Which Way Is It Moving?
Guidelines for Diagnosing Heave, Subsidence and Settlement

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ABSTRACT

Heave, subsidence and settlement are all descriptions of soil movement that commonly affect residential and other lightly loaded foundations. Laypeople in the local foundation industry commonly refer to all three movement types as simply "settlement". Many foundation repair contractors in the business of lifting foundations do not guarantee their work for upward movements caused by heave, rather only the downward movements caused by subsidence and settlement. Misdiagnoses of heave, subsidence, and settlement are common, sometimes invalidating the repairs and warranties, and are usually due to the lack of understanding of the mechanisms behind each type of movement. This paper addresses these three movement types: their definitions, their causes, their diagnoses, their symptoms, and the appropriate repairs for each movement type. Other movement types are also briefly described.

DEFINITIONS

The following definitions are taken from the Foundation Performance Association's Document No. FPA-SC-13-0, *Guidelines for the Evaluation of Foundation Movement for Residential and Other Low-Rise Buildings*, published 15 Jul 07 at http://www.foundationperformance.org/:

Heave is upward movement of an underlying supporting soil stratum usually due to the addition of water to an unsaturated expansive soil in the active zone. When moisture is added to a soil with clay content, expansion occurs within the structure of the soil, and the corresponding area of the foundation and superstructure is moved upward. Heave normally only occurs within clayey soils that have a high suction potential and an available moisture source.

Subsidence is downward movement of an underlying supporting soil stratum due to the withdrawal of moisture. When moisture is extracted from the soil, shrinkage occurs within the structure of the soil, and the corresponding area of the foundation and superstructure move downward. Subsidence normally occurs within clayey soils and is often the result of soil desiccation that is caused by trees or other large vegetation.

Settlement is downward movement of an underlying supporting soil stratum due to loading in excess of the bearing capacity of the soil below. When the vertical loads from above are in excess of the bearing capacity of the soil strata directly below the foundation, the foundation and superstructure move downward. Encompassed in settlement are a) the immediate elastic consolidation and distortion of granular or clay soil particles, b) slope instability, and c) the long-term consolidation resulting from gradual expulsion of pore water from voids between saturated clay soil particles. Settlement may occur in all types of soils.

INTRODUCTION

In the Houston area, the common movement types plaguing light foundations are subsidence and heave. Settlement occurs rarely and primarily in cases that involve embankment instability or where slab-on-grade foundations are founded on silts underlain by relatively impermeable clays that cause perched water tables and subsequent loss in bearing capacity of the silts.

While settlement is rare and easy to prevent, heave is much more common and is a difficult movement to mitigate. Foundation design engineers sometimes specify "Isolated Structural Systems with Deep Foundations" when they are aware at the design stage that the site has a damaging heave potential. These systems are described in Section 4.1.1.1 of the Foundation Performance Association's Document No. FPA-SC-01-0, *Foundation Design Options for Residential and Other Low-Rise Buildings on Expansive Soils*, published 30 Jun 04 at: http://www.foundationperformance.org/.

The foundation design engineer bases his design on the soils data from the geotechnical report. Unfortunately, we find that some geotechnical reports produced for the Houston area have underestimated the swell (heave) potential of soils, leading to unacceptably flexible foundation designs that are susceptible to damaging movement.

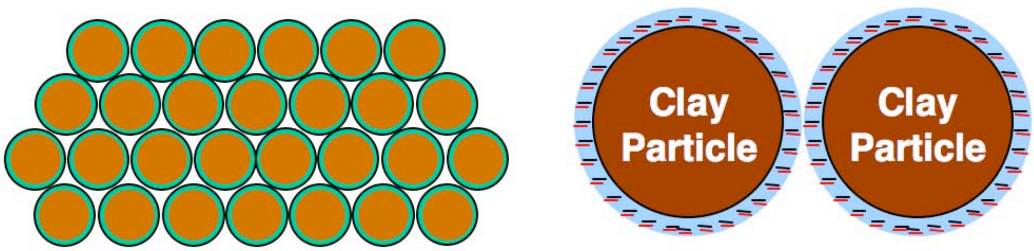
Foundation repair contractors, many of whom sell repairs without the benefit of proper forensic engineering evaluations, often will not warrant their work if heave is later proven to be the cause of continued movement and distress. Some of the larger foundation repair contractors may provide a warranty for heave if they are allowed to sell an entire foundation lift, i.e., raising the entire foundation a certain elevation above the soil to ensure that heaving soils cannot apply uplift forces to the underside of the foundation.

Heave can be a difficult movement to predict, diagnose and mitigate. Local geotechnical engineers sometimes do not provide the required testing or engineering needed to accurately predict heave. This promotes the selling of full remedial lifting after unplanned heave occurs, which can be expensive. We have seen both remedial lifting and isolated foundation designs fail to perform as planned when the depth of the piers or piles are not sufficiently anchored below the active zone. The common reason this occurs is lack of proper geotechnical testing that identifies the depth of the active zone.

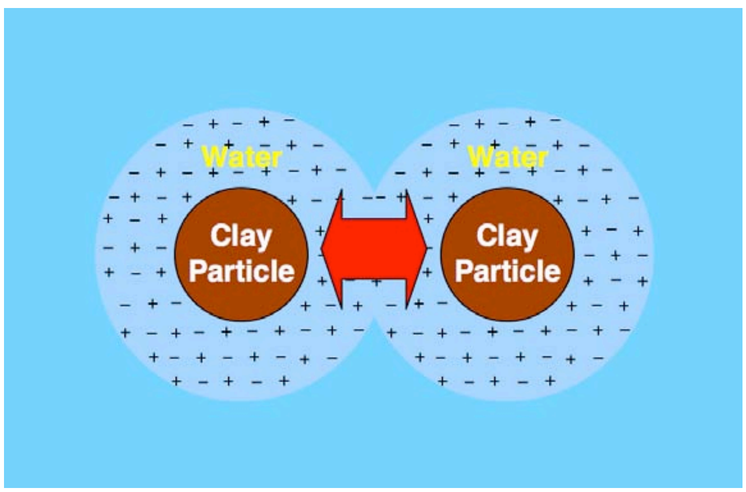
The proper depth to prevent heave or subsidence of a pier or pile should be computed based on suction testing and is normally 1.5 to 2.0 times the depth of the active zone. In Houston, we have measured active zones as deep as 20 ft, meaning the builder's piers or the repair piers or piles may need to be founded as deep as 30 to 40 ft penetration, depending on the site characteristics.

