DEVELOPMENT OF DESIGN AND REMEDIAL MEASURES FOR LIGHTLY-LOADED STRUCTURES FOUNDED ON EXPANSIVE SOILS WITH TREES IN MIND

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ABSTRACT

A review of the current literature in the United States shows there may be an absence of practical approaches for the design of lightly-loaded structures founded on expansive clay soils where trees are involved. As a result, many such structures which have experienced distress as a result of the lack of the consideration of the effect of trees in the design of these structures. The authors of this paper are a part of a Houston organization called the Foundation Performance Committee. One of the activities of this Committee is the investigation of the adverse effect that the presence and/or the removal of trees can have on lightly-loaded structures. This paper includes the results of this activity, and also includes the results of a literature survey, a review of the failures of some foundations whose cause has been attributed to the presence of and/or the removal of trees, design recommendations, and repairs where trees have been identified as the primary cause.

INTRODUCTION

A significant number of residential buildings were constructed in the greater Houston are in the 1950 through 1970 time periods. Many of these buildings were founded on expansive soils and on building lots, which were void of vegetation. Trees were then planted after these building were sold and eventually the trees matured and caused foundation failure to occur. Corrective measures generally included the underpinning of the foundation perimeter beam using drilled piers and later pressed piles. When piers were used, this approach had, at best, a limited degree of success. The type of failure mode, whereby trees cause the settlement of the perimeter of residential, and other low-rise buildings, has received a significant amount of publicity in recent times and, as a result, home owners, building remodeling contractors, home builders, etc. have become aware of this problem. From this, an entire industry has grown which provides measures to control this problem.

Some notice of the manner in which trees can produce downward deflections in residential slab-on-ground foundations began to appear in the early 1970's. For example, in 1972, Davis[1] summarized existing papers which indicated that near-by trees could adversely affect foundation performance. Davis and Tucker[2] published a Technical Note which provided data which showed that Post Oak trees located South of Arlington, Texas, incurred vertical movements varying from 1.2 inches to 3.4 inches between the end of the summer months and the end of the winter months. The University of Texas at Arlington conducted an investigation of 69 abandoned residential buildings which were founded on clay soils and reported, among other things, that the extraction of moisture from the soil through the roots of trees, caused moderate to severe deflections in foundations.[3] In 1974, Buckley [4] presented data which showed damage to foundations caused by trees. Kramer and Kozlowski[5] identified the comparatively high transpiration rates of some trees in 1960. In 1987, Peverley and Hanys[6] provided measured deflections in a residential foundation which had been produced by near-by trees.

The manner in which trees can cause downward deflections in residential slab-on-ground foundations has, therefore, been well documented. Simply stated, in order to satisfy their need for soil water, trees can desiccate the soil upon which the outer edge of a foundation rests, resulting in the shrinkage of the soil with the attendant loss of soil support. Foundation distress attributable to such causes have occurred with such regularity in the greater Houston area as to have caused a major alteration to the fundamental foundation design and construction concepts

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with were in effect for years. Not as well understood, however, are the adverse effects that the removal of large trees can have on reconstructed foundations, even where they are resting on drilled piers. Equally misunderstood is the relationship between tree root growth and under-slab sewer leaks.

The purpose of this paper is to explore the adverse effects that trees can have on residential foundation performance based on the experience of others as documented in the literature, based on the personal experience of the authors, and based on an accumulation of information form the Foundation Performance Committee. This paper will be presented in the three following basic parts; foundation edge settlement produced by soil shrinkage, foundation edge heaving caused by soil swelling, and foundation center settlement caused by the interaction between tree roots and under-slab sewer leaks. The mechanics of such conditions along with proposed corrective measures will be discussed. Examples will be presented.

SOIL MECHANICS AS AFFECTED BY TREES

THE PHYSIOLOGY OF TREES

Trees have long been considered to be a benefit to mankind. Trees have been written about as many as 4000 years ago.[7] Trees absorb heat as they transporate, provide shade, and reduce solar radiation. They enhance air purification, aid in the control of erosion, and can, to a limited degree, provide some noise reduction benefits. Perhaps their most appreciated benefit is their ability to enhance the beauty of the surrounding landscape. One can appreciate the beauty of old oaks whose branches provide an umbrella for many of the roads in the old South or whose sculpture enhances the skyline of the Pacific Coast.

Trees do have their downside. Their limbs fall injuring property and people. In the Gulf coast, people have been injured or killed by falling trees. Tree roots clog sewers and break sidewalks. Trees can also increase the ozone content of the air, damage electrical power lines, and interfere with UHF reception. Perhaps the highest cost of trees is in their damage to residential foundations. In 1973, Jones and Holtz [8] estimated the annual cost of expansive soils in the US to be 2.2 billion dollars. In 1982, Peverley & Hanys [9] estimated the cost to repair only those residential foundations in the greater Houston, Texas real estate market for a 6-month period of time to be in excess of 28.5 million dollars. If one were to conservatively estimate that only 50% of these foundation failures were caused by trees, the costs would be obviously enormous.

Trees are the largest plants in the world.[9] Trees can generally be classified as needle-leaf or broad leaf (deciduous). The essential parts of a tree are the crown, the trunk, and the roots. The crown contains the leaves, which essentially absorbs sunlight and converts it into food. The roots are the fastest growing part of a tree. They collect water and transport it through the trunk to the leaves in the form of sap. The trunk provides the transporting mechanism between the leaves and the roots and is made up of the heartwood in the center, the cambium layer at the outer edge of the trunk, and the bark, which provides the primary protection. Roots grow only as fast as they are provided energy from the leaves. The tree system consists of the circulation of water from the roots upward through their trunk in the form of sap. When the sap reaches a leaf, the water evaporates into the air. The sap brings mineral salts from the earth to the leaves. The chlorophyll in the leaves acts with sunlight to convert the salts into food through photosynthesis. This food then flows back into the tree system through paths just below the bark. It is this system which makes a tree live.

