

SECTION 3 – CAUSATIVE FACTORS

3.1 Overview

Freeman et al. (1994) suggests foundation movement may result from a wide range of factors, which can include: (1) compression of a soft layer in the ground as a result of the applied foundation or perimeter loads; (2) shrinkage and swelling of clays caused by changes in moisture content; (3) soil softening; (4) compression of filled ground; (5) frost heave; (6) variations in groundwater level; (7) erosion; (8) nearby construction or excavation; (9) chemical attack on foundations; (10) collapse of mine workings or natural cavities; and (11) vibration. Interestingly, nearly all these factors (except item 9) were suggested by homeowners, engineers, town officials, and others during the course of this study. The first six factors are perhaps the most pertinent to Amherst.

Aside from soil conditions, Meehan and Karp (1994) describe housing damage related to expansive soils in California as one where marginally effective foundation designs have led to differential foundation movements. Diaz et al. (1994) suggests inadequate design of basement walls before construction probably accounts for 75 to 85 percent of all problems in residential structures in Ohio. In this study, the mode of basement wall failure and computer modeling also suggest that marginally effective foundation design is a related factor for basement failure in Amherst.

With the constraints of a one-year field investigation, we elected to separate foundation problems into two broad classes based on the predominant damage characteristics. The two classes – *lateral pressure* and *differential settlement* – represent basement failure caused by horizontal and vertical movements. Both classes have numerous potential but generally few primary causative factors. Our investigation attempts to demonstrate the potential for or existence of primary causative factors. Therefore, we did investigate every potential factor (e.g., vibration).

3.2 Lateral Wall Pressure

Four sources likely contribute to lateral pressures on basement walls in Amherst: (1) pressure from soil weight, (2) pressure from soil swell, (3) hydrostatic pressure, and (4) pressure from frost. Identifying lateral pressure damage is not particularly difficult, but accurately quantifying the contribution from each source to past maximum lateral pressures is very difficult. In addition, the four sources depend upon numerous factors that vary throughout the life of any given wall. This section describes each source in greater detail.

3.2.1 Symptoms

The inward bowing of a basement wall is the simplest indication of a lateral pressure problem. The bowing generally occurs when external forces exceed the wall

strength and/or the strength of the wall supports. Along the length of the wall, the maximum bowing will often occur near the center of the wall because the adjoining perpendicular walls provide support in the corners. Photo 5 shows a typical bowing wall. If bowing becomes severe, basement walls can collapse inward.

Cracking can also occur when stresses induced by lateral pressure exceed the strength of the concrete or CMU wall. The most common crack pattern originates in the corners and radiates up or down at approximately 45-degree angles. For CMU walls, the cracks propagate along the mortar joints in a stair step pattern. Often these cracks terminate at a long horizontal fracture that parallels the basement floor about two-thirds the way up the wall. The third crack type is vertical and is located near the mid-span (major), but minor cracks can form near the corners (Photos 4, 5, 6). Many cracks have telltale offset that indicates relative movement of the two wall sections.

Excessive lateral pressure can affect the overall integrity of a house. Severe damage results in a visible opening between the superstructure and the top of the basement wall. Like other major fractures, water and pests can easily enter the basement. Exceptional movement destroys a portion of the sill plate and wood frame of the house. In extreme cases, the sill plate loses its support and downward movement of the wood frame occurs.

3.2.2 Soil Weight

Due to a difference in elevation between the outside ground surface and the basement floor, a basement wall supports an adjacent mass of soil, preventing the soil from entering the basement. Therefore, the weight of the retained soil mass induces lateral pressure on the basement wall. Lateral pressure from soil weight is typically considered during design of engineered basement walls using theoretical at-rest earth pressures.

3.2.3 Soil Swell

Soils containing clay undergo volume change when the moisture content of the soil changes (Section 1.5.6.5). When expansive soils are placed against basement walls, the swelling of these soils can induce lateral pressures not typically accounted for in design and construction of walls. For example, swelling pressures from marine clay backfill soils have reportedly damaged basement walls in Northern Virginia (DPWES, 2002). These marine clay backfills often go through several yearly cycles of shrinking and swelling before damaging the walls, and lateral pressures are believed to increase over time due to gradual settlement and infilling of shrinkage cracks. Cyclic shrink/swell can also reduce the shear strength of the backfill and thereby increase lateral earth pressures.

According to Section R403.1.8.1 of the *Residential Code of New York State* (NYS DOS, 2003), soils meeting all four of the following provisions are classified as expansive:

1. Plasticity Index (ASTM D 4318-00) of 15 or greater

2. More than 10 percent of the soil particles pass the No. 200 sieve
3. More than 10 percent of the soil particles finer than 0.005 mm
4. Expansion Index (UBC Standard 18-2) greater than 20.

In order to characterize backfill materials in Amherst for this study, hand auger borings were placed adjacent to nineteen basement walls sites in Amherst to obtain representative samples of backfill. Seventeen of the nineteen basement walls exhibited damage related to lateral pressure. Figure 28 shows the boring site locations. Composite backfill soil samples were tested to facilitate expansive soil classification in accordance with Section R403.1.8.1 of the *Residential Code of New York State* (NYS DOS, 2003). The results of laboratory testing for backfill soils are presented in Table 8.

The expansive soils criteria described above are provided at the bottom of Table 8. Note that all backfill soil samples satisfy all four criteria and are classified as expansive (column 16). The potential expansion rating (ASTM D4829-03) for all but one of the backfill samples ranged from *medium* to *high*. These results indicate that the backfills used at many Amherst sites contain expansive soils.

