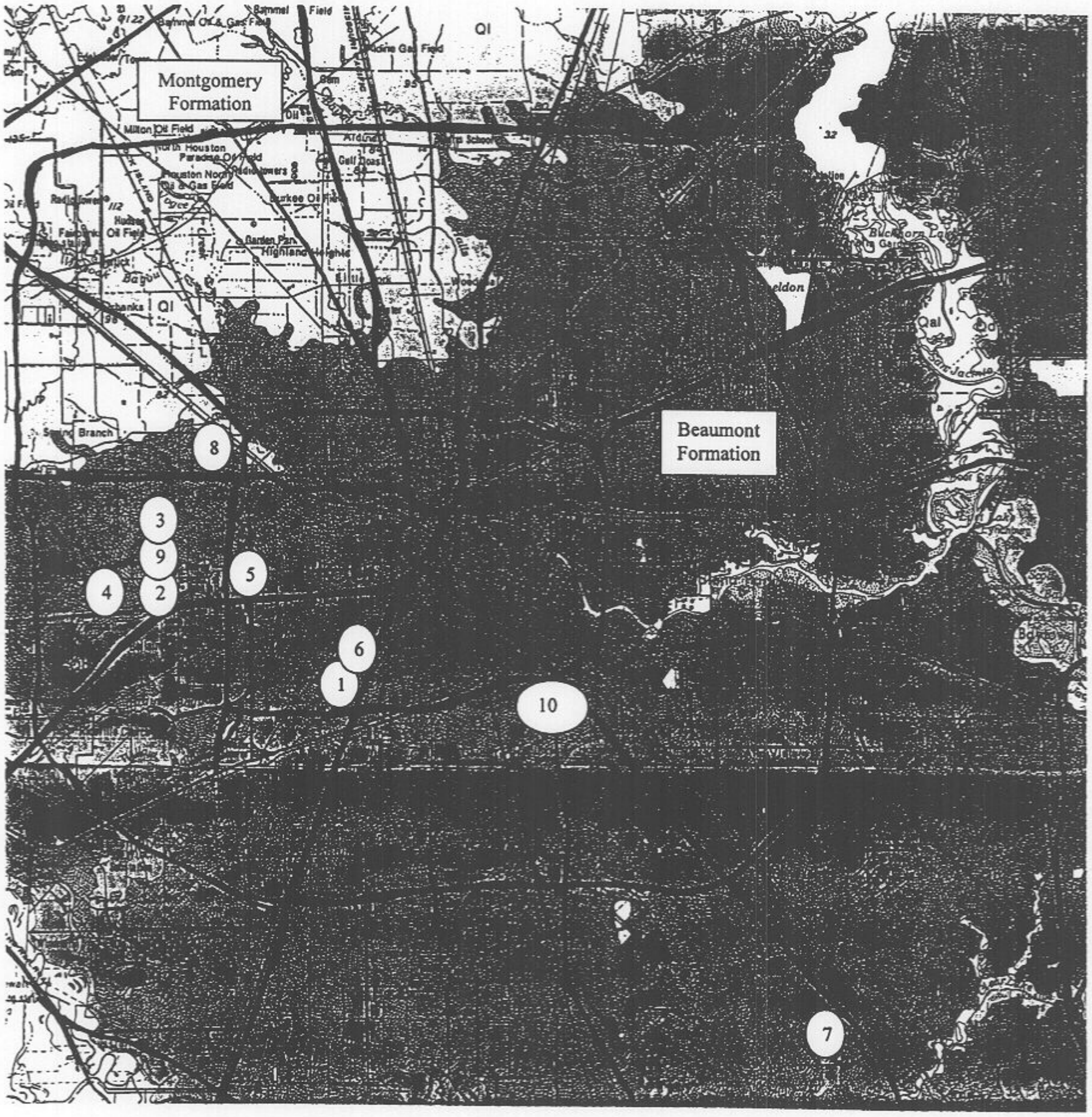
INTRODUCTION

The greater part of Houston is situated on a geologic formation known as the Beaumont Clay (see Figure 1). Expansive clay is the dominate soil type within this formation, and foundation problems due to shrink/swell of the clays are a relatively common occurrence.

The shrink/swell potential of the clay is high in most locations, but can range from moderate to very high. The fact that there are more than 100 foundation repair contractors listed in the yellow pages is a good indication of the instability of the expansive clay subsoils. Peverly estimated that the cost of home repairs due to expansive clays in the Houston area was in the order of $43 million in 1987. Adjusting for inflation, the estimate would be in the order of $80 to 90 million dollars today. This figure did not include repairs to commercial buildings or loss of value of real estate, and the total cost is much higher.

Historically, geotechnical engineers in the U.S. have primarily directed their concerns to the swelling nature of the clays, not to shrinkage. One reason is that most of the technical literature in the professional journals is directed at predicting the potential vertical rise (PVR) of expansive clay subsoils. The purpose of this paper is to address foundation problems that occur due to shrinkage of expansive clays (settlement).

Figure 1
Regional Geologic Formations
Houston, Texas



My first encounter with settlement due to shrinkage of expansive clays was in the late 70's when I observed about 2 to 3 inches of settlement of a floor slab near a tree at an office/warehouse complex in southwest Houston. In 1980, I observed cracks in an exterior brick wall at a school in Spring Branch that was supported on underreamed footings bearing at a depth of 8 feet. The footings were next to a cluster of large oak trees, and had settled as much as 2 inches due to moisture demand from trees. In 1982, I investigated settlement of foundations at two other schools in Spring Branch where moisture demand from trees also caused settlement of underreamed footings.