In engineering terms, we are primarily concerned with the term evapotransporation; i.e., the withdrawal of moisture from the soil and its eventual transporation into the atmosphere. Attempts have been made to quantify this term; however, the results have not always been uniformly accepted in the engineering/ arborist communities, primarily because of the inability to accurately measure the moisture loss/replacements in the soil under most trees. Driscoll[10] presented a ranking of trees in terms of their damage potential. A modified copy of this ranking is contained in Table 1.[11]

In the greater Houston area, we do not have an abundance of Poplar trees; however, there well may be more Oak trees than any others. Also contained in this document is an example of seasonal moisture content variations, which is shown in Figure 1. Of interest is the identification of a zone of permanent moisture deficiency. This concept was further explored by Biddle[12] who measured the soil moisture content in the close proximity of various kinds of trees which were growing in a variety of clay soils, all of which were in England. A combined moisture reduction/moisture deficit curve for a Poplar tree growing

Table 1. Risk of damage by different varieties of tree

Ranking	Species	Maximum height of tree (H): metres	Separation between tree and building for 75% of cases: metres	Minimum recommended separation in shrinkable clay: metres
1	Oak	16-23	13	1H
2	Poplar	24	15	1H
3	Lime	16-24	8	0.5H
4	Common Ash	23	10	0.5H
5	Plane	25-30	7.5	0.5H
6	Willow	15	11	1H
7	Elm	20-25	12	0.5H
8	Hawthorn	10	7	0.5H
9	Maple/ Sycamore	17-24	9	0.5H
10	Cherry/Plum	8	6	1H
11	Beech	20	9	0.5H
12	Birch	12-14	7	0.5H
13	White Beam/ Rowan	8-12	7	1H
14	Cypress	18-25	3.5	0.5H

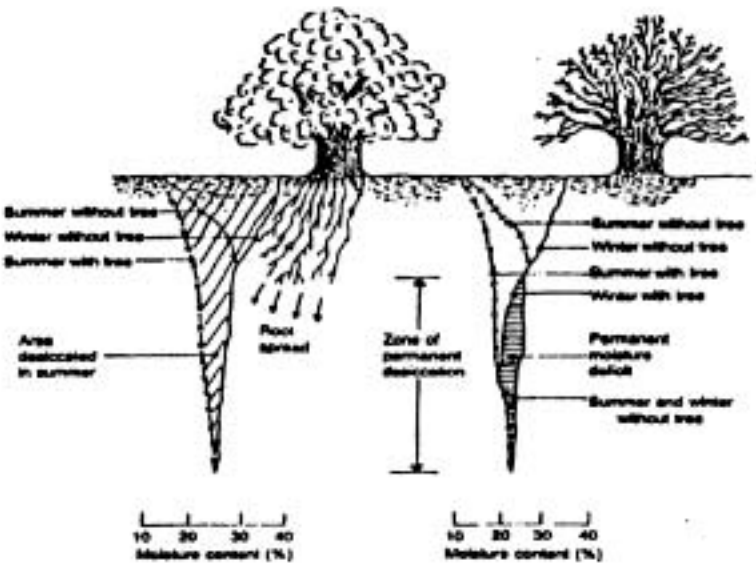

Figure 1. Seasonal variation in moisture content with and without trees

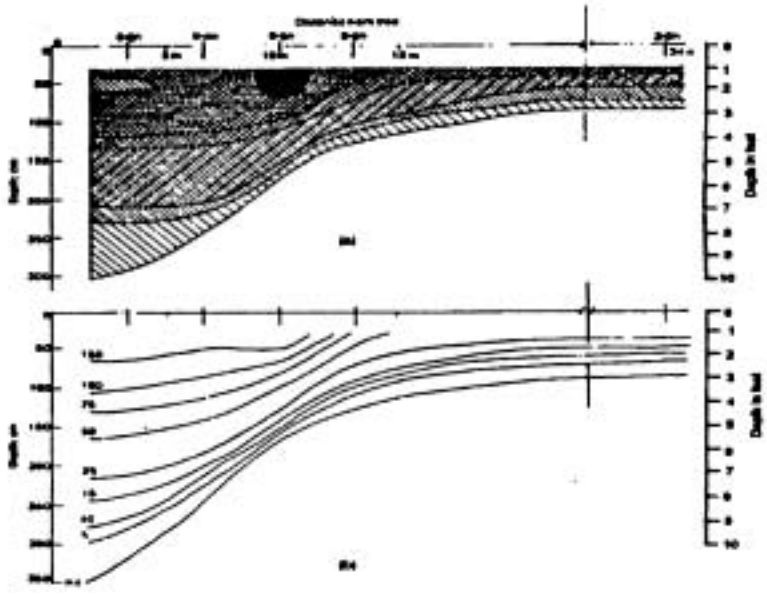

Figure 2. An example of soil moisture and soil moisture deficit reduction curves for popular trees on a bolder clay soil in London, England

in a Bolder Clay (PI = 29%) is shown in Figure 2. The moisture deficit curves are calculated by multiplying the change in moisture content by the appropriate layer thickness. In reviewing this curve, it is significant that it does represent the most severe condition for a tree which has been judged to be of a lesser threat than would be an Oak tree growing in a soil whose Plasticity Index is less than some of the major areas in the greater Houston, Texas area. The availability of such data in England has had significant impacts on the construction business. Whereas it was considered to be impractical to plant any tree closer to a foundation than its ultimate height, these data do provide some bases for the planting of certain trees closer to buildings, assuming the data provided for these curves are considered. They also demonstrate the folly of simply removing existing trees in expansive soils for the construction of a new residential structure.