CAUSES

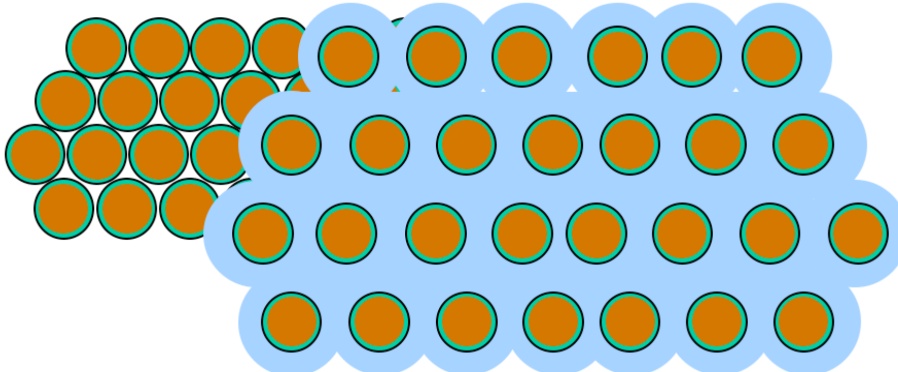
Why does heave occur? Basically heave occurs because the moisture increases in an active soil. At the molecular level, a negative pressure potential (suction) in the soil particles attracts water molecules to a tight bond around the surface of the soil particles. Because water is incompressible, the clay particles are forced apart, causing soil movement. The graphics below (courtesy of Environmental Soil Stabilization, LCC) demonstrate this behavior.



Clay particles exhibit a net negative charge and pack tightly when dry



When water becomes available, it is attracted by the clay's negative charges, and bonds tightly to the surface of the clay.



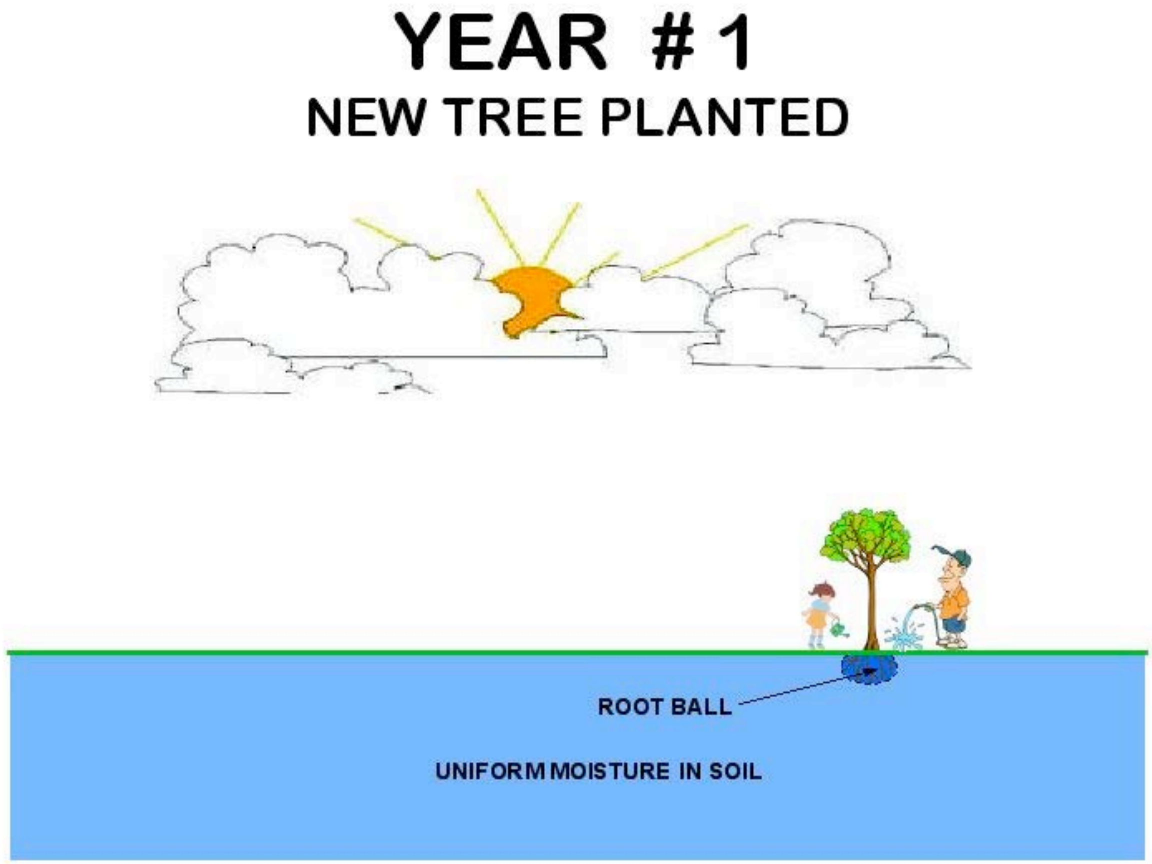
Because water is incompressible, it pushes the clay particles apart, causing an expansion or swelling of the clay.

In which direction will this soil movement occur? It will occur in any direction the laws of physics will allow. At deeper penetrations, the soil + water particles will be restrained, reducing the potential for attraction of water particles and subsequent expansion. Closer to grade, depending on the amount of overburden from the soil and structures, the soil movement will expand upward, defined as "heave" and sometimes laterally, commonly known as "walking" when observed in flatwork or other foundations.