It was hard to convince the owners and structural engineers that settlement of relatively deep underreamed footings had occurred due to moisture demand from trees. The convincing evidence was that foundation performance was good in areas away from trees, and that distress was only occurring in areas close to trees. Since the early 80's, I have conducted numerous distress evaluations in the Houston area, and have observed that settlement of commercial buildings on expansive clays due to shrinkage of the clays has occurred almost as often as problems due to swelling of the clays.

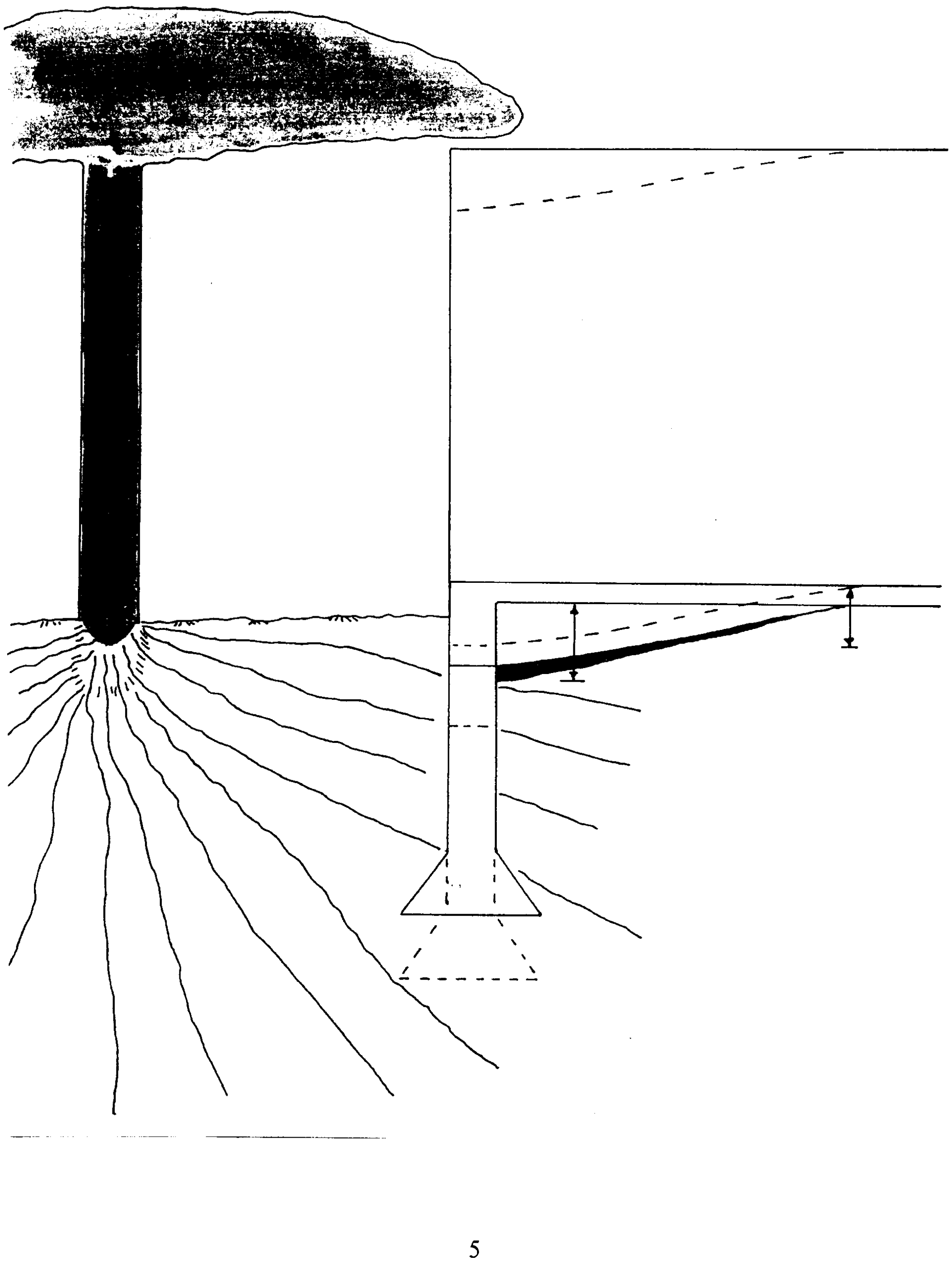
Several excellent presentations at the 2001 National ASCE convention in Houston document problems related to settlement of foundations and paving on expansive clays. These papers are contained in the proceeding "*Expansive Clay Soils and Vegetative Influence on Shallow Foundations*" which can be purchased through ASCE. The authors discussed sites in the USA, including north Texas, and in other countries. However, there were no case histories reported for the Houston area.

This paper discusses my personal observations at 10 sites in Houston where significant settlement of commercial buildings and one apartment on expansive clays occurred due to moisture demand from trees. The foundation type for the case studies discussed in this paper is underreamed footing with a ground supported floor slab. Case histories of residences or commercial buildings supported on slab-on-ground foundations with load bearing grade beams were not included because there is often soil movements that occur due to both shrink and swell of the clay subsoils that cause uncertainty about contributory movements. In each of the case studies, there were portions of the buildings where the elevation of the floor slab was relatively level, or where visual distress was not evident, thus providing a baseline for evaluating the magnitude of differential settlement that had occurred.