WHAT CAUSES EXPANSIVE SOILS TO SHRINK OR SWELL

As clay particles are formed, there are usually several points in the particle arrangement where there is an electrical imbalance; the electrical imbalance is increased whenever a "string" of clay particles is broken apart. Thus,

the result is that a clay particle typically has a negative net electrical charge on its surface. Since nature likes all things to be balanced, whenever a water molecule drifts close enough to the surface of a clay particle, the negatively charged surface of the clay particle causes the positive end of the water molecule to turn toward the particle. If it is close enough to the particle, the water molecule is attracted to the clay particle surface sufficiently strongly that the water molecule becomes trapped. Also, unattached or "free" positively charged particles, called "cations", tend to acquire a spherical-shaped arrangement of water molecules which have their negative ends directed toward the positively charged cation (and their positive ends directed away from the cation). When the free cation is "captured", water molecules approach a clay particle. The attraction between the negatively charged clay particle surface and the positively charged outside of the cation sphere of water molecules causes the cation to be "captured" by the clay particle, thus increasing the amount of water associated with the clay particle.

Clay particles are very small. A typical kaolinite particle might have a total surface area (top, bottom and edges) of approximately 1 x 10-5 mm^2 (1 x 10-10 ft^2, or 0.0000000001 ft^2). As areas go, this is very small. Smectite particles have a diameter that is 100 to 1,000 times smaller than kaolinite particles and a thickness that is 10 to 400 times thinner than kaolinite[13] and, consequently, typically have a larger surface area per particle. Thus, a single pound of montmorillonite particles would have an incredible total surface area of approximately 800 acres (325 hectares) [13] with which to attract water.

Thus, expansive soils are very small in size and have a large surface area that attracts free water. Because of these characteristics, it is easy to see why it is said that expansive soils are those clays that exhibit an extreme change in volume.

Soil suction is a measure of free energy of the pore-water or tension stress exerted on the pore-water by soil matrix. Soil suction is, in practical terms, a measure of the affinity of the soils to retain water and can provide information on soil parameters that are influenced by soil water; e.g., volume change, deformation, and strength characteristics of soil. The soil suction is measured using the filter paper method in accordance with ASTM D-5298.

The soil suction is divided into two components; Matrix suction and osmotic suction. The matrix suction is the negative pressure (expressed as a positive value) relative to ambient atmospheric pressure on soil water, to which solution identical in composition with the soil water must be subjected in order to be in equilibrium through a porous permeable wall with soil water; pressure equivalent to permeable wall with the soil water; and pressure equivalent to that measured by test methods D2325 and D3152.

The osmotic suction is the negative pressure to which a pool of pure water must be subjected in order to be in equilibrium through a semi-permeable membrane with a pool containing a solution identical in composition with soil water; decrease in relative humidity due to the pressure of dissolved salts in pore-water.

FOUNDATIONS AND RISKS

Many lightly loaded foundations are designed and constructed on the basis of economics, risks, soil type, foundation shape and structural loading. Many times, due to economic considerations, higher risks are accepted in foundation design. Most of the time, the foundation types are selected by the owner/builder, etc. It should be noted that some levels of risk are associated with all types of foundations and there is no such thing as a zero risk foundation. All of these foundations must be stiffened in the areas where expansive soils are present and trees have been removed prior to construction. The foundation types typically used in the area with increasing levels of risk and decreasing levels of cost are discussed in Table II.

The above recommendations, with respect to the best foundation types and risks, are very general. The best type of foundation may vary as a function of structural loading and soil types. For example, in some cases, a floating slab foundation may perform better than a drilled footing type foundation.

FOUNDATION PROBLEMS CAUSED BY TREES

FOUNDATION SETTLEMENT PRODUCED BY SOIL SHRINKAGE

Several authors as far back as 1960 have documented this type of distress.[9,14] Buckley[3] proposed that trees be placed no closer to a residential foundation than its ultimate height. The basis for this recommendation is contained in Figure 3. It was not, however, widely recognized by the designers and constructors of the millions of

Table II.

Structural Slab with Piers	This type of foundation (which also includes a pier and beam foundation with a crawl space) is considered to be a minimum risk foundation. A minimum crawl space of six-inches or larger is required. Using this foundation, the floor slabs are not in contact with the subgrade soils. This type of foundation is particularly suited for the area where expansive soils are present and where trees have been removed prior to construction. The drilled footings must be placed below the potential active zone to minimize potential drilled footing upheaval due to expansive clays. In the areas where non-expansive soils are present, spread footings can be used instead of drilled footings.
Slab-On-Fill-Foundation Supported on Piers	This foundation system is also suited for the area where expansive soils are present. This system has some risks with respect to foundation distress and movements, where expansive soils are present. However, if positive drainage and vegetation control are provided, this type of foundation should perform satisfactorily. The fill thickness is evaluated such that once it is combined environmental conditions (positive drainage, vegetation control) the potential vertical rise will be minimum. The structural loads can also be supported on spread footings, if expansive soils are not present.
Floating (Stiffened) Slab Supported on Piers. The Slab can either be Conventionally-Reinforced or Post-Tensioned.	The risk on this type of foundation system can be reduced sizably if it is built and maintained with positive drainage and vegetation control. Due to presence of piers, the slab can move up if expansive soils are present, but not down. In this case, the steel from the drilled piers should not be doweled into the grade beams. The structural loads can also be supported on spread footings if expansive soils are not present.
Floating Slab Foundation (Conventially-Reinforced or Post-Tensioned Slab)	The risk on this type of foundation can be reduced significantly if it is built and maintained with positive drainage and vegetation control. No piers are used in this type of foundation. Many of the lightly-loaded structures in the state of Texas are built on this type of foundation and are performing satisfactorily. In the area where trees have been removed prior to construction and where expansive clays exist, these foundations must be significantly stiffened to minimize the potential differential movements as a result of subsoil heave due to tree removal.