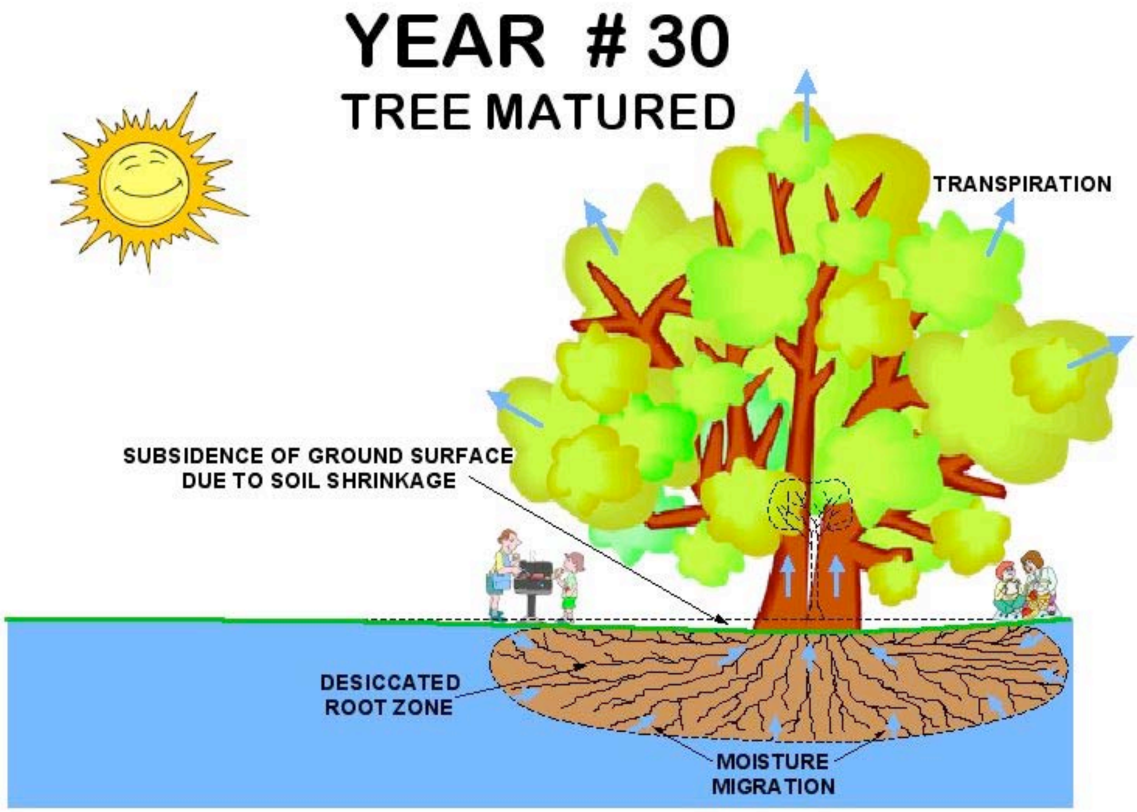
Can the opposite soil movement also occur? Most certainly. As water leaves an active soil, the gaps between soil particles close and shrinkage occurs, the vertical downward component of which is defined as "subsidence". This is the usual reason for needing to lift an older foundation in the Houston area. Builder's piers are commonly added to new slab-on-grade foundations in the Houston area to later prevent or minimize this effect from newly planted trees.

Why does moisture enter and leave active soil, causing heave and subsidence*?* The most common reason is trees are planted or naturally occur, mature, and are then removed. Tree or other large vegetation roots are capable of removing water from active soils such that subsidence occurs. This takes years or decades as the tree matures and its roots propagate deeper and farther away from the trunk, creating a powerful suction. However when the trees are removed, the sudden lack of water uptake by the tree creates an imbalance, with the ongoing soil suction attracting available moisture from any direction. This moisture movement can happen over several months or several years depending on the quantities of cracks and root channels in the soil fabric. Rehydration continues until the soil reaches moisture equilibrium, determined by the amount of available moisture.

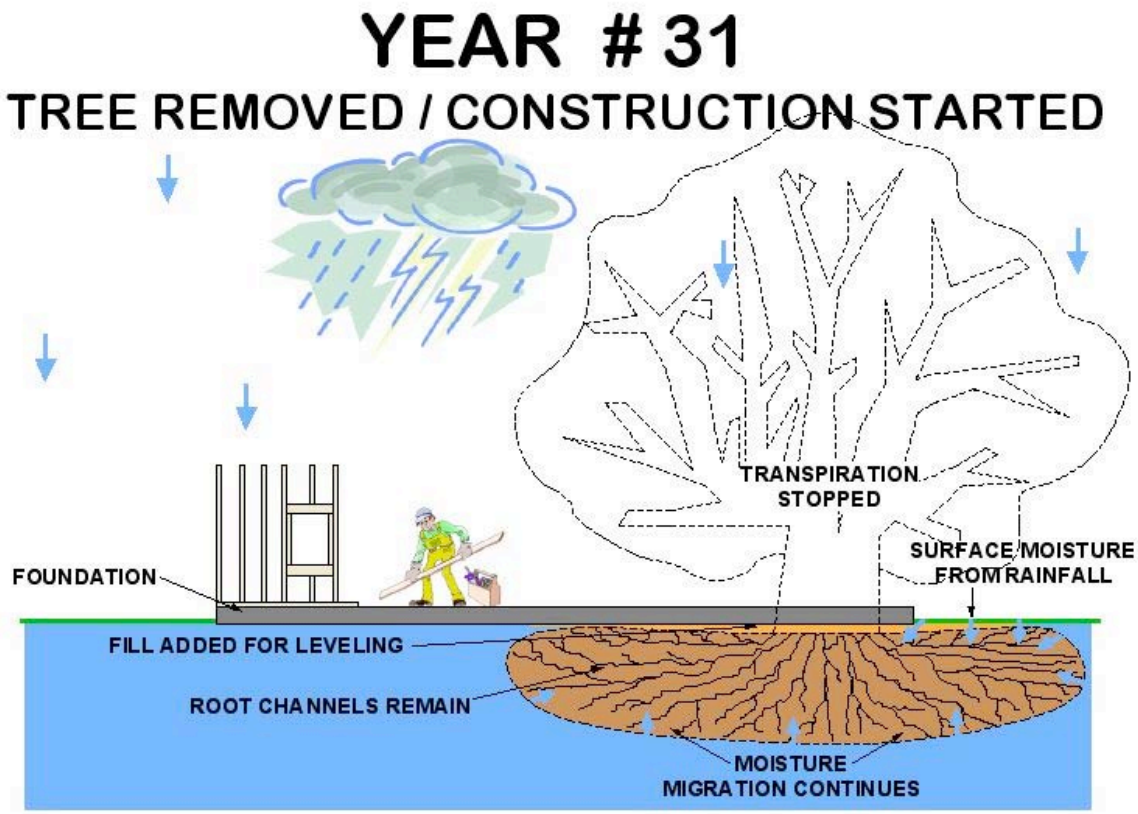
The below graphics illustrate the cycle from subsidence to heave that is commonly experienced in the Houston area:



At year 1, a small tree is planted (or naturally occurs) in clay soils. The soil around the tree has uniform moisture content; the soil is in equilibrium. The tree receives water and sunlight, and it thrives.