Historically, the specified depth for underreamed footings supporting light commercial buildings in the Houston area was about 8 feet, but was sometimes as shallow as 6 feet and as deep as 12 feet. The relatively deep footings provide somewhat of a settlement plate to evaluate settlement due to shrinkage of the expansive clays. The measured movement of the floor slab next to columns/walls in areas where distress has occurred, and in areas where distress has not occurred provides an estimate of the settlement (shrinkage) that occurred below the footings. The measured deflection of the slab, plus voids that are found under the slab, indicate the total amount of surface settlement that has occurred. The difference between these two measured values of settlement would indicate the magnitude of settlement that occurred between the ground surface and bottom of the underreamed footing (see Figure 2). Of course, there will always be some uncertainty about measured settlement using these methods because of deviations in elevation that occur during construction, and the fact that some shrink/swell of the structure may have occurred in areas believed to be stable (assumed benchmark), and some load induced settlement of the underreamed footings could have occurred. Thus, the estimates of settlement reported in this paper should be considered as approximate. It is my opinion that the accuracy is ± ½ inch for most cases, but may be ± 1 inch for some cases.

This report does not discuss methods to predict settlement due to moisture demand from expansive clays, or methods to stabilize or repair the foundations.

Figure 2
Settlement of a Foundation
Due to Moisture Demand from Trees



AREA GEOLOGY

The site is located on the Beaumont formation. The subsoils 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 clay portion is composed of montmorillonite, kaolinite, illite, and fine ground quartz. The presence of montmorillonite results in a shrink/swell potential. The clays were overconsolidated to significant depths due to desiccation that resulted when the water table was lowered during the Second Wisconsin Ice Age. Desiccation also produced a network of fissures and slickensides in the clay that increased the mass permeability of the clays.

The cohesionless soils, sands and non-plastic silts, are composed of quartz, the feldspars and occasionally hornblende. They vary in compactness from medium dense to dense, and are sometimes lightly cemented.

ENVIRONMENTAL CONDITIONS

The Thornthwaite Moisture Index (TMI) is about 18 which would catagorize 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.

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 is sloped to provide maximum drainage away from the buildings. Along with urbanization came landscape improvements to include trees and scrubs 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 water for transpiration has been greatly reduced.

TREE AND ROOT SYSTEM

The tree loses water during photosynthesis and resupply of water from the ground is necessary for survival. The lose of water from the leaves causes a suction which extends thru the branches down the trunk, and then thru the system of distribution roots to the fine feeder roots. The feeder roots actually extract the water and nutrients from the soil thru suction.

The negative head actually pulls up water to the leaves. There must be head loss thru the root/tree pipeline. There may exist a limit to the negative head that can be sucked just like there is a limit on the column of water a well point system can suck.

Thus, there may be a physical limit on the distance that water can be effectively moved from the ends of the feeder roots to the top leaves of the tree. I have not found a discussion in the geotechnical engineering literature on this matter.

Some types of vegetation, such as desert plants, are very efficient in conserving water. Their leaves are coated with a waxy substance to minimize water loss. These types of plants generally have a slow growth rate. Fast growing vegetation generally has a high demand for water. The rate of water demand is greatest in the warm growing season, and is practically non-existent in the dormant months except for evergreen varieties. Evergreens do not go entirely dormant, but they have a lower moisture demand in the cooler winter months.

Most of the root mass is within the upper 5 to 10 feet. However, the root must find water for survival and thus will send its roots to places where water exists, i.e. plumbing leaks or deep water bearing layers. The roots can easily penetrate soft porous soil but cannot penetrate dense soil. In very stiff to hard clay, the roots often penetrate into fissures and slickensides. If the fissures are filled with sand, they are conduits for collecting ground water and will thus provide a source of water for the tree. These conditions exist in the Montgomery formation on the north side of Houston.

I have observed that pavement distress often occurs near or slightly beyond the drip line of trees. My observations initially led me to an incorrect assumption that the drip line was about the maximum extent of root growth. In my studies, I began to notice that there was distress under buildings well beyond the drip line.

I now believe that the environmental conditions around the tree will effect the lateral and vertical extent of root growth. The tree will grow a root mass that is sufficient for its present water needs. As the tree grows, it must extend its roots to tap new sources of water.

Paving and buildings placed next to and/or around a tree will greatly effect recharge of moisture from rain. A 1-inch caliper tree planted in a 10 by 10 landscape island may initially get enough water for survival. But when the diameter is 24 inches and the crown is 50 feet in diameter, larger quantities of water are needed for survival. Once the feeder roots under paving or building slabs have used all the water supply available at the tips of the feeder roots, they must keep extending the roots out further to find new sources of water. Thus, the root system grows out past the drip line.

Trees in forest areas and in rows or clusters have to compete for water to survive. They must extend out their root system to greater depths and lateral distances for survival. One published rule of thumb is that the lateral extent of moisture demand for a single tree is equal to the height of the tree. However, the lateral extent is reported to be 50 percent greater when the trees are closely spaced in a row.

I believe that there are no absolute rules governing the vertical and lateral extent of root growth. However, there are physical limiting factors such as hardness and porosity of the soil, and perhaps head loss that affect root growth. The tree will hunt for water using whatever means it has for survival, and survival is the only absolute rule that the tree plays by.

SUMMARY OF CASE STUDIES

I was the geotechnical engineer that evaluated the cause of distress at all 10 sites. The buildings ranged from about 20 to 40 years in age, and no litigation was involved. However, the project name, owner, or exact location will not be disclosed for reasons of client confidentially.

The pertinent facts for each of the sites are summarized on Table 1. However, two well documented case studies are discussed in detail to explain how the conclusions were obtained.