homes built on concrete slab-on-ground foundations in the 1950 time period. In Houston, Texas, as an example, the post World War II building boom included upwards of 100,000 homes constructed in the Southwest part of the City, where the soils were typically very expansive. In most cases, these homes were initially constructed in subdivisions outside of the City limits, but were later annexed by the City. Thus, no building codes were applied. Since this real estate was largely farm land which was barren of trees, one of the things that were done by individual homeowners (and even some subdivision developers) was to plant trees in the yard close to the foundation. Trees such as Oaks, China Berry, and Pecan were popular because they were hardy. When the trees entered into their period of major growth, their water demands steadily increased and foundation problems began.

Studies[15] have shown that when a slab is placed on ground, evaporation of soil moisture is retarded. If the

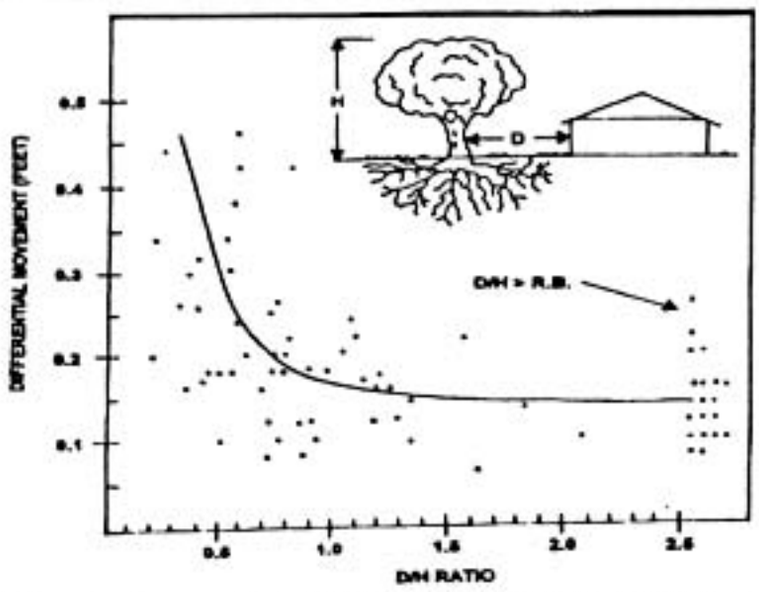

Figure 3. A curve of foundation vertical movement versus tree height

soil is desiccated at the time of construction, moisture will move toward the center of the slab and is going to be higher than at the edge. Trees use soil moisture for growth. Therefore, during wet periods, sufficient supply of mois-

ture is available for tree growth and soil moisture contents may not be substantially affected by vegetation. During dry summer months, when evaporation rates are high, the trees will obtain large quantities of moisture from already dry soils. If these trees are located in close proximity to lightly-loaded structures such as houses, their root system will move toward the structures, in an attempt to find a moisture supply. If trees are too close to a house, desiccation of the soils below the slab may occur, causing settlement of the slab.