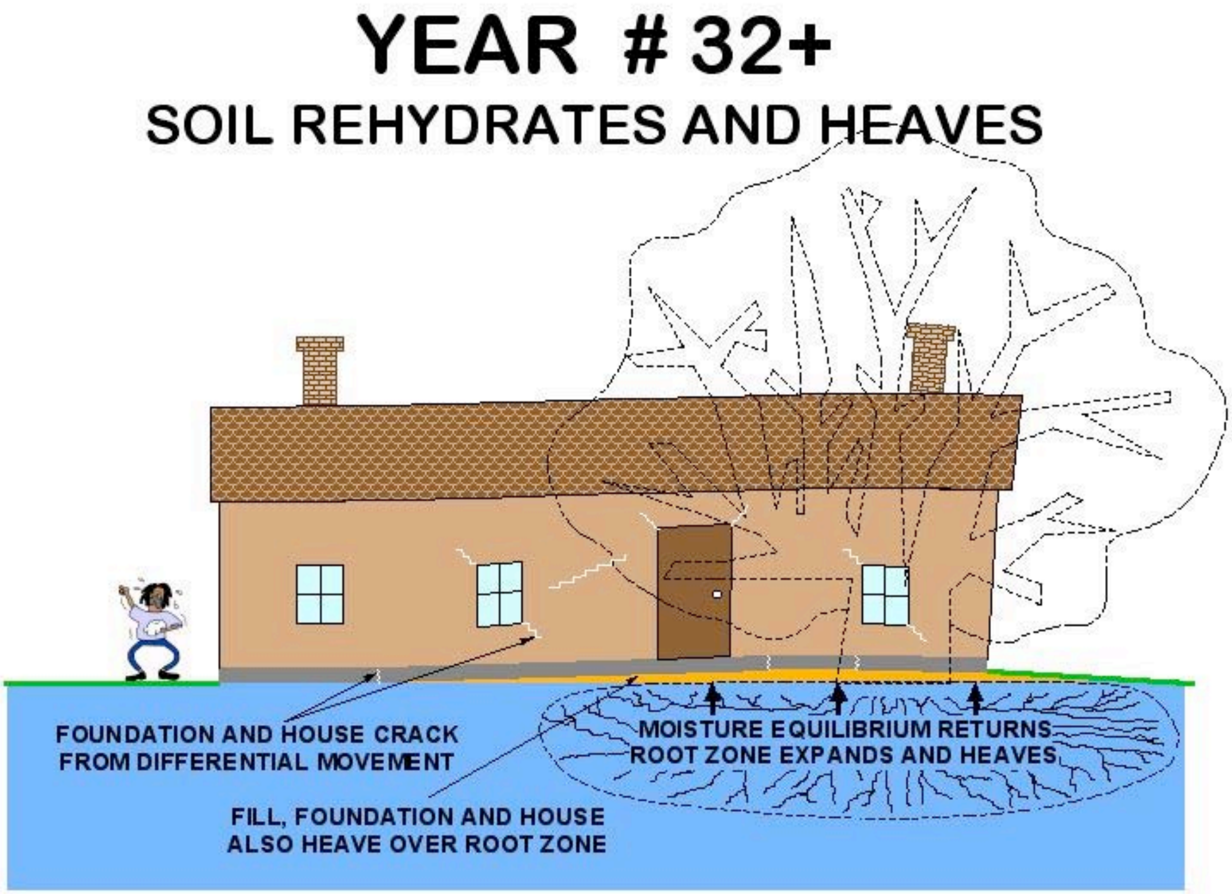


By year 30 (depending on the species and other factors), the tree is mature. The above graphic shows the typical cycle of drawing large quantities of water from the soil and releasing nearly all of it into the air by the process of transpiration. Depending on the surrounding vegetation and cover, a mature tree often requires more groundwater than the environment can supply and consequently the soil in the root zone becomes desiccated, creating a high suction potential in the structure of the clay. As the clay soil is desiccated it subsides, as shown in the graphic above. The dashed line is the original soil level.



The following year, the mature tree is felled so that a house can be constructed on the site. The high suction potential in the clay structure is unchanged. Before the foundation is placed, compacted fill is added to the subsided area to level the pad. Some of the upper tree roots may be removed prior to adding fill, though this is not always the case. Then the foundation is placed, often very soon after tree felling, before the soil has a chance to reach moisture equilibrium. The roots and rootlets (i.e., hair-like roots) in the soil shrivel up and die after the tree is felled, and in their place they leave tiny hair-like channels.

Capillary action is a natural occurrence via the rootlet channels, as moisture seeks to reach equilibrium and migrates from the wet soil to the dry desiccated soil, i.e., the soil with a high suction potential. With the tree gone, the transpiration has stopped, so that the moisture pulled in by capillary action is abundant in the soil and rehydrates it.