SITE 1

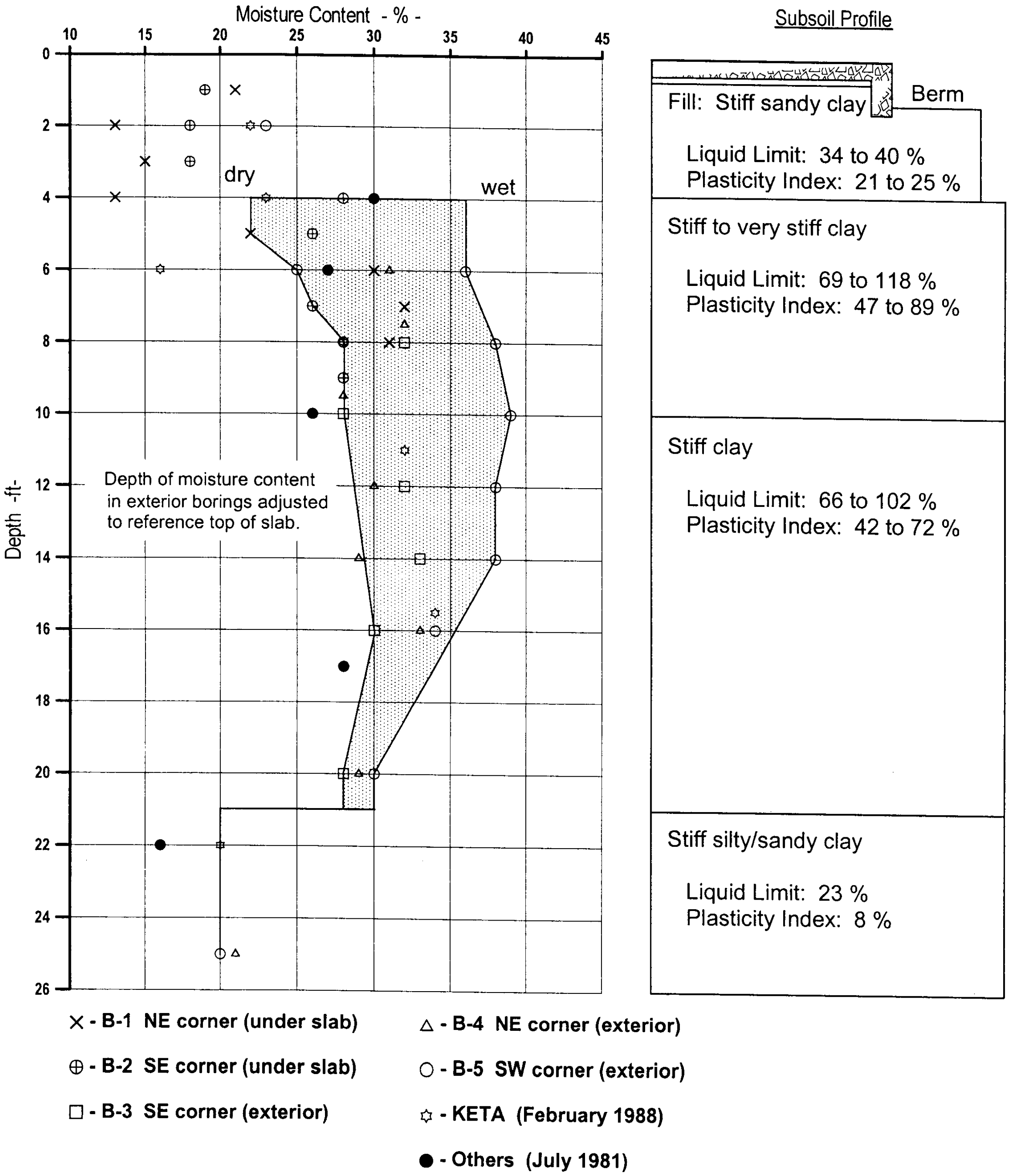
The office building at Site 1 is a 2-story steel frame structure constructed in the late 60's or early 70's (~ 30 years old). The exterior finish is Marblecrete. The floor slab is elevated about 1 to 1½ feet above a berm that was placed around the building. The berm is about 1 to 2 feet higher than exterior perimeter grade. Surface drainage around the building is good.

An aerial photo dated 10/29/65 shows rectangular patches suggesting that prior land use was farming. At this date, there were already commercial buildings in the immediate vicinity. There was an east/west row of large trees south of the southeast corner of the building in 1965, but none along the east or north sides of the building. An aerial photo dated 5/11/81 shows the same line of trees plus what appears to be a new tree near the middle of the south wall, 3 new trees near the northeast corner, and 2 new trees just east of the southeast corner.

I made my initial visit to the site in February 1988 to evaluate the cause of settlement in an area along the center of the south wall. The ground surface next to the grade beam had settled at least 6 inches in this area, and there was a 2 to 4 inch void under the grade beam. There were not any cracks in the grade beams, nor were there any visual signs of movement in the exterior walls. There were minor cracks in the interior walls on the first floor next to the area of settlement. An elevation survey to evaluate the magnitude of settlement was not performed.

The structural plans indicated that the foundation type was underreamed footings bearing 17 feet below top of slab (~ 14 feet below natural grade) with a ground supported slab. The drawings indicated that the size ranged from 48 to 60 inches in diameter.

Figure 3
Subsoil Moisture/Profile
Site 1



A 20-foot deep soil boring was drilled in February '88, and Atterberg limit tests were performed to evaluate the shrink/swell potential of the clay subsoils. The subsoil conditions are shown on Figure 3, along with data collected in November 2000. The clays were moist at the surface as would be expected for a typical wet period, but they were dry between the depths of 4 to 8 feet. There was a large tree south of the building, and the drip line extended over the roof at the point of maximum settlement.