3.2.4 Hydrostatic Pressure

Hydrostatic pressure is pressure exerted by a fluid due to its weight. Hydrostatic pressure against a basement wall develops when water fills the void spaces within the backfill immediately adjacent the wall. Water buildup against basement walls was confirmed in a survey of 41 homeowners who reported having moderate (43%), some (17%), or minor (14%) leaking. We observed and homeowners described evidence of water buildup that included spurting, dripping, dampness, or efflorescence (salt residual). Other homeowners described leakage during rain events, in the crawl space, and around wall anchors. The following conditions can promote water accumulation against basement walls in Amherst:

- Allowing the ground surface to pitch toward the basement walls. This problem tends to worsen with time after construction because backfill materials adjacent to basement walls typically consist of clay soils (Table 8) classified as silty clay (CL) or fat clay (CH). Clay backfills are very susceptible to densification and subsequent settlement with time as clumps of clay break down. Evidence of post-construction settlement of backfill is widespread in Amherst, and the result is a depression where surface water tends to accumulate.
- Approximately 27% of all inspected homes had detached downspout/gutter systems that discharge water onto the backfill soils adjacent to basement walls.
- Subsurface drains were not installed against the exterior of basement walls of many older houses in Amherst.
- Desiccation cracks, which channel water against basement walls, are common in clayey backfill materials in Amherst.

For newer houses where subsurface gravel drains are installed adjacent to wall footings, drainage of water through the relatively impervious clay backfill soils to the gravel drain is not ensured. If the gravel drain is not protected with a suitable filter

fabric, the drain can clog over time as soil is carried into the drain by water moving through the backfill. The effectiveness of a gravel drain for removing water from backfill will be reduced by clogging. Approximately 9 of 52 older houses reported having a drain tile repair.

It is clear that the potential exists for hydrostatic pressures to buildup against basement walls in Amherst due to the factors presented above. Like soil swell, lateral hydrostatic pressure is not typically considered during design and construction of basement walls.

3.2.5 Frost

Water accumulation in backfill soils against basement walls in Amherst is common. If this water freezes, large lateral pressures may develop against basement walls as the freezing water expands. Damage from frost-induced lateral pressure on basement walls in Ohio has been reported by Diaz et al. (1994). The potential depth of frost penetration in Amherst is 3.5 to 4 feet (USACE, 1992). However, lateral pressures from frost may be uncommon because of heat loss from houses combined with the insulating effects of snow. Nonetheless, the potential exists for frost-induced lateral pressures, which are not typically considered during design and construction of basement walls.

3.2.6 Summary

Clay-rich soils often present long-term problems as backfill materials. Their lumpy, cohesive nature, as produced by common excavation techniques, makes it difficult, if not economically or practically impossible to recompact them to states of uniform moisture content and density that will ensure minimum future settlements, minimum swelling potential, minimum hydrostatic pressures, and thus minimum lateral pressure. Beyond the obvious problems of large and protracted surface settlements, clay backfills require significantly stronger basement walls to withstand the larger horizontal earth pressures (CMHC, 2004; Jalla, 1999).

3.3 Settlement

Structural settlement is characterized as either total and/or differential settlement. Total settlement is the magnitude of downward movement. Differential settlement is the difference in vertical movement between various locations of the structure causing distortion of the structure. Generally, the magnitude of total settlement is not a critical structural factor as long as it is uniform. Even relatively small differential settlements can cause cracks in floor slabs, exterior masonry walls, and wall finished with plaster or drywall. Differential settlement can also interfere with the function of the structure.

Settlement can be tolerated in most residential structures provided it is within certain specified limits. A small amount of settlement, including differential settlement, is usually anticipated. However, when houses are constructed on very poor soils where the potential for excessive settlement exists, special procedures must be employed to

limit the amount of settlement and/or provide a structure that can tolerate the estimated settlement (Whitlock and Moosa, 1996).

3.3.1 Symptoms

Several damages that result from settlement are described in Section 2.4.2. Total settlement of houses can damage connections to outside utilities, interfere with drainage of surface water away from houses, and/or interfere with the effective functioning of entryways. Differential settlement can cause wood-framed floors to become out-of-level and framed walls and other components can become distorted and distressed. In addition to measured differential settlements, other symptoms include cracking of basement/foundation walls, cracking of concrete slabs, and deflection of structural members directly supported by footings.

Differential movements along strip footing supporting basement/foundation walls can cause walls to crack. Wall cracking associated with differential settlement can be difficult to distinguish from wall cracking caused by lateral pressure (see Diaz et al., 1994, and Freeman et al., 1994). Wall cracks associated with differential settlement tend to extend through the full thickness of the wall and tend to be nearly vertical or diagonal. Diagonal cracks with a stair-step pattern are common in concrete block walls. Diagonal cracks induced by differential settlement are caused by the wall segment on the bottom side of the crack moving down relative to the wall segment on the upper side of the crack. Close examination of vertical cracks will often indicate the relative direction of differential movement across the crack. Rotation associated with differential settlement may result in wider crack thickness at the top of the wall relative to the bottom.

3.3.2 Allowable Settlement

Typically, three types of settlement can affect the performance of a house foundation system in Amherst. The three types of settlement include; 1) total settlement of the house, 2) general differential settlement across the foundation footprint, and 3) differential settlement along the longitudinal axis of perimeter strip footings.

According to *Settlement Analysis* (USACE 1990), total settlement should not exceed 2 inches for most facilities, and a typical specification of total settlement is 1 inch to prevent problems associated with total settlement.

Differential settlement can be quantified in terms of angular distortion. Angular distortion is vertical settlement divided by the horizontal distance over which the settlement occurs. Poulos et al. (2002) suggests angular distortion of 1/250 to 1/150 as an allowable range for preventing structural damage in framed buildings. Meehan and Karp (1994) discuss allowable differential settlements for wood-framed slab-on-grade houses. They suggest that floors experiencing angular distortion of between 1/240 and 1/120 usually indicate post-construction movement with associated damage – cracking of walls and ceilings, sticking doors, etc. In addition, they suggest that angular distortions exceeding 1/120 are usually associated with moderate to severe damage for typical residential buildings. Duncan (1993) suggests that architectural damage, which implies

impairment of aesthetics or function, seldom occurs if the angular distortion is less than 1/500.