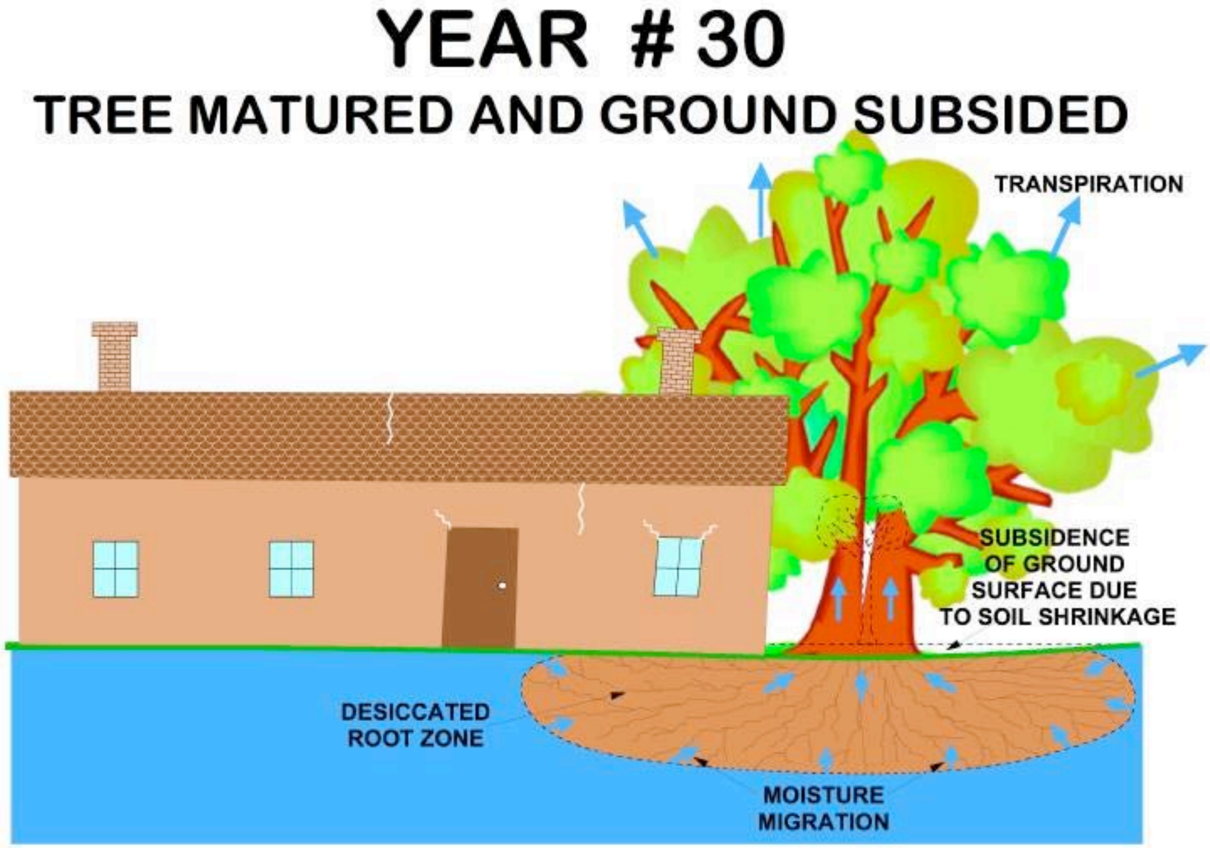


All new foundations provide a prime condition for water collection as their coverage stops the normal evaporation process that existed before construction. By the time construction is complete, the clay soil has already begun to rehydrate. As the rehydration occurs over a period of (typically) years, it causes the formerly desiccated and subsided soil to expand and heave. The fill, foundation and house are forced upward over the root zone, leading to differential movement of the foundation and cracking in the superstructure. The further from the edge of the foundation that the felled tree occurred, the longer this process usually takes, unless an interior water source, such as a plumbing leak, is present. Poor drainage, i.e., soils sloping towards the foundation, often causes the process to speed up, as more water is available for rehydration.

After the soil rehydrates, the soil suction drops and the capillary action ends. The moisture content in the previously desiccated soils will tend to go above moisture equilibrium as compared with the surrounding soils that are uncovered. However, another source of water, such as poor drainage or a pool or plumbing leak, will bring even more water to the pad area, making the soil too wet and causing a myriad of other problems for the foundation.

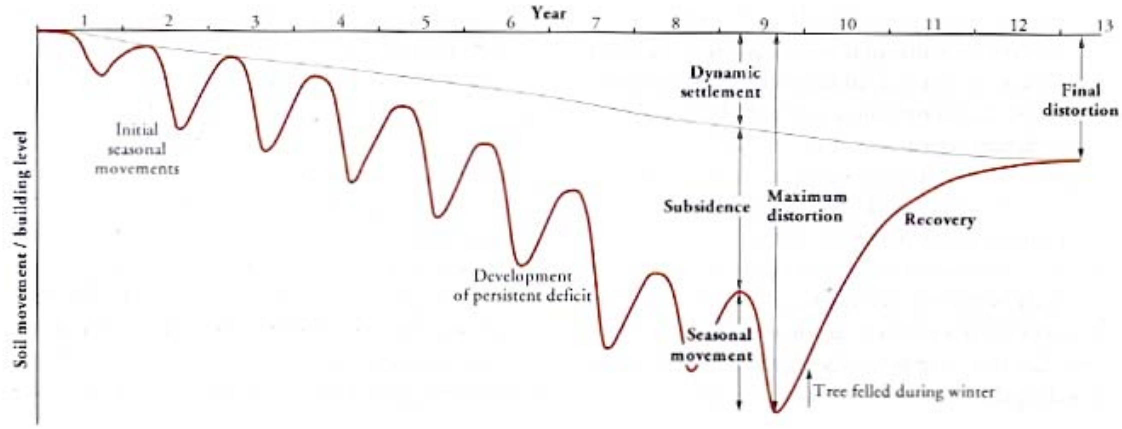
Why does subsidence occur? Subsidence is the reverse of heave. The below graphics illustrate how subsidence commonly occurs in the Houston area:

At year 1 the foundation is in place and a young tree is planted near the foundation. The soil is at a uniform moisture condition and the tree will grow. If there are gutter downspouts that exit at grade and flowerbeds installed around the house that are regularly watered, as is typical in new construction, the tree will receive extra water from the foundation side, and it will thrive.