I came to the conclusion that moisture demand from the tree on the clay subsoils was causing the settlement, and recommended removal of the tree. The building was not underpinned, nor was the slab lifted by mud jacking. The tree was removed (date unknown), and KETA was not called back to the site until November 2000 to evaluate the distress in another area of the building. Thus, removal of the tree was effective in preventing further distress.

In November 2000, I made another site visit to witness distress at the northeast and southeast building corners. The floor slab at these two corners sloped down towards the east wall, there were cracks in partition walls, and one window had cracked due to differential settlement.

Two 10-foot deep soil borings were drilled thru the floor slab at these two corners, and three soil borings were drilled to depths of 20 to 30 feet around the perimeter of the building. Samples were obtained by driving 3-inch O.D. Shelby tubes at the two borings inside the building and by hydraulically pushing the Shelby tubes in the three borings around the building. Free swell and Atterberg limit tests were performed to evaluate the shrink/swell potential. The subsoil data is plotted on Figure 3 along with data obtained in 1988.

There are two large trees close to the northeast corner (Photo 1) that range in diameter from 18 inches (oak) to 42 inches (ash). The branches of the ash tree had to be pruned so that they did not rub against the east wall. There are two oak trees about 30 feet east of the east wall near the southeast corner (Photo 2) that range from 20 to

32 inches in diameter. The drip line of the trees is within 6 feet of the east wall. There are large roots at the ground surface around the trees and indications of root thrust under the asphalt parking lot on the east side of the building.

The elevation survey indicates that the footing at the southeast corner settled about 2⅞ inches, and that settlement decreased in magnitude north along the east wall to about ¼ inch at the south side of the entrance lobby. There was a 5½ inch void under the floor slab suggesting that 8½ inches of total settlement had occurred in this area.

About 1⅛ inches of settlement of the footing at the northeast corner has occurred. The footing south of this location appears to have settled about 1⅜ inches, and the settlement decreases south along the east wall to zero at the north edge of the entrance lobby. A 3¾ inch void was found under the slab near the southeast corner suggesting that about 5 inches of total settlement had occurred in this area.

It appears that settlement along the north wall is confined to the east 20 feet. However, settlement along the south wall ranges from 2⅞ inches at the southeast corner to about ½ inch 50 feet west of the southwest corner. As previously discussed, a tree had been removed in this area sometime ago. I suspect that complete rebound of the ground surface after removal of the tree has not occurred.

Several 12-inch diameter probe holes were drilled next to the northeast and southeast corners to evaluate the depth/size of the underreamed footings. The bearing depth of the underreamed footing at the northeast corner is about 15 feet below exterior perimeter grade (~16.5 feet below top of slab), and the bearing depth of the underreamed footing at the southeast corner is about 13 feet below exterior perimeter grade (~14.5 feet below top of slab). The exact size of a deep underreamed footing cannot be determined without underpinning the building and excavating around the footing. The field crew "blind" probed to the edge of the footings and estimated their size to be 44 ± 2 inches in diameter. The structural engineer computed that the dead plus sustained live load on the two footings to be in the order of 45 kips. This results in a net bearing pressure of about 4,200 pounds per square foot on the base of the footings. The net allowable bearing pressure (SF~3) for these footings was computed to be about 4,500 psf for dead plus sustained live load, and thus it is my opinion that load induced consolidation was not the primary cause of settlement.

Shown on Figure 3 is a plot of moisture content with depth. Analysis of the data indicates that the difference in moisture content is **very** high near the surface, and that it is about 20 feet below exterior perimeter grade.

I found feeder and fine roots in the soil samples from the surface to 10 feet (depth of borings) inside the building. Also, I found both fine and feeder roots to a depth of 15 feet in the boring near the southeast corner, and found one 1/32 inch diameter live root in the soil sample at a depth of 18 to 20 feet. Thus, it appears that the depth of the feeder roots is below 20 feet. The roots found in the borings under the floor slab are beyond the drip line which is commonly assumed to be the major zone of root growth. Along the south wall near the southeast corner, we found one ½-inch diameter root at the surface which was about 17 feet beyond the drip line of the 32-inch oak tree near the southeast corner.

SITE 2

The building is a 1-story school that was constructed in the late 50's (~ 40 years old). The exterior perimeter walls are load bearing CMU block and brick veneer, with concrete "T" beams for the roof. The interior walls are also CMU block. The foundation was underreamed footings bearing at 6 feet below natural grade with a ground supported slab. The site was elevated with about 1½ foot of fill, and thus the footings bear at about 7½ feet below exterior perimeter grade.

By 1990, the west wing had settled extensively and the exterior and interior CMU walls were extensively repaired. The building continued to settle and in October, 2000 the client authorized geotechnical studies to evaluate the cause of settlement at the west wing. Large cracks in the interior CMU walls (see Photo 4) occurred due to settlement. Settlement also occurred in other parts of the building, but geotechnical studies were not performed in these areas.