The most damaging type of differential settlement related to house foundations in Amherst may be caused by differential settlement along the longitudinal axis of perimeter strip footings that support perimeter basement/foundation walls. Differential movements along strip footings can cause walls to crack, allow water to leak in, decrease the capacity of walls to resist lateral pressure, redistribute structural loads causing concentration of loads on portions of footings, and cause progressive structural deterioration.

Unreinforced basement/foundation walls are much more susceptible to significant cracking due to differential settlement than are reinforced walls. Poulos et al. (2002) suggests limiting angular distortion to between 1/2500 and 1/1250 to prevent unacceptable cracking of unreinforced bearing walls, i.e., where the end of the wall settles relative to the midspan. For reinforced bearing walls, the angular distortion should be limited to 1/500 to prevent unacceptable cracking (Poulos et al., 2002).

The use of angular distortion to define allowable differential settlements excludes many important factors (Poulos et al., 2002). A more rational but complicated approach would involve consideration of flexural and shear stiffness of house sections, degree of slip between the foundation and the underlying soils, and house configuration. In addition, the level of distress induced by differential settlement can be affected by the rate at which the settlement occurs (Feld, 1965). Relatively high rates of differential settlement can induce more damage than slower rates of settlement due to the inability of a structure to adjust to rapidly changing foundation support conditions.

3.3.3 Differential Settlement

Figures 7 and 8 shows that house footings built in Amherst's lacustrine soils are typically positioned on the stiff silty clay stratum (hereafter, *stiff stratum*). In many places, the stiff stratum is underlain by firm grading to very soft clay (hereafter, *soft stratum*). *Both the stiff stratum and the soft stratum can contribute to differential settlements of houses* as discussed below. Differential settlement in this section refers to any relative vertical movement between/along footings, including upward and downward movements.

3.3.3.1 Stiff Stratum

Soil volume change due to changes *in soil moisture content* is the primary settlement-related issue for the stiff stratum. Foundation settlement or heave occurs when the moisture contents of soils supporting the foundation change after construction. If the changes in moisture content are not laterally uniform across the footprint of the foundation, differential settlement will occur. Due to the relatively low permeability of the stiff stratum and dynamic causative factors, post-construction changes in foundation soil moisture content can occur from months to decades after construction (see Table 2).

3.3.3.1.1 General Characterization

Soil samples were obtained from stiff soils beneath house foundations at fourteen sites across Amherst (Figure 29). Stiff lacustrine soils were encountered below the typical footing bearing elevations at all of the sites on Figure 29 except sites 5, 13, and 27. Soils immediately below footings at site 5 were generally firm rather than stiff. Foundation soils at sites 13 and 27 consisted of till. Twelve samples of stiff foundation soils were subjected to laboratory testing to facilitate expansive soil classification in accordance with Section R403.1.8.1 of the *Residential Code of New York State* (NYDOS, 2003). Figure 29 shows the sampling locations, and Table 9 shows the results of laboratory testing. All samples were from lacustrine soils except at sites 13 and 27, which were from glacial till. The criteria used to classify expansive soils are provided in Table 9. All of the lacustrine samples satisfy all four criteria and are classified as expansive soils (column 16). The potential expansion rating for lacustrine soils ranged from medium to high (column 12). The two glacial till samples had potential expansion ratings of low and very low. In summary, the stiff stratum is comprised of expansive soils and foundations placed on the stiff stratum are susceptible to differential settlements caused by moisture-related volume changes.

Regarding the expansive soil criteria, the laboratory test results (Tables 8 and 9) suggest that plasticity index is the most sensitive criterion. That is, if the plasticity index is 15 or greater, the remaining three classification criteria are exceeded. Anderson and Lade (1981) report good correlation between expansion index and both liquid limit and plasticity index. We correlated the 36 expansion index tests with the liquid limit and plasticity index results (Figure 30 and 31). These results suggest that expansion index, which is a relatively time-consuming and expensive test, can be reasonably estimated using liquid limit and/or plasticity index.

3.3.3.1.2 Vertical Strain and Moisture Content

In general, the volume of the stiff stratum changes with moisture content. The vertical component of volume change, hereafter referred to as vertical strain, can induce settlement/rebound of overlying foundations. Shrink testing (Briaud et al., 2003) can be used to estimate the relationship between vertical strain and moisture content. Shrink testing involves measuring the moisture content and corresponding sample volume as an undisturbed sample is dried in the laboratory.

The undisturbed shrinkage limit can be estimated from shrink testing. At moisture contents above the undisturbed shrinkage limit, volume change is approximately linearly proportional to moisture content (Briaud et al., 2003). For conditions dryer than the undisturbed shrinkage limit, the change in volume is relatively small. For conditions moister than the undisturbed shrinkage limit, the slope of the vertical strain versus moisture content line is referred to as the vertical shrink-swell coefficient, or S_v . S_v equals the amount of vertical strain for each percentage point change in moisture content.

Six shrink tests were performed on undisturbed soil samples of the stiff stratum. Undisturbed samples were collected from open excavations across Amherst using a 3-inch diameter drive-cylinder (Photo 7).

Shrink test results are presented in Table 10, and sampling location are shown on Figure 29. All the samples satisfy the expansive soils criteria (column 12) and have a potential expansion rating of medium (column 10). The undisturbed shrinkage limits determined from shrink testing are presented in column 15, and the calculated values of S_v are presented in column 16. The average value of S_v is 0.61. Therefore, we estimate that soils comprising the stiff stratum experience approximately 0.6% vertical strain for each percentage point change in moisture content.