As the tree grows, it desiccates the surrounding soils, including those soils at the edge and somewhat inward of the foundation. If poor drainage or an interior sewer leak is present, the tree will direct its roots towards and possibly under the foundation, causing the desiccation to reach even further under the foundation. As the soils subside, they take the shallowly supported foundation (i.e., a slab-on-grade or a foundation with piers founded in the moisture active zone) down with it, leading to differential movement of the foundation and distress in the superstructure. This is depicted in the above graphic. The mature tree, at ±30 years, depending on the species, has desiccated the soil, causing significant subsidence and the right edge of the foundation has subsided as well, damaging the superstructure.

The graphic below is an example of cyclical subsidence (the thick red line) of a foundation founded in clay soil due to the growth of a tree over a period of 9 years. The graphic also shows that after the offending tree is felled, the soil rehydrates over a period of several years, but it never reaches its original level. There is a portion of the downward movement labeled "Final distortion" that cannot be reversed except by adding soil.



Plot showing cyclical and permanent subsidence over time and partial heaving after tree felling. (taken from "Tree Root Damage to Buildings" by P.G. Biddle, 1998)

Note that Dr. Biddle's labeling of "Dynamic settlement" in the above graphic should not be confused with our definition of settlement. His "Dynamic settlement" is actually a final vertical distortion of the soil that is not recoverable. Also note that the label "Recovery" is the rehydration or heave that occurs when a large tree in active clay is removed.

Why does settlement occur? Settlement occurs when the vertical loads from above are in excess of the bearing capacity of the soil strata directly below the foundation, causing the foundation and superstructure to move downward. There are three common types of settlement: immediate, slope instability and long-term.

Immediate settlement, as the name implies occurs immediately upon loading due to an elastic consolidation and distortion of granular or clay soil particles. Adding a second story to a foundation designed for one-story loads may cause immediate settlement if the new loads exceed the bearing capacity of the clay soil strata beneath the foundation. The bearing capacity, directly related to shear strength, can be easily measured using a pocket penetrometer. Measurement of a clay soil's shear strength is the best indicator to determine whether or not the movement type is settlement. Minimum values for the ultimate shear strength for several types of structures are given in the table below:

Failure Shear Strength of Clays at Grade Beam Depth*

Structure Type	Ultimate Undrained Shear Strength (TSF)
1 Story Siding or Stucco	0.25
1 Story Brick Veneer	0.30
2 Story Siding or Stucco	0.25
2 Story Brick Veneer	0.40
3 Story Siding or Stucco	0.30
3 Story Brick Veneer	0.45

* Based on 12" wide grade beams, typical loading conditions, typical geometry of dimensional wood framing, standard bearing capacity theory for strip footings 12" below grade, without safety factors

Please note the more accepted method of determining undrained shear strength is a laboratory test called the unconfined compression test. However a simple field test using a pocket penetrometer gives acceptable results in the Houston area's weak, homogeneous clays. The unconfined test should be used though in cases of non-uniform sediments, such as slickensided clays. From the above table, it can be seen that even for a typical three-story brick veneer structure, settlement will not be suspect unless the pocket penetrometer readings at the grade beam bearing levels are less than 0.5 tons/square-foot.

Slope instability settlement occurs when a foundation is built upon sloped land and does not penetrate deep enough. When the slope fails due to earthquake, landslide, faults, floods, or other natural occurrences, the foundation loses part of its stability and can move down and away with the soil.

Long-term consolidation settlement is caused by gradual expulsion of pore water from voids between saturated clay soil particles.

DIAGNOSES

Who can properly diagnose the type of movement that has occurred? Only experienced forensic engineers that carry out Level C investigations have a reasonable chance to properly diagnose the movement type. We find others who perform Level A or B investigations tend to misdiagnose the type of movement.

What is a Level C investigation? In accordance with Section 3.3 of the Foundation Performance Association's Document No. FPA-SC-13-0, *Guidelines for the Evaluation of Foundation Movement for Residential and Other Low-Rise Buildings*, published 15 Jul 07 at: http://www.foundationperformance.org/, a Level C investigation includes, but is not limited to the following steps:

- Interview the occupant, owner and/or client, if available, regarding a history of the property and performance of the structure
- Document visual observations made during a physical walk-through
- Review pertinent documents including geotechnical reports, construction drawings, field reports, and repair documents
- Observe factors influencing the performance of the foundation
- Determine relative foundation elevations to assess levelness and establish a baseline
- Document locations of large trees and other vegetation
- Determine whether site drainage issues exist
- Document the analysis process, data and observations

- Site specific soil sampling and testing, if applicable
- Hydrostatic leak test, with leak location and flow test, if applicable
- Material testing, if applicable
- Post-tensioning cable testing or steel reinforcing survey, if applicable
- Aerial photographs to determine prior land usage or construction issues
- Observations of cut and fill.

If the client requests a report, it should contain the following as a minimum:

- Scope of services
- A list of the reviewed documents
- Description of factors that affect soil moisture
- Observations
- Scaled drawings
- Site photographs
- Survey elevation plan
- Detailed phenomena plan
- Results from any testing done as part of the investigation
- Discussion of factors identified as influencing the foundation performance and rationale in reaching opinions concerning the foundation
- Conclusions and recommendations for further investigation, remediation, or preventative measures

Why is monitoring used? A single site visit provides only a snapshot of the foundation's condition. Only by making more than one site visit to document distress and foundation elevation changes can an engineer determine whether a foundation continues to move. If monitoring is pursued it should follow the procedures outlined in the Foundation Performance Association's Document No. FPA-SC-12-0, *Guidelines for Evaluating Foundation Performance by Monitoring*, published 9 Jan 06 at: http://www.foundationperformance.org/.

By correlating time-change elevations with events such as climate, change in drainage patterns, distress observations, etc., it is possible to correctly ascertain the direction of movement even when an interior datum is used. When an external deep benchmark is available, it becomes easier to determine the direction of movement. Monitoring is also used to determine when heave has ended so that repairs to the superstructure can be made.

SYMPTOMS

Following are some symptoms that can help provide the basis for a forensic engineer to opine on the type of foundation movement, but not all symptoms will be present or observable.