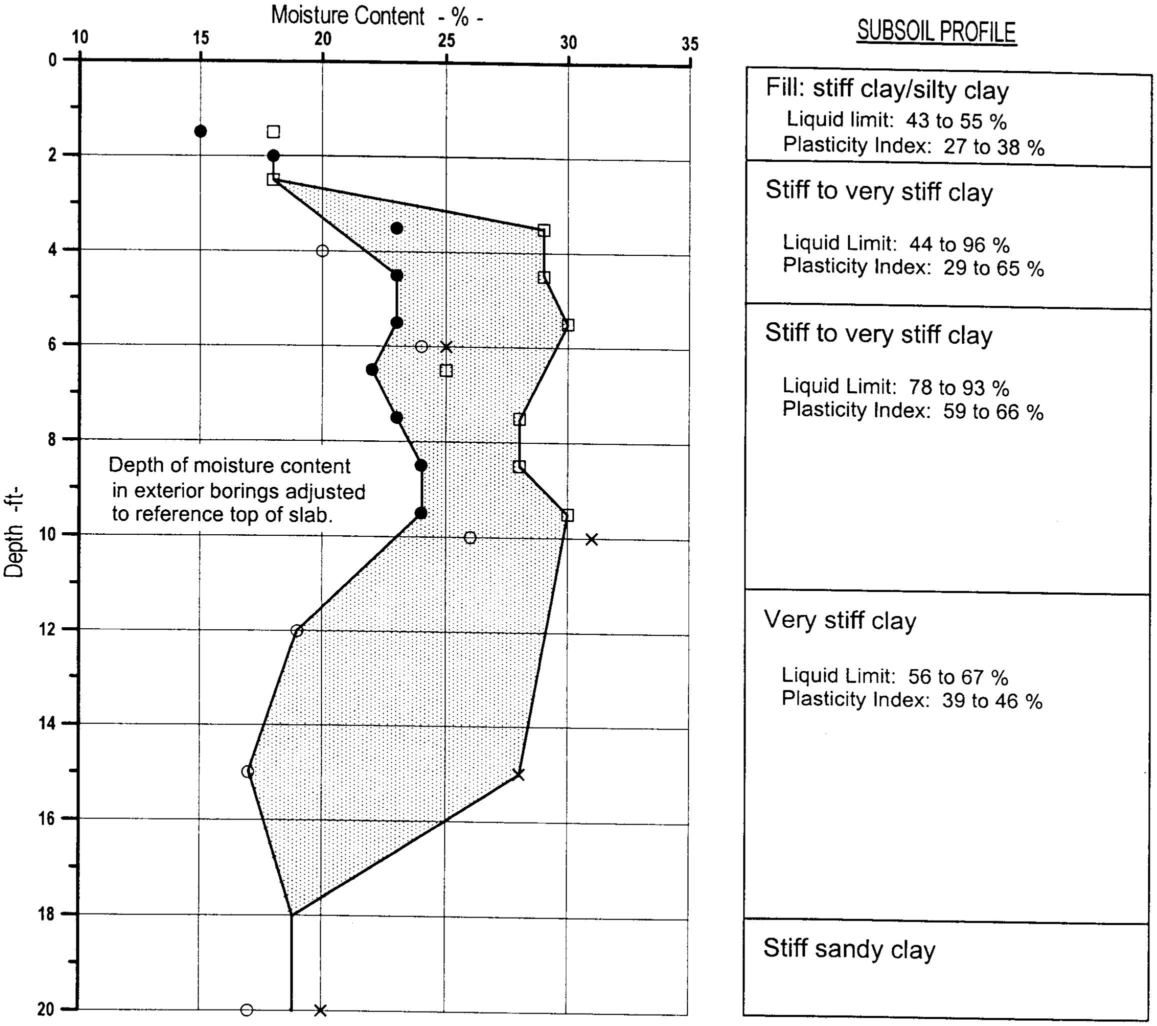
An elevation survey indicated that the interior hallway in the southeast wing was relatively level. Also, no visual distress was observed in the CMU block walls along the hallway. The survey indicates that the footings in the northwest corner of the west wing settled about 5 inches. A 3 inch void was found under the floor slab indicating that total settlement of the ground surface was about 8 inches.

Two oak trees varying from 28 to 30 inches in diameter (see Photo 3) had been planted close to the area where the maximum amount of settlement was observed. The drip line of the trees was at the edge of the roofline. There were 4 inch diameter roots at the ground surface that were heading straight for the building.

Soil boring B-2 was drilled inside the school at the northwest corner 8 feet from the west wall in an area where maximum settlement had occurred. Soil boring B-1 was drilled in a hallway about 50 feet east of boring B-2 where no noticeable movement had occurred. Also, three additional soil borings were drilled to depths of 20 feet around the perimeter of the building. Samples were obtained by driving 3-inch O.D. Shelby tubes at the two borings inside the building and by hydraulically pushing the Shelby tubes in the three borings around the building. Free swell and Atterberg limit tests were performed to evaluate the shrink/swell potential. The subsoil data is plotted on Figure 4.

The upper 1½ feet below the slab was sand and clay fill. The liquid limit of the clay fill ranged from about 43 to 55, and the plasticity index ranged from 27 to 38. The underlying natural soil is stiff to very stiff clay to a depth of about 20 feet. The liquid limit ranged from 44 to 96 percent with an average of 79. The plasticity index ranged from 29 to 74 percent with an average of 58. The water level is below the depth of 20 feet.

Figure 4
Subsoil Moisture/Profile
Site 2



□ - B-1 (Interior of floor slab - wet)

● - B-2 (Interior of floor slab - dry)

○ - B-3 (Exterior near tree - dry)

× - B-4 (Exterior /no tree - moist)

Feeder roots were observed in the soil samples to a depth of 10 feet at boring B-2 where the maximum settlement had occurred, but no roots were observed in boring B-1 where little settlement, if any, had occurred.

Shown on Figure 4 is a plot of moisture content with depth. The depth of moisture change appears to be greater than 20 feet. However, this assumption is based on limited test data from two borings drilled at the perimeter of the building. Boring B-3 was drilled at the drip line of an oak tree, and boring B-4 was drilled in a lawn area about 70 feet east of boring B-2 where no trees were present. The pocket penetrometer tests at 18 to 20 feet were very similar at these two borings suggesting that the moisture content is reasonablely similar. Thus, the difference in moisture content could be due to material changes and the depth of moisture change could be between 15 and 18 feet. For purpose of this report, a depth of 18 feet is assumed.