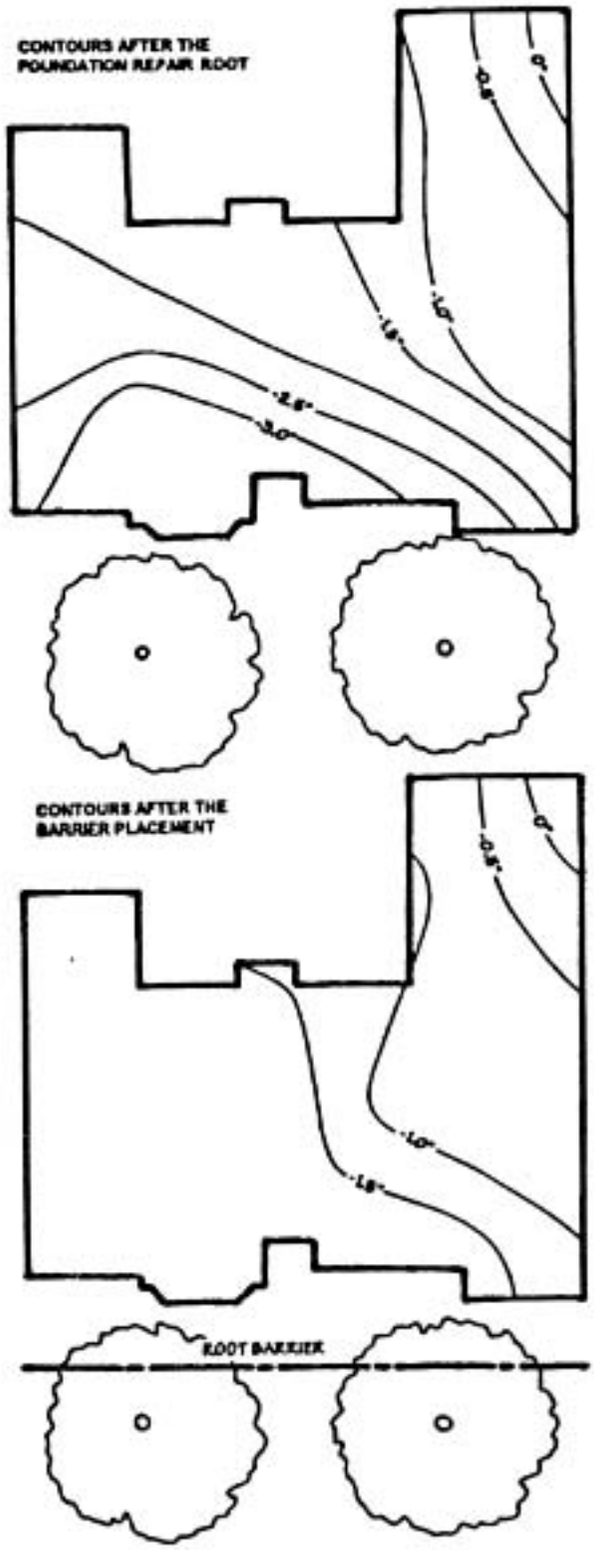

Figure 4. An example of failure of a foundation as a result of the depletion of moisture at the edges because of trees. Measurements were taken after pier installation and after root barrier installation

Figure 4 shows an example of a home located in the Southwest part of Houston, Texas, whose slab-on-ground foundation was underpinned using drilled piers. During the 1988 to 1990 drought, the foundation incurred additional deflections. At our suggestion, a root barrier, combined with an automatically actuated soaker system was applied, and the foundation not only stabilized, but some rebound occurred. The example contained in Figure 4 is not, unfortunately, an isolated example. Better results have been obtained in the recent past using pressed segmented piles and helical piers.[16] Vertical moisture barriers have enjoyed a very limited use.

FOUNDATION EDGE HEAVING CAUSED BY SOIL SWELLING

To compensate for the settlement of the outer edge of a foundation due to the extraction of moisture from the soil through the roots of nearby trees, an accepted preventative measure was to place the foundation on top of drilled piers. Most recently, however, a condition has occurred where the piers became a detriment. In the inter part of the City of Houston, Texas, there are subdivisions with comparatively small building lots, which often contained small, older homes, became very desirable because of their location. In many cases, the lots contained large, prolific trees, which were removed to make way for the construction of larger homes. In many such cases, nothing was done to compensate for the inevitable swelling of the soils which would occur when the tree, which had desiccated the soil in its near vicinity, was gone and soil suction forces moved soil water into the desiccated areas. It does not take much imagination to invision the mood of a homeowner who, in many cases, paid extra moneys to have a sturdy foundation constructed only to have it begin to move soon after the owner moved in. An example of such a condition is shown in Figure 5. The foundation, in this example, was founded on 10-foot deep drilled piers, which had 42-inch diameter bells that were inspected during construction. The pier shafts were tied to the concrete perimeter beam. The soils had a plasticity index in the 60% range. A Pecan tree was remove during the construction process, or shortly thereafter. Signs of foundation induced damage became manifested within the first year of construction and have, in the interim, worsened steadily. A literature search failed to reveal any documented discussion of this phenomenon, not only in the state of Texas, but in the United States, as well. Such discussions were, however, found in literature from outside of the United States. A listing of such sources is