Heave Symptoms
Following are some symptoms of heave:

- ❑ Slab cracks resemble spider webs or chicken feet with at least two intersecting cracks.
- ❑ The damage began to occur during or soon after construction, accelerating within the first few years of construction.
- ❑ Nearby trees died or were felled within a year or two that the first distress was observed.
- ❑ The driveway concrete or other flatwork adjacent to the foundation translated upward and away, relative to the foundation.
- ❑ The soil plasticity index (PI) is greater than 25.
- ❑ The moisture content (MC) of the upper soil strata below the foundation has increased in recent years.
- ❑ There are gaps between grade beams and builder's piers, or foundation repair shims are loose.
- ❑ There are no gaps between the perimeter grade beams and the adjacent soil at grade.
- ❑ There have been known leaks in the under slab plumbing or from nearby ponds or pools.
- ❑ There is a large amount of damage in the foundation and superstructure for a relatively small amount of level distortion in the foundation.
- ❑ Water meters or irrigation valve pits are submerged.
- ❑ A nearby in-ground pool is out of level.
- ❑ Site drainage around the foundation is flat or sloping toward the foundation.
- ❑ The soil just below the perimeter beam is easy to probe.
- ❑ Probing or excavating around the foundation reveals wet muddy soil in the upper several feet below the perimeter grade beam.
- ❑ Most of the damage is in the ground level flooring materials and elevations show that the slab is bowed up between grade beams when the grade beams are connected to builder's piers that are founded well below the active zone.
- ❑ Time-change elevations show the high point of the foundation to move laterally while the foundation tends to not increase its overall level distortion.

Subsidence Symptoms
Following are some symptoms of subsidence:

- ❑ Matured or maturing trees and other large vegetation are growing near the lower area of the foundation.
- ❑ Cracks in the superstructure tend to open wider in the drier months and tend to close in the wetter months.
- ❑ The foundation is at least ten years old and there are matured or maturing trees nearby that are of similar age as the foundation.
- ❑ Large tree roots are visible at grade, extending towards the structure.
- ❑ The owner is unable to maintain carpet grass below the trees near the foundation.

- ❑ The soil plasticity index (PI) is greater than 25.
- ❑ The moisture content (MC) of the upper soil strata below the foundation has decreased in recent years.
- ❑ Pocket penetrometer readings of the soil near grade is high, on the order of 4 TSF.
- ❑ Slab cracks are single lines, i.e., without intersections.
- ❑ The concrete driveway is broken up or in poor condition.
- ❑ Exterior walls tend to lean outward at the top.
- ❑ The foundation was raised around the perimeter several years prior and it now has a bowl shape with the low point near its center.
- ❑ The soil just below the grade beam is difficult to probe more than an inch or two, and is dry when excavated.
- ❑ There are no gaps between piers and grade beams.
- ❑ There are gaps between the exterior foundation grade beam and the adjacent soil at grade, particularly during the drier months.
- ❑ Time-change elevations show the level distortion of the foundation to increase with time and seasonally, particularly in drier years.

Settlement Symptoms
Following are some symptoms of settlement:

- ❑ Pocket penetrometer readings for the clay supporting a slab-on-grade at the foundation grade beam bearing level are below 0.5 TSF.
- ❑ There is more relative downward movement in areas of the foundation with higher gravity loads.
- ❑ The heavier structures in the area appear to have more damage than the lighter ones.
- ❑ Nearby flatwork, pools or other lighter structures do not show signs of movement.
- ❑ The grade soil is loamy or silty material.
- ❑ The foundation is near a steep embankment without a proper retaining wall and there are signs of soil sloughing down the slope.
- ❑ Slab cracks are single lines, i.e., without intersections.
- ❑ The soil plasticity index (PI) is less than 15.
- ❑ There are no gaps between builder’s piers and grade beams.
- ❑ The soil just below the perimeter beam is easy to probe.
- ❑ The ground surface near the foundation appears to drain quickly with little slope, tends to vibrate when excited, and also tends to become soft after heavy rains.

REMEDIES

Most foundation repairs made in the Houston area consist of segmented concrete pilings driven against the weight and stiffness of the foundation and superstructure. This repair type has performed well in active soils, largely because of its ability to penetrate deeper through the active zone than the drilled and cast-in-place piers it has replaced. The design and installation of segmented concrete piles should follow the Foundation Performance Association’s Document No. FPA-SC-08-0*, Design, Manufacture, and Installation*

Guidelines of Precast Concrete Segmented Piles For Foundation Underpinning, published 17 Jul 05 at: http://www.foundationperformance.org/.

Because segmented concrete pilings are the norm for underpinning in the Houston area, the remedies discussed below will assume this type of repair is being done. As with other underpinning concepts, segmented concrete piles are used to lift the lower parts of concrete foundations toward a more level condition. The most current standard for determining whether a concrete foundation has sufficient level distortion to be considered functionally damaged, thereby requiring this repair, is the Foundation Performance Association's Document No. FPA-SC-13-0, *Guidelines for the Evaluation of Foundation Movement for Residential and Other Low-Rise Buildings*, published 15 Jul 07 at: http://www.foundationperformance.org/. However, some owners may prefer their foundation to be more level than the above document provides.

Whatever the reason for repairing level distortion of a foundation, it is imperative to accurately understand and diagnose the movement types because their remedies may be different, as discussed below:

Heave Remedies

There are three common remedies for heave: 1) remove the source of moisture such that no heave can occur, 2) wait for the heave to run its course or, 3) lift the entire foundation so that continued heaving soil will not contact the underside of the foundation.

The first option, removing the water source, depends on the water source. It may be costly to find the source and sometimes it is not feasible to stop it. For a sewer leak, the obvious fix is to repair the leak. For poor site drainage, the fix is to repair the grade to provide proper drainage, perhaps including some underground piping for downspouts and area drains. For general wetting of soil due to rainfall or underlying soil phenomena, a moisture retarder may help.