SUMMARY OF FINDINGS

- The tree must develop a root system sufficient to supply water for its survival. The feeder roots extract moisture from the subsoils thru suction. As the clay loses water, it shrinks. Shrinkage occurs in both the vertical and horizontal directions. Shrinkage results in settlement of foundations, paving, and etc., bearing above the maximum depth of shrinkage.
- The largest measured settlement of a shallow (~ 7½ feet) underreamed footing due to shrinkage was about 5 inches. The largest settlement of a deep (~ 11 feet) underreamed footing was about 3 inches.
- The largest measured total settlement of the ground surface below a floor slab was about 8 inches.
- The deepest live root that I have found was at 19 feet below grade in a boring at Site 1. The boring was drilled at the drip line of a large oak tree. The root

was about 1/32 inch in diameter, and the feeder roots must be below this depth. Thus, the maximum depth of root penetration is somewhat deeper than 20 feet. The root had penetrated into a water bearing layer of sandy clay/clayey sand.

- The bulk of the root growth that I have observed has been in the upper 10 feet. However, the presence of paving and buildings will prevent recharge of moisture, and thus the tree must send its roots out further than normal to find water once the roots are under the paving or slab. Trees in forested areas and in clusters will compete for water for survival. Thus, they will also send their roots out further and deeper than normal to find water.
- My observations suggest that the most active area for moisture demand by hardwood trees in the Houston area is within a zone bound by the drip line and 10 feet beyond the drip line. However, I observed settlement as far as 40 feet beyond the drip line at Site 1 and Site 2.
- The feeder roots suck moisture from the subsoils. At Site 1, it is obvious that the depth of moisture change is deeper than 20 feet because the feeder roots are below this depth. At Site 2, the depth of moisture loss appears to be in the order of 18 feet although the subsoil data was limited when rendering this opinion.
- The clay subsoils below the depth of seasonal moisture change will reach a state of equilibrium prior to planting trees. The growth of trees will upset this balance resulting in a loss of moisture, and thus the clays will shrink. If the trees are later removed, and there is a source of moisture available, the clay subsoils will rehydrate causing heave. Heave could cause the ground surface to return to its original elevation, but there could be a hysteresis effect where all the movement is not recoverable.

TABLE 1
Summary of Case Histories

Site	No. Stories (age)	Depth Footings -feet-	Maximum Settlement -inches- Footings	Surface	Type Trees (Diameter) -inches-	Location of Drip Line (canopy dia.)	Thickness of Fill -feet- (I_P)	Thickness of Clay -feet- (I_P)	Depth of Moisture Change -feet- (depth roots)
1	2 (30)	(11)	3	8½	2 oaks (20 to 32)	at wall (45 to 50)	4 (21 to 25)	17 (42 to 89)	20+ (20+)
2	1 (40)	7	5	8	2 oaks (28 to 30)	over roof (35 to 55)	2 (27 to 38)	16 (29 to 66)	18 (10)
3	1 (40)	9	4½	8½	row oaks (15 to 21)	over roof (42 to 83)	1 (23 to 42)	20+ (42 to 83)	14 (12)
4	1 (20)	12	<1	5½	2 oaks (12 to 24)	at wall (30 to 35)	5 (27 to 43)	15+ (35 to 64)	15 (14)
5	1 (—)	8	<1	1½	row trees (—)	at wall (—)	2 (NP to 22)	6+ (48 to 60)	— (3)
6	3 (20)	(9.5)	4	4½+	ash/oak (15 to 24)	at wall (—)	2 (24 to 29)	17 (42 to 78)	20+ (—)
7	1 (20)	8	2½	—	2 oaks (18 to 30)	over roof (30 to 35)	— (—)	cl/sa/cl (17 to 39)	19 (14)
8	1 (10)	(8.5)	2⅔	3¾	mix woods (2 to 8)	wall (—)	4 (27 to 32)	16 (19 to 34)	16 (—)
9	2 (—)	—	<1	6½	oak (30)	at wall (~60)	2 (40 to 42)	8+ (38 to 55)	— (4)
10	1 (—)	8	~1	5½	oak (~24)	~5' away (—)	½ (NP)	6+ (41 to 70)	>8 (—)

Notes:
1. The footing depths shown in the columns are from the structural drawings except when in parentheses (measured).
2. The depth of root penetration is the deepest root found in the borings. The location of roots is variable. Thus, the depth will probably be deeper at other locations due to the small size of sample.
3. The depth of moisture change is estimated at the drip line where the borings generally have to be drilled due to clearance. It will probably be deeper under the tree.