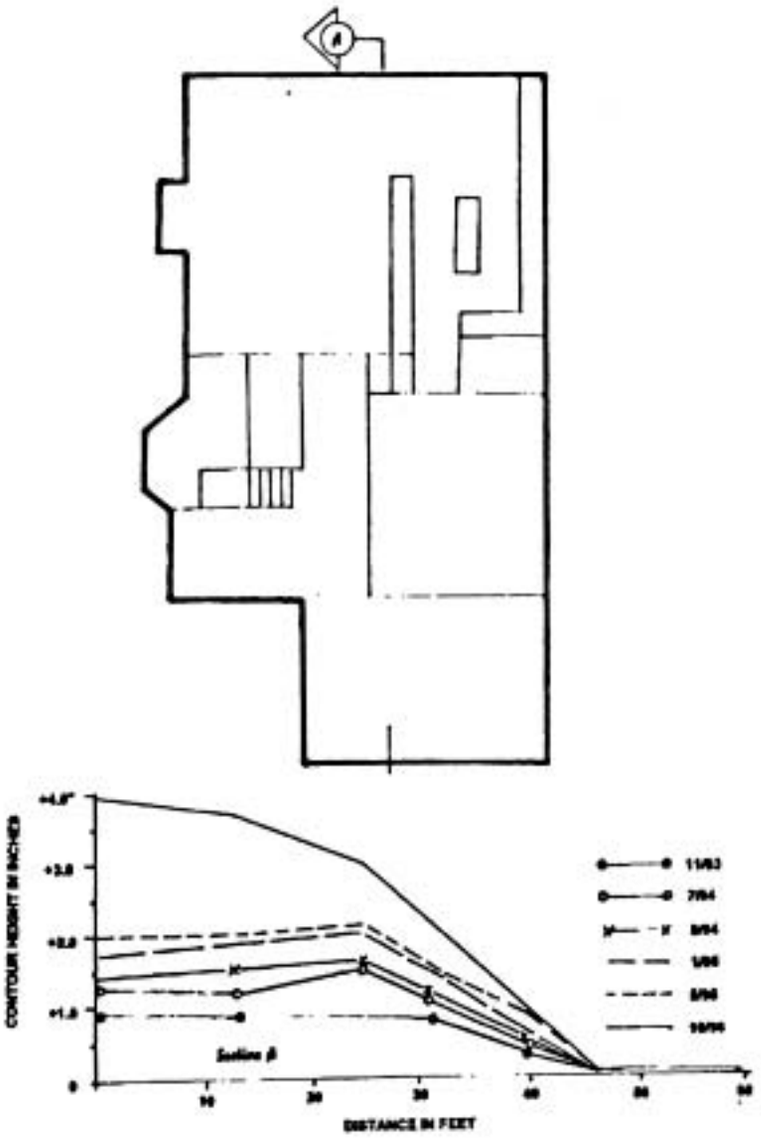

Figure 5. An example of a home which had been adversely effected by the removal of a Pecan tree

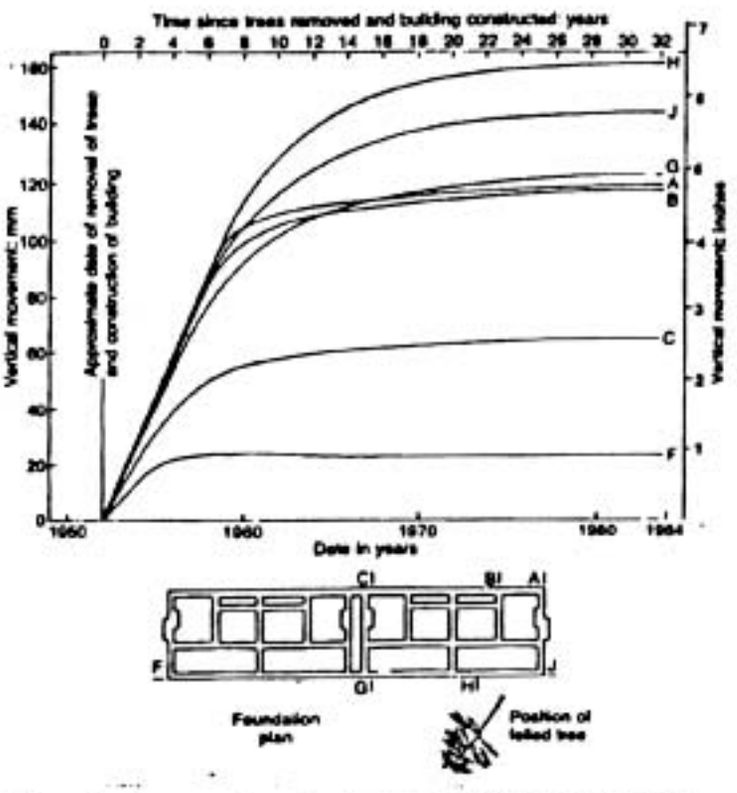

Figure 6. A copy of a vertical movement that occurred as a result of the removal of a Poplar tree in London, England

contained in the Bibliography Section of this paper. This significance of the tree removal situation is perhaps best illustrated in Figure 6[17]. In this case, the removal of a Poplar tree caused over 6 inches of heaving which was monitored over a 30-year period of time.

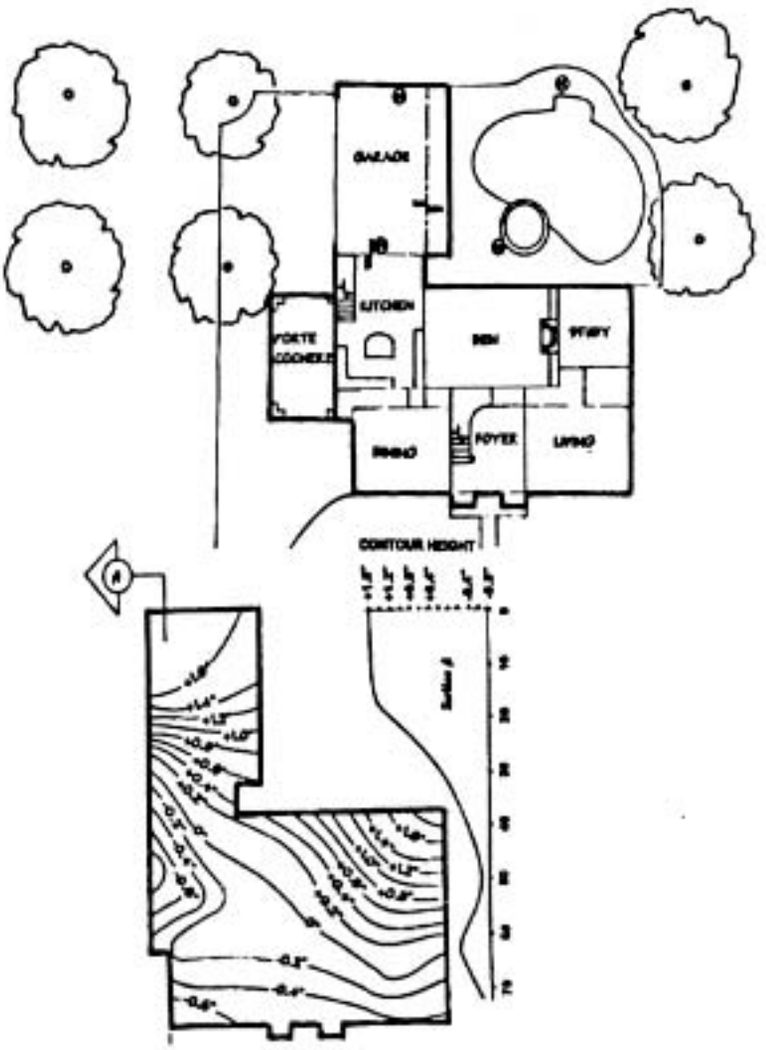

Figure 7. An example of a home in Houston, Texas, which had been constructed on a roadway that was lined with Post Oak trees