Alternatively, the vertical shrink-swell coefficient can be theoretically estimated. In theory, in-situ clay is fully saturated or nearly saturated when the moisture content exceeds the undisturbed shrinkage limit. The shrink test results for undisturbed samples collected in Amherst support this statement and samples were saturated or nearly saturated above the undisturbed shrinkage limit (see Briaud et al., 2003). If water and soil solids are considered to be incompressible, volume change of the saturated soils due to changes in moisture content simply equals the volume of water gained or lost. If strain is equal in all directions, the theoretical vertical shrink-swell coefficient can be calculated using the following equation:

$$S_{v(\text{theor})} = \gamma_d / 3\gamma_w$$

where,

$S_{v(\text{theor})}$ = theoretical vertical shrink-swell coefficient

γ_d = dry unit-weight of the soil

γ_w = unit-weight of water

$S_{v(\text{theor})}$ values for the six shrink test samples are presented in column 17 of Table 10. In general, S_v determined via shrink testing approximates $S_{v(\text{theor})}$. The average S_v is 0.61 compared with the average $S_{v(\text{theor})}$ of 0.54. In general, S_v exceeds $S_{v(\text{theor})}$ due to anisotropic strain.

3.3.3.1.3 Foundation Soil Moisture Content

As discussed above, S_v defines the relationship between moisture content and vertical strain. If soil moisture contents beneath a house foundation are laterally uniform at the time of construction, subsequent laterally variable changes in foundation soil moisture content will induce differential settlements. Therefore, current lateral variations in soil moisture content beneath the footprint of a house would suggest that post-construction changes in foundation soil moisture content could or have contributed to observed differential settlements.

Potential lateral variations in foundation soil moisture content were investigated at five sites in Amherst. At four of the five locations, evidence of post-construction differential settlement between perimeter basement strip footings and interior basement spread footings was observed. Differential settlement at the remaining site consisted of settlement of one perimeter basement strip footing relative to other footings. Magnitudes of observed differential settlements ranged from approximately 2 to 5 inches.

At each site, a hand auger boring was used to obtain soil samples beneath and adjacent to both the relatively low footing and the relatively high footing. A piece of the concrete floor slab was removed to gain access to soils near interior footings. A hand auger was advanced and discrete soil samples were generally collected every 6 inches. The discrete soil samples were subjected to laboratory moisture content testing.

At three of the five locations, moisture content testing indicated that foundation soils beneath the relatively low footing were significantly drier than those beneath the relatively high footing. Figures 32 and 33 show lateral moisture content variations between interior and perimeter foundation soils at Site 7 and Site 4, respectively (Figure 28 and 29 show site locations). Assuming that moisture contents of foundation soils were laterally uniform prior to construction, the existing measured moisture content profiles at these sites suggest post-construction changes in foundation soil moisture content have contributed to observed differential settlements.

3.3.3.1.4 Estimated Differential Settlement

Using S_v determined by shrink testing, the change in thickness of a soil stratum due to changes in soil moisture content can be estimated if the change in soil moisture content is known. The equation used to estimate the change in thickness of a soil stratum is:

$$\Delta h = h_o S_v \Delta w$$

where,

Δh = change in thickness of soil stratum;

h_o = initial thickness of soil stratum;

S_v = slope of vertical strain vs. moisture content plot as determined by shrink testing;

Δw = average change in moisture content in soil stratum.

Assuming that foundation soil moisture content was laterally uniform at the time of construction, post-construction differential movements resulting from development of the measured moisture content profiles at Site 7 and Site 4 are calculated using the preceding equation. An average S_v value of 0.61 was assumed based on shrink testing of undisturbed samples (Section 3.4.3.1.2.) The calculated differential movements at sites 7

and 4 are 1.9 and 1.8 inches respectively. Calculations are provided in the Appendix 6.6. These calculated differential settlements would produce angular distortion of 1/128 and 1/102. Recall, Meehan and Karp (1994) suggest limiting angular distortion of floors to 1/240 to avoid damage in wood-framed houses.

The calculated magnitudes of differential movement at Sites 7 and 4 only consider moisture content variations down to 4 and 5 feet below footing elevation, respectively. Moisture content variations likely continue below these depths. Moisture content variations below these depths will increase the magnitude of calculated differential settlements beyond those calculated. Furthermore, soil samples were collected in early July 2004 during a relatively wet summer season. We speculate moisture content variations between interior and exterior foundation soils have been more severe during past periods of drier weather.

3.3.3.1.5 Moisture Content Changes

If the moisture content in the stiff stratum beneath a house changes after the house is constructed, the soils will shrink and/or swell, and foundation settlement and/or heave will occur. Post-construction moisture content changes in the stiff stratum are generally controlled by four factors including, 1) concentration and mineralogy of clay in the soil, 2) water availability, 3) confining pressure, and 4) initial moisture content. Each of these factors is discussed below.

3.3.3.1.5.1 Concentration and Mineralogy of Clay

Laboratory determinations of the clay-sized fraction, liquid limit, plasticity index, unified classification, and expansion index reflect expansive potential due to clay concentration and mineralogy. The combined laboratory test results for soils collected from the stiff stratum (Table 9) indicate medium to high potential for changes in soil moisture content and corresponding shrinkage and/or swelling.

3.3.3.1.5.2 Water Availability

When free water is available to the stiff stratum, it is more susceptible to hydration and swell. The removal of water or the absence of free water makes the stiff stratum more susceptible to desiccation and shrinkage.

Sources of water available to the stiff stratum include infiltration of surface water and capillary rise from the groundwater table. Varved clays contain silt seams that promote the movement of groundwater into and out of the stiff stratum. Leaking utility lines can also feed water to the stiff stratum. Evaporation, transpiration, and subsurface drainage reduce the amount of water available to the stiff stratum and can remove water from the stiff stratum.