As heave in the Houston area is most often caused by the rewetting of previously subsided soils, the second remedy, and often the most economical "fix", is to just let the heave happen; heave will continue until the soil reaches moisture equilibrium, assuming that poor drainage or leaks are not exacerbating factors. Periodic monitoring of the foundation's elevations and the superstructure's distress will allow the engineer to determine when the movement due to heave has ended. Then, if the level distortion is not within acceptable limits after the foundation has stopped moving, the foundation can be underpinned much the same as outlined for subsidence below. Typically, for heave cases it will be easier to achieve a deeper penetration (and get beyond the active zone) than if subsidence had occurred, because in a heave condition the clays tend to lose much of their shear strength and therefore they also lose some of their resistance to driving.

The third remedy, lifting the entire foundation sufficiently so that continued heaving soil will not contact the underside of the foundation is offered by some local repair contractors. It is considerably more expensive but allows these contractors to offer a warranty, which they otherwise may not offer for heave conditions. Lifting an entire foundation adds engineering challenges because the typical foundation that was originally engineered as a slab-on-grade must now be designed as a suspended structural slab foundation. In addition, there are plumbing and other interfaces to consider as well as new vertical steps at porches and at the attached garage apron/driveway junction.

Subsidence Remedies
The remedy for repairing a concrete foundation where the level distortion is due to subsidence involves removing or heavily pruning trees and other large vegetation. It is almost certain that mature vegetation is involved if the movement type is subsidence, even if on a neighbor's property. In subsidence repairs the soil is often hard, desiccated clay with a deep active zone, making it difficult to achieve sufficient penetration below the active zone to stop future subsidence particularly when the structure used for driving the piles does not weigh much.

Repair contractors normally accept these problems and offer lifetime warranties to adjust their pilings should movement continue. When subsidence is known to be the movement type, the repair contractor can reduce his call-back rate by educating the owner on the cause of subsidence and encouraging the owner to heavily prune or in some cases remove the offending vegetation, either of which can raise the active zone and help keep the piling more stationary.

Settlement Remedies
The remedy for repairing a concrete foundation where the level distortion is due to settlement is perhaps the safest of the three movement types when a lifetime warranty is offered. Knowing where the active zone ends is not of as much concern as with subsidence and heave, only that sufficient capacity is achieved during driving. The goal should be to support the foundation at a deeper stratum to achieve more bearing capacity than is available near grade.

OTHER TYPES OF MOVEMENT

There are other less common types of foundation movement occurring in the Houston area of which the forensic engineer should be aware. Though they are outside the scope of this paper, we will briefly cover active fault slippage and root heave, two movement types we have found in our work.

There are more than 350 known active faults in the Houston area, although only about one-third of these are well documented. Hundreds of structures have been built across fault lines, often inadvertently. The following photo is an example of a road and house in the Spring Branch area built across a fault line.

Fault slippage rates in the Houston area vary, with the faster ones moving about 1 inch per year. It has been found that soil and foundations near the active fault line will translate at a rate of 3 vertical to 1 horizontal, meaning that there will be walking in addition to vertical movement.

Root heave is another type of movement that can be seen in the flatwork in many areas with mature trees nearby. As the following photo shows, the tree roots can grow under the flatwork, and as the root diameter increases, the flatwork is raised. Reinforcing the flatwork can slow the movement, though a maturing tree is usually able to break up the flatwork.

Root heave in a foundation is less common in the Houston area, because roots require oxygen, and oxygen is not usually plentiful beneath a foundation. One exception occurs when the perimeter grade beam is raised for leveling purposes, as tree roots (and roots of other large vegetation) will grow under the foundation simply because they are able to. If an interior plumbing leak is present, or if the grade slopes towards the house causing water to pond near/under the foundation, then the roots will thrive and extend further under the foundation. This may lead to localized distress.

A second exception is when there are sandy soils with high bearing capacity and good oxygen transmission. In this case the grade beams and walls are typically unaffected, while the slab between the stiffening grade beams exhibits heave-like cracks. The slab movement due to root heave can occur over a short period of time. The following photos depict the diagnosis and remedy of one such case.

	A pine tree was growing too close to this house, in an area with sandy soils with high bearing capacity. Due to the high bearing capacity, as the roots grew under the foundation they were unable to fail the soil to expand downward so instead they caused cracks in the slab as they expanded upward.
	Heave-like slab cracks were visible in the slab. No distress could be seen in the grade beams or superstructure as a result of the tree. A coring was made through the an intersection of the heave-like slab cracks

	The concrete coring showed a crack that was wider at the top and did not penetrate the entire slab thickness. Were this a crack due to heave, we would expect the crack to penetrate the entire slab and into grade beams.
	Further coring revealed a portion of tree root. Based on odor and texture, it was determined to be a pine tree root, correlating with the too-close tree seen growing outside.
	The slab and rebar were removed to expose the root system. The offending tree was just behind the white wall near the top of the photo.

	The tree roots were removed.
	Select fill was brought in and properly compacted, rebar was replaced and the slab section was placed.
	Finally, the offending tree was removed to prevent a repeat performance.

SUMMARY

1. The three common foundation movement types requiring foundation repair in the Houston area are heave (up), subsidence (down) and settlement (down).

2. All three movement types in the Houston area are commonly misdiagnosed. Misdiagnosis is minimized when a forensic engineer performs a Level C investigation and when foundation monitoring is implemented.

3. Heave is the most difficult movement type to mitigate while settlement is the simplest movement to diagnose and mitigate.

4. At least a dozen symptoms are common for each type of foundation movement to help the forensic engineer identify the movement type. Regardless, when heave is present there will be an available moisture source nearby; when subsidence is present there will be mature trees or other large vegetation nearby; and when settlement is present the ultimate shear strength of the clay supporting a slab-on-grade at the grade beam bearing level will be below 0.5 TSF.

5. Remedial foundation work varies depending on the type of foundation movement present: Unless monitoring shows the movement has stopped, heave repairs often do not work and are usually not warranted by repair contractors unless the entire foundation can be lifted above the soil's potential upward movement elevation; subsidence repairs work for a period but are often difficult to maintain because offending trees are not removed or heavily pruned on a regular basis; and settlement repairs have the best chance for no call-backs from a warranty standpoint. However, settlement occurs rarely in the Houston area as compared to heave and subsidence.

6. Forensic engineers need to be aware there may be other types of foundation movement that do not fit the symptoms of the three common movement types described in this paper. Two examples given in this paper are active fault slippage and root heave.