Figure 7 shows how a residential building was placed on the edge of a roadway, which, before the time of construction, had Post Oak trees on either side. The removal of the trees caused significant heaving of the foundation at the rear of this, and several other buildings, which were constructed along this roadway. We have been able to measure heaving in a limited number of cases and the results are contained in Figure 8. In comparing our data with that shown in Figure 9, we can see that the slope of our data is steeper, even though one of the curves seemed to level out after 7 years.

As mentioned earlier, tree roots tend to desiccate the soils. In the event that the tree has been removed prior to building construction, during the useful life of the structure, or if a tree dies, subsoil swelling can occur in the expansive

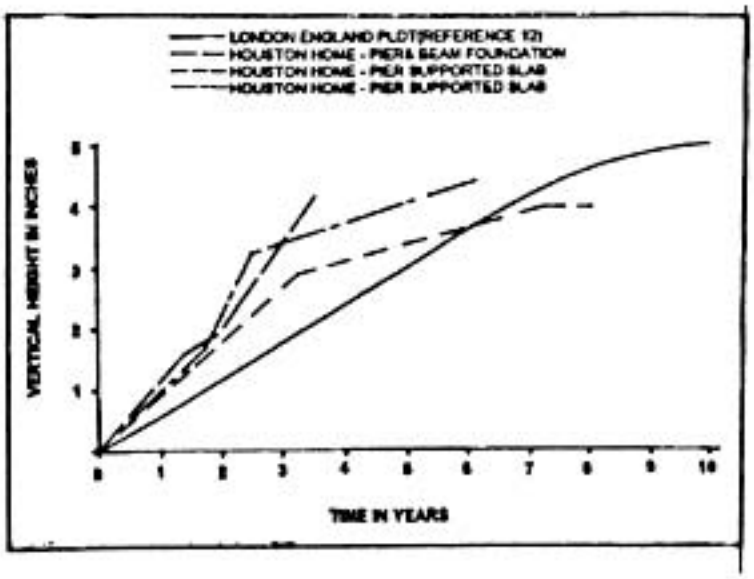

Figure 8.

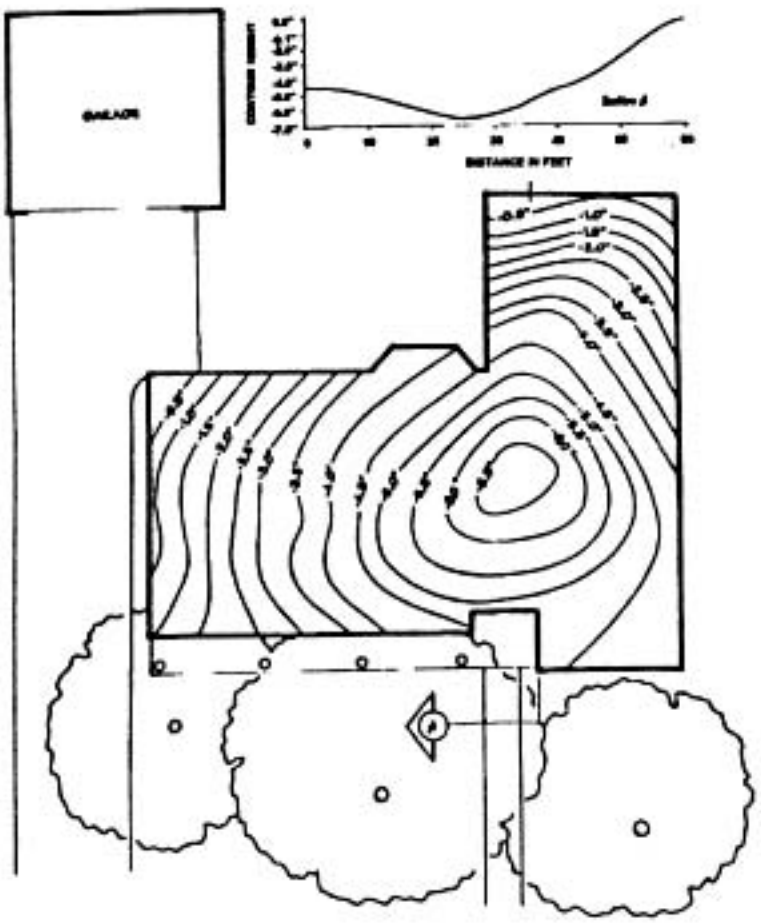

Figure 9.

soil areas for several years. Studies have shown that this process can take several years in the area where highly expansive clays are present. In this case, the foundation for the structure should be designed for the anticipated maximum heave. Furthermore, the drilled footings, if used, must be placed below the zone of influence of tree roots. This depth should be evaluated as follows:

a) The pier should be placed below the depth of constant suction or the zero movement line.

b) The pier depth should be such that it could resist the uplift loads due to expansive soils that extend along the shaft perimeter.

c) More extensive soil tests are required. Soil borings near a tree must be, as a minimum, 25 to 30 feet deep. The depth to which tree root fibers exist must be determined since they are a basis of identifying the depth of constant soil suction. Potential Vertical Movement values should also be calculated.