Site development and typical house construction can significantly alter water availability. The following factors can increase the amount of water available to the stiff stratum as a result of site development and house construction.

- It is common for water to collect in basement excavations during construction.
- Water accumulation within backfill soils adjacent to basement walls and foundation walls is common (Section 3.2.4).
- Water can collect in gravel beneath basement slabs.
- Water can accumulate in relatively loose and/or relatively pervious soils used to backfill utility trenches.
- Leaking utility lines can feed water to the stiff stratum.
- A basement slab will reduce the evaporation rate beneath the slab.
- Watering of plantings adjacent to a house can feed the stiff stratum with water.

As a result of site development and house construction, the following factors can decrease the amount of water available to the stiff stratum or remove water from the stiff stratum.

- Sump pumps and foundation drainage systems can remove water.
- Roots from trees and vegetation can remove water.
- Surface grading, pavement, and storm sewage collectors can reduce infiltration.
- Relatively loose and/or relatively pervious soils used to backfill utility trenches can intercept and remove groundwater.

3.3.3.1.5.3 Confining Pressure

The stiff stratum is more susceptible to absorbing water and swelling at lower confining pressures than at higher confining pressures. To investigate the effects of confinement on swell potential, two undisturbed soil specimens obtained from the stiff stratum at Site 31 were subjected to swell testing at different confining pressures. Table 8 shows that soil from Site 31 is representative of the stiff stratum at other sites in Amherst. Swell testing of the undisturbed specimens involved applying a confining pressure to the specimen prior to inundating it with water in accordance with ASTM D 2435-03. The moisture content of the specimen confined with 1800 pounds per square foot (PSF) increased 0.3 percentage points and exhibited one-dimensional swell of 0.09% after being inundated. The moisture content of the specimen confined with 400 PSF increased 1.8 percentage points and exhibited one-dimensional swell of 0.91% as a result of inundation. These results demonstrate that confining pressure significantly influences the ability of the stiff stratum to absorb water and swell.

3.3.3.1.5.4 Initial Moisture Content

Portions of the stiff stratum that are initially relatively moist during house construction are more susceptible to post-construction desiccation and shrinkage. Conversely, foundation soils that are initially relatively dry are more susceptible to post-construction hydration and swell. Therefore, the initial moisture content of foundation soils influences the potential for post-construction moisture content changes. For example, if water accumulates in a basement excavation for an extended period of time during construction, the foundation soils may become relatively moist. If post-construction conditions promote desiccation of the foundation soils, the foundation soils will shrink and settlement will occur. Conversely, if the basement excavation remains relatively dry during and after construction, the same post-construction conditions are less likely to cause desiccation and shrinkage of the foundation soils.

3.3.3.1.5.5 Laterally Variable Moisture Content Changes

If the moisture content in the stiff stratum beneath a house changes after the house is constructed, the soils will shrink and/or swell and foundation settlement and/or heave will occur. If moisture changes are laterally variable across the foundation footprint, differential settlements will occur. Several factors promoting laterally variable moisture content changes and corresponding differential settlements are described below:

- Confining pressure on the stiff stratum beneath a typical house foundation can vary significantly across the foundation footprint.
- Typically, basement excavations are not consistently sloped to achieve positive drainage to the sump. During and after the house is constructed, water may enter the excavation and begin to permeate into and moisten foundation soils. In areas with positive drainage, ponded water is only temporary. However, in areas without positive drainage, water may pond for extended periods of time, resulting in laterally variable moisture content changes.
- A common situation promoting laterally variable moisture content changes is when footings are located at different elevations. For example, strip footings supporting crawl-space foundation walls are typically located higher in the soil profile than strip footings supporting basement walls. The amount of water available to soils beneath crawl-space footings is more likely to fluctuate on a seasonal basis. Furthermore, confining pressures beneath crawl-space footings are generally less than those beneath perimeter basement wall footings (Photo 8).
- Concrete slabs influence evaporation, infiltration, and transpiration variably across the foundation footprint. For example, during prolonged dry periods, evaporation and transpiration may remove moisture from perimeter foundation soils while a concrete slab restricts moisture loss from interior foundation soils.
- Trees or other vegetation near foundation walls intercept and remove moisture from beneath their canopy. Normally 90 percent of a tree's root system is within two feet of the ground surface (Biddle, 2001), but roots are opportunistic and will

- proliferate where conditions are most conducive for obtaining water. We observed root hairs in the sump pits at a few houses (Photo 9).
- Negative surface drainage or other sources may feed foundation soils with water nonuniformly across a foundation footprint.
 - The initial moisture content of the stiff stratum can vary laterally across the foundation footprint prior to construction. For example, soils below large trees, which are removed during construction, may initially be drier than other foundation soils due to transpiration (Meyer and Read, 2001)
 - Foundation drainage systems may remove water near the sump pit and/or adjacent to perimeter footings while failing to remove water beneath interior areas of the basement.
 - Cyclic drying and wetting of foundation soils combined with variable confining pressures across the foundation footprint can promote laterally variable moisture content changes and differential settlements. Soils beneath slabs and relatively lightly-loaded footings are relatively lightly confined. After these soils dry and shrink, the lack of confining pressure allows them to absorb water and swell when water is reintroduced. Confining pressure for foundation soils beneath relatively heavily loaded footings is much greater. As such, after these soils dry and shrink, the relatively high confining pressure prevents these soils from absorbing water and swelling when water is reintroduced
 - Soil temperature can influence soil moisture content (Nelson et al., 2001), therefore temperature gradients beneath a foundation footprint may contribute to laterally variable moisture content changes.