Site 1
Vicinity of Texas Medical Center

Photo 1
Ash & oak trees near NE corner of building

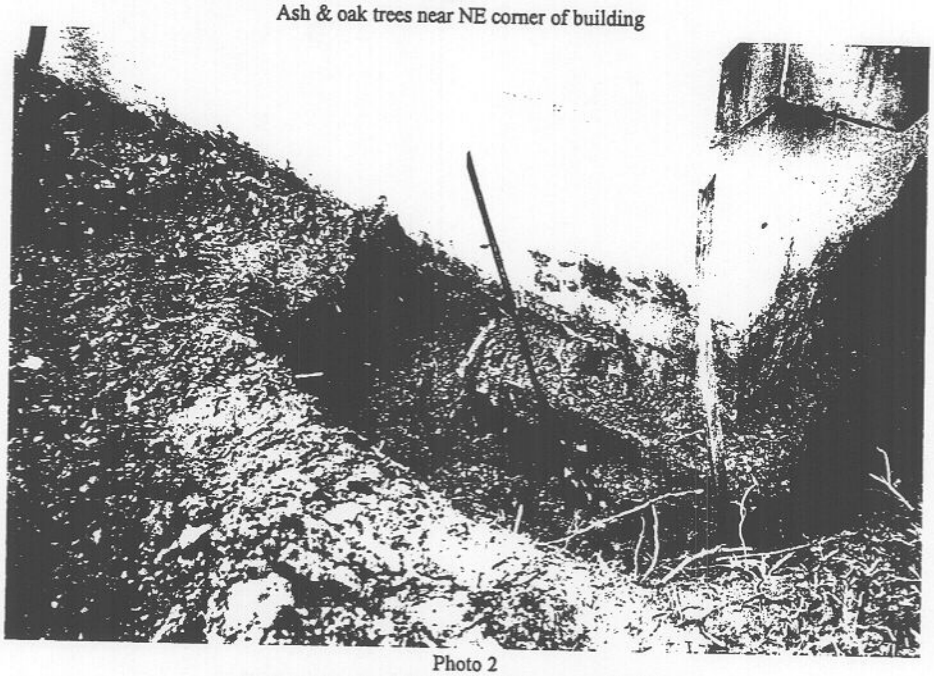


Photo 2
Root penetrating below slab at NE corner of building

Site 2
Vicinity of Galleria

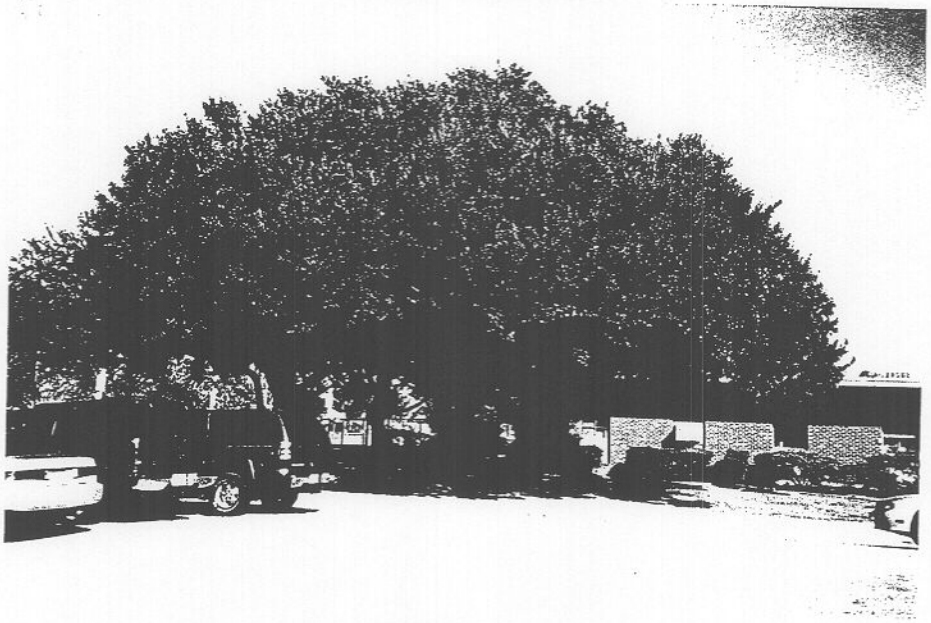


Photo 3
Oak trees near NW corner of building

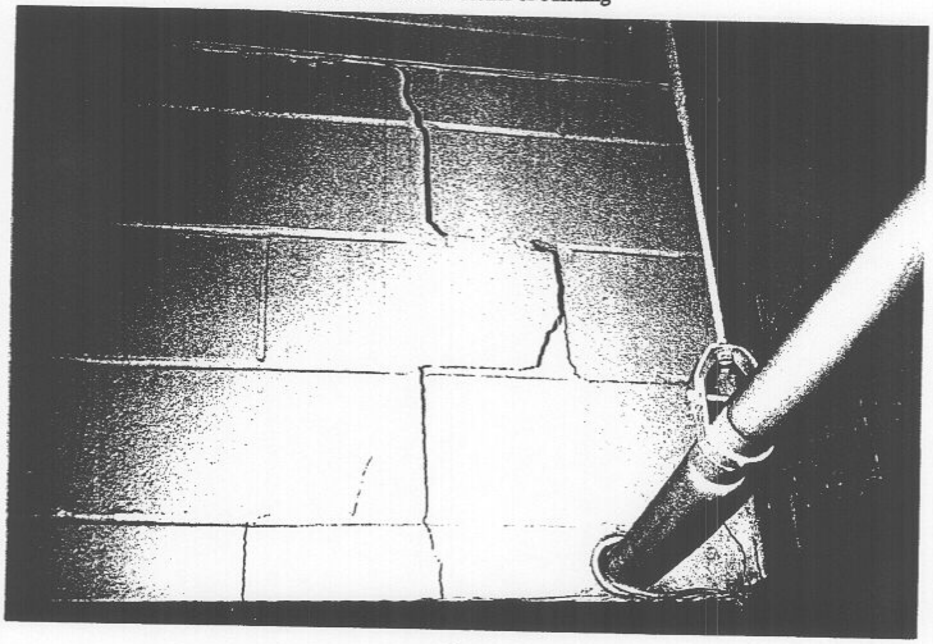


Photo 4
Typical cracks in interior CMU walls