In the event that a floating slab foundation is used, we recommend the slab be stiffened to resist the subsoil movements due to the presence of trees. In addition, the area within the tree root zone may have to be chemically stabilized to reduce the potential movements. Alternatively, the site should be left alone for several years so that the moisture regime in the desiccated areas of the soils (where tree roots used to be) become equalized/stabilized to the surrounding subsoil moisture conditions. The length of time required for subsoils to regain their moisture is dependent on the tree species, soil type and the amount of rainfall. For most trees, one wet season may be enough for the subsoils to regain their moisture; however, removal of trees such as Live Oak, Poplar, etc. may result in moisture deficits in the soil profile that may require several years to stabilize.

Remedial measures to correct the adverse effects of this type of soil heaving are somewhat limited. One method is to raise the entire foundation out of the potential vertical rise of the soil using underpinning techniques. Soil testing will generally show the PVM (Potential Vertical Movement) values in the soil where the trees were removed. It may then become necessary to raise the foundation out of this zone. An alternative is to use a vertical moisture barrier. A combination of partial underpinning and the use of moisture barriers may also have to be used to stabilize the foundation system.

FOUNDATION CENTER SETTLEMENT

There has been an ever-increasing problem with regard to the interaction between trees and foundation performance; i.e., foundation performance induced by under-slab sewer leaks. Many of the homes constructed in the 1950 time period had cast iron, under-slab sewer pipes buried in clay soil. Over the past 40 (+) years the effect of this unfortunate marriage has produced a proliferation of

under-slab sewer leaks. Since most (if not all) of the home insurance policies allow a homeowner to collect on damages caused by such leaks, there has been an attendant number of such claims filed.

Typically, the insurance carrier hires a plumbing testing company and an Engineer to determine if the leak has caused any foundation related damage. It is likewise typical that this same Engineer will observe that the foundation has deflected downward in its center section, which is the opposite of what one might anticipate if water were to be induced into expansive soils. Other contradictions may be observed which included the following:

- The timing of the damage appeared coincidental to the occurrence of the sewer leak.
- There were plumbing leaks; yet, where soil tests were conducted, the soils were comparatively dry.
- There was always a reasonable degree of correlation between the presence of the sewer leaks and the points of deflection.
- In a majority of cases, the soils were expansive, the foundation was constructed on drilled piers or was underpinned using drilled piers subsequent to the time of original construction, and there were trees growing near the foundation which were almost always mature. It is a known fact that the water demands of mature trees tend to stabilize. Could these trees then suddenly become the source of additional foundation deflections?
- In the 20(+) cases which we examined, the foregoing conditions existed and the foundation settled in the center instead of heaving, as was anticipated. An example is shown in Figure 9. In this case, the sewer system could not be tested since it would hold no water.

We are of the opinion that the introduction of the sewer water spurred the growth of the tree roots to grow towards the source.[18, 19] The tree roots then extracted not only the moisture provided from any sewer leaks which occurred, but also any moisture which was in the soil before the leak occurred. The presence of an under-slab sewer leak then resulted in a net soil moisture loss where large trees were growing adjacent to the foundation with the ultimate result that the foundation subsided instead of heaving, as one might anticipate.

This opinion does, of course, involve a number of assumptions for which no proof exists. In fact, there is little of no real proof that any sewer leak did, or did not, cause foundation deflections to occur. More testing and study is required.

CONCLUSIONS AND RECOMMENDATIONS

The design and manufacture of most of the material things we use in our lives is based, to at least some degree, on some type of research. Automobiles are designed and extensively tested before they reach the market, manufacturers of appliances subject them to extensive testing before new models are put up for sale, new food products must be given extensive testing, etc. It is then somewhat ignominious that the design and construction of the fundamental part of what is perhaps the most expensive investment for most of us is based on little, if any, current research; at least in the United States. Instead, we tend to learn in the most fundamental, and in the crudest, of ways - by trial and error. The cost of this process is born by the builders, homeowners, and engineers much to the delight of many attorneys.

We have, in this paper, pointed out some of the problems that can be caused by our failure to learn to live with trees in an urban environment. Although much of this discussion was based on Houston, Texas, experience, this information certainly applies to much of Texas and to other parts of the country, as well. All of us who are involved in the design and construction of residential and other low-rise buildings need to be cognizant of these problems and to conduct ourselves accordingly. This may require additional pre-construction testing and may necessitate the need for more expensive designs. Some may say that our clients may not be willing to pay the price for such extra work. So long as there are engineers who are willing to do cheap work, the problems we discussed herein will recur and we will be left to ponder why some people are more willing to pay their attorneys more than they are their engineers and or builders.

We have pointed out the need for research. To the best of our knowledge, the last 2 large research studies conducted on residential foundation issues were the BRAB in the 1960's and the University of Texas at Arlington stud-

ies in the 1970's. We do know of some smaller studies, which have been conducted at some Universities, but we believe that larger studies are needed not only on the issues presented herein but on sister issues, as well. Some of the study areas are listed below:

- A relationship needs to be developed that would address the tree type (species), distance from the foundation, and height of the tree.
- Studies similar to those conducted by Biddle should be done using trees more typically found in the United States (Oaks, Pecans, China Berry, etc),in clay soils and varying weather patterns that are typical of this country.
- How to better design floating slabs that would resist the effect of trees.
- Develop a simple mathematical module that would relate sewer leaks, tree moisture removal, and subsoil movements.

Perhaps the information contained herein will help in the search for research dollars.

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