3.3.3.1.6 Summary

Many house footings in Amherst are resting on the stiff stratum that is comprised of expansive soil (Photo 7,10). In general, volume change will occur with changes in soil moisture content. Measured lateral variations in foundation soil moisture content at several sites in Amherst suggest that post-construction changes in moisture content have contributed to the observed differential settlements. Post-construction moisture content changes in the stiff stratum are generally influenced by four factors that include: 1) concentration and mineralogy of clay in the soil, 2) water availability, 3) confining pressure, and 4) initial moisture content. There are numerous factors that promote laterally variable changes in moisture content across the foundation footprint.

3.3.3.2 Soft Stratum

Like the stiff stratum, changes in moisture content in the soft stratum will result in volume changes. Unlike the stiff stratum, the soft stratum is sufficiently below the seasonally fluctuating water table to maintain a relatively stable soil moisture content. Therefore, variations in moisture content within the soft stratum primarily depend on changes in confining pressure, which is commonly referred to as effective stress. An increase in effective stress will squeeze water out of the clay resulting in settlement. Conversely, a reduction in effective stress will result in rebound, which pulls water into the soil. The strain response of clay soils due to changes in effective stress is *gradual*

because fluid must migrate to/from void space in the soil. This gradual strain response is known as primary consolidation.

In order to characterize soils from the upper portion of the soft stratum, samples were collected at six sites across Amherst using a hand auger. Laboratory test results and sampling locations are shown in Table 11 and Figure 29 respectively. In general, the samples collected from the soft stratum exhibit higher plasticity than samples collected from the overlying stiff stratum.

The soft stratum was further characterized by investigating the stress-strain behavior of undisturbed samples collected with a drill rig from four sites in Amherst. Laboratory consolidation test (ASTM D 2435-03) results were used to investigate the strain response of the soft stratum due to changes in effective stress. Sampling at sites 30 and 31 was performed in late 2004 with project funding (Figure 29). Laboratory test results for samples collected from sites 29 and 32 were obtained from existing geotechnical engineering reports (Ward, 1973; Daigler, 2004). Table 12 summarizes the consolidation test results. Compression ratios ranged from 0.15 to 0.26, and recompression ratios ranged from 0.015 to 0.025. These results are in agreement with McGuffey et al. (1981), who published results of consolidation testing performed during design of the Lockport Expressway in Amherst. Compression ratios reported by McGuffey et al. (1981) for 68 consolidation tests performed on samples of the soft stratum ranged from 0.13 to 0.35, with a mean of 0.23. Recompression ratios reported for 19 consolidation tests performed on samples of the soft stratum ranged from 0.014 to 0.031, with a mean of 0.022 (McGuffey et al., 1981).

McGuffey et al. (1981) found that the soft stratum is overconsolidated at the top of the stratum, and the apparent preconsolidation stress decreases with depth. The laboratory test results presented in Table 12 are consistent with their findings. Columns 7 and 8 indicate that samples collected from a depth of 14 feet to 17 feet were over consolidated, and samples collected from greater than 20 feet were normally consolidated. We speculate that a historical drop(s) in the groundwater table and desiccation are responsible for the apparent overconsolidation in the upper levels of the soft stratum.

The consolidation test results can be used to estimate the strain response of the soft stratum due to various loading conditions. If the soft stratum beneath a house strains non-uniformly across the foundation footprint, differential settlement/rebound will occur. There are at least three potential loading conditions that can contribute to non-uniform straining of the soft stratum beneath houses in Amherst including 1) removal of soil from basement excavations during construction, 2) raising lots with significant amounts of new fill around the perimeter of houses, and 3) long-term lowering of the groundwater level.

In order to evaluate the potential for these loading conditions to induce significant magnitudes of settlement and/or rebound, we considered a hypothetical house at Site 29. Figure 34 shows a schematic drawing of the hypothetical square house located within a 30' x 30' x 6' basement excavation. Four specific load cases are described below:

- Load Case I – This load case considers only rebound induced by the difference in weight between the excavated soil and the house. It is assumed that 50% of the rebound occurs after excavation but prior to foundation construction.
- Load Case II – Load Case I combined with the addition of 2 feet of fill placed around the perimeter of the house after construction.
- Load Case III – Load Case I combined with a 4-foot drop in the water table after construction.
- Load Case IV – Load Case II combined with a 4-foot drop in the water table after construction.

For settlement analyses, the soft stratum was divided into two substrata. Consolidation test results for samples collected from the middle of each substratum at Site 29 were used to estimate the strain response of the substratum due to changes in effective stress induced by the various loading conditions. Changes in effective stress at the middle of each substratum were estimated using Boussinesq analysis. Settlement/rebound calculations are included in the Appendix 6.6.

3.3.3.2.1 Load Case I

If house construction involves a significant amount of excavation to facilitate basement construction, the weight of excavated soil typically exceeds the weight of the house and its contents. For example, the combined total live and dead weight for a 30' x 28' rectangular two-story house with basement is approximately 80 tons (Willenbrock et al., 1998). Assuming the basement slab and loading on the basement slab contribute an additional 20 tons, the total weight supported by underlying foundation soils is approximately 100 tons. Soils removed from a 30' x 28' x 6' basement excavation weigh approximately 300 tons - nearly 3 times the combined live and dead weight of the house. Therefore, the soft stratum beneath the basement generally “feels” less stress after construction of the house than it did prior to construction due to removal of the weight of the excavated soil. The degree to which the soils beneath the basement are unstressed varies across the basement footprint. For example, soils beneath the center of the basement are unstressed significantly more than those soils beneath the corners of the basement. This unbalanced unloading will result in differential rebound of the soft stratum.

For the hypothetical house and subsurface conditions illustrated in Figure 34, a net average pressure reduction of 480 PSF at the base of the basement excavation is realized due to the difference between the weight of the excavated soil and the live and dead weight of the house. The soft stratum will rebound as a result of this pressure reduction.

As previously discussed, the strain response of clay to changes in effective stress occurs gradually. The results of consolidation testing at sites 30 and 31 were used to estimate the coefficient of consolidation during unloading. Laboratory coefficients of consolidation for the soft stratum during unloading were calculated to be approximately

0.1 feet²/day. Based on this information, the time required to achieve 50% rebound due to excavation is approximately 200 to 400 days. However, relatively pervious silt seams within the soft stratum likely cause pore pressures to equilibrate faster than predicted by consolidation theory, and rebound will probably occur significantly faster than predicted by laboratory consolidation testing. Therefore, considering the conceptual nature of the calculations, it is reasonable to assume that 50% of the rebound occurs after house construction is completed. Using this assumption, the magnitudes of post-construction rebound are calculated for various locations across the footprint of the house. The calculated magnitudes of post-construction rebound at the center of the basement, wall midpoints, and the corners of the basement are presented for Case I in Table 13, and the corresponding magnitudes of angular distortion are presented for Case I in Table 14.

3.3.3.2.2 Load Case II

Many homes in Amherst, both past and present, use one to four feet of fill to raise the surface elevation of the lot (Photo 11). When the new grade is significantly higher than the pre-construction grade, the soft stratum beneath the perimeter of the basement “feels” the weight of the new fill much more than soils beneath the center of the basement. The degree to which the soils beneath the basement are stressed by the placement of perimeter fill varies across the basement footprint. For example, soils beneath the center of the basement are stressed significantly less than soils beneath the corners of the basement. This unbalanced stressing will result in differential settlement.

Case II considers the hypothetical house (Figure 34) and the combined strain response of the soft stratum due to basement excavation and placement of 2 feet of fill adjacent to basement walls. The combined effects of basement excavation and perimeter filling result in rebound at the center of the basement and settlement at the perimeter. The magnitudes of rebound/settlement and angular distortion are presented in Tables 13 and 14.

3.3.3.2.3 Load Case III

Section 1.5.8 suggests that groundwater elevation in the middle soil zone may fluctuate several feet during some periods and that land development can impact the hydrologic budget of an area. Here we consider how a drop in the groundwater level within the soft stratum beneath houses can contribute to laterally variable straining of the soft stratum. As the groundwater level drops, previously submerged soils become effectively heavier due to a loss of buoyancy. The increase in effective weight of these soils increases effective stresses in the soft stratum. Also, a drop in the groundwater level within the soft stratum will induce negative pore pressures in the previously submerged soils that remain saturated due to capillarity. The negative pore pressures increase effective stresses in the capillary zone. In short, a drop in the groundwater level within the soft stratum increases effective stresses in the soft stratum due to a combination of loss of buoyancy and negative pore pressures.

For the hypothetical house (Figure 34), the combined strain response of the soft stratum due to basement excavation and a 4-foot drop in the water table results in varying magnitudes of settlement across the basement footprint. The magnitudes of settlement and angular distortion are presented in Tables 13 and 14.

3.3.3.2.4 Load Case IV

Case IV considers the strain response of the soft stratum due to basement excavation, with placement of a 2-foot thick fill around the perimeter and a 4-foot drop in the water table. The calculated strain response of the soft clay stratum produces varying magnitudes of settlement across the basement footprint. The magnitudes of settlement and angular distortion are presented in Tables 13 and 14.

3.3.3.2.5 Summary

The estimated magnitudes of settlement/rebound presented in Table 13 demonstrate that fill placement around the perimeter of a house and/or a drop in the groundwater level can result in significant total and differential settlements due to laterally variable strain response of the soft stratum. Meehan and Karp (1994) suggest limiting angular distortion of floors to 1/240 to avoid post-construction damage of wood-framed houses (Section 3.4.2). The magnitudes of angular distortion presented in Table 14 do not exceed 1/240 but approach this limit for Case IV conditions (1/280). For unreinforced bearing walls, where the end of the wall settles relative to the midspan, Poulos et al., (2002) suggest limiting angular distortion to between 1/2500 and 1/1250 to prevent unacceptable cracking. The limiting value of angular distortion proposed by Poulos et al., (2002) depends on the length to height ratio of the wall. For the hypothetical basement walls illustrated on Figure 34, the limiting value for angular distortion is 1/1500. The magnitudes of angular distortion between the wall midpoint and the corner exceed 1/1500 for the Case II, III, and IV loading conditions (Table 14). These results only consider primary consolidation response of the soft stratum and not potential movements due to shrink/swell of the overlying stiff stratum. In summary, *the soft stratum, where present, is a potential primary causative factor* for settlement and must be considered in the design of houses in Amherst.

3.4 DESIGN AND CONSTRUCTION

The following section briefly discusses design and construction practices that affect the wall strength, particularly with respect to lateral pressures. We examined foundation drawings during home inspections and noted common design features that, in some cases, may have contributed to foundation problems. This section reviews these design features and highlights some discrepancies between drawings and the actual structure.

3.4.1 Design

A structurally stable house foundation begins with an accurate design that accounts for horizontal and vertical forces. The horizontal component of these lateral

forces is transferred largely through a combination of soil friction along the bottom of the footings and passive soil pressure on the sides of the footings and foundation walls. Foundation walls generally provide support for the superstructure above as well as enclose a basement or crawl space below.

3.4.2 Footing

The blueprints for about 40 houses revealed that all designs utilized the minimum footing thickness (8”) and met the minimum footing projection based on conventional “rules-of-thumb” and the current building code requirements (NYSDOS, 2003). Only 19% of the houses had footing projections that were greater than one-half the foundation width.

We speculate nearly all builders prior to 2003 relied on general presumptive values (Section 1.6.3) instead of a geotechnical evaluation in their foundation design. Diaz et al. (1994) states that caution should be taken when using average values supplied by codes because they *are* simply presumptive values. Several home designers/engineers address unforeseen potential bearing capacity problems by annotating the house plans with the instruction, “if excavation uncovers soil of less than this value, notify engineer.” In areas with problem soils such as Amherst, these procedures are likely too lenient.

In general, rules-of-thumb and presumptive guidelines result in foundation designs intended for average conditions, but soil conditions in Amherst are generally not average and warrant more detailed designs.

3.4.3 Concrete Strength

Concrete strength can be an important factor when discussing the overall strength of a foundation wall. We investigated concrete strength using a non-destructive testing procedure that utilizes a rebound hammer (similar to Schmidt Hammer®).

At the majority of inspection sites, we measured the concrete strength on a representative number of walls (4 to 10). Twenty readings were recorded on each wall, with the highest and lowest values being rejected. The indicated average strength for all the homes tested exceeded the current NYS Residential Building Code minimum compressive strength requirement of 3,000 pounds per square inch (psi, 28 days after placement). More importantly, no particular wall showed a significantly lower compressive strength than any other wall; with all values being greater than 3,900 psi. This finding suggests that concrete strength does not appear to be a primary causative factor. We recognize the limitation of this testing method and recommend core sampling where more accurate measurements are needed.

3.4.4 Wall Thickness

All houses we inspected had 8” thick cast-in-place concrete or CMU walls except for walls supporting brick facia, which used 10” walls. These wall dimensions generally represent the minimum standard for the current building code, and we presume the minimum requirement during the period of construction. Moreover, the foundation

drawings do not indicate reinforcement steel was used in the walls, but we did not independently confirm this with alternative testing methods (e.g., ultra sonic) because of cost. Section 3.5.11.1 will show that unreinforced concrete walls can yield to lateral pressure forces generated by typical soil conditions in Amherst.

3.4.5 Backfill

As cited by Diaz et al. (1994), lateral pressure problems are exasperated by using unsuitable backfill material, usually from on-site excavation. None of the foundation blueprints prescribed the material to be used for backfill. As shown in Section 3.2.3, all backfill soils analyzed in this study are classified as being expansive, which is generally not recommended for backfill material (Jalla, 1999).

3.4.6 Anchor Rods

Approximately 81% of the blueprints called out the inclusion of anchor rods through the sill plate to securely attach the wood frame superstructure of the house to the foundation walls (Figure 35). This additional lateral support is important for the header walls (i.e., walls that are perpendicular with the floor joists), but are even more critical for the stringer walls (i.e., the walls that are parallel with the floor joists).

3.4.7 Geometry

House geometry in Amherst has evolved from comparatively rectangular to more irregular designs. For example, modern homes include cubbyholes, bay and build out windows, and mudrooms. These features result in additional concentrated stresses in the basement walls and should be accounted for in the design. Additional design measures were not evident on the blueprints we reviewed.

3.4.8 Concentrated Loadings

Chimneys, pilasters and other heavy masonry-type features can add tremendous weight to a standard foundation. We did not observe design features that account for these concentrated loads.

3.4.9 Exterior Foundation Drains

Only 13% of the blueprints called out a drainage system below the backfill on the exterior of the foundation. Town Inspectors confirmed that perforated pipe systems along the exterior of the footings are a relatively new house construction feature in Amherst.

3.4.10 Construction

Nearly 58% of blueprints did not match the structure built. The degree of modification varied but typically included a reversal in position of the garage, bedrooms, or crawl space, but changes in the position of the support beams, construction material, sump pump or utilities were also common. Only 7% of the homes actually had anchor

rods installed (c.f., 81% of the blueprints). Approximately 1% of the homes had missing structural members that were intended to carry superstructure loadings in the home.

Regarding new building sites, we speculate that geotechnical recommendations from the geotechnical engineer are not being utilized by all contractors. For example, many geotechnical engineers recommend that foundation excavations should not become saturated, frozen, and disturbed prior to footing construction (Photo 12), but the practice seems relatively common.

3.4.11 Wall Strength Modeling

Basement wall computer modeling was accomplished using GTSTRUDL–Version 26 (GIT, 2002). This software was developed by Georgia Institute of Technology as a structural engineering analysis and design tool. Several computer-based models were developed to analyze the forces, specifically lateral pressures, acting on and in the basement walls of the homes in the study. Finite element modeling was used to generate graphical analyses of the stress and strain in the walls. These analyses were done to develop an understanding of the internal forces acting in the basement walls to assist in identifying and classifying field observations. As more and more home inspections were completed, this analysis was also edited and then used to possibly confirm and explain what was witnessed in the field. The analyses were not intended to determine the structural soundness of the basement walls or to provide a design for use by the Town, or any designer/engineer, or homebuilder. As a check of the finite element analysis, another analysis was performed using only a simple beam method. Parameters used in the model are provided in Appendix 6.5.

Two different unreinforced concrete wall thicknesses (8” and 10”) were analyzed for this study. The lengths of walls analyzed were 20 and 40 feet. Two support conditions were also included in our modeling. The supported condition presumes support at the top in addition to the bottom and both ends of the wall. This was utilized to represent a foundation wall that had the appropriate number, size and location of anchor rods at the top of the wall, while the unsupported top condition was one without any anchor rod attachments being supplied. The soil types used in this analysis were a compilation of soil information available in the early part of this study. Generally speaking the five backfill types acting against the walls for this modeling are (1) a granular soil in the dry condition, (2) a granular soil in the saturated condition, (3) a non-expansive wet clay, (4) a dry moderately expansive clay, and (5) dry highly expansive clay.

3.4.11.1 Modeling Results

Figures 36 and 37 summarize the output of the finite element analyses for the various wall thicknesses, support conditions, and soils types. These results highlight regions of stress, which are especially concentrated from the bottom corners of the wall at approximate 45-degree angles towards the center of the wall, similar to the fracture patterns observed during house inspections (Section 3.2.1). Values above the red line exceed the maximum tensile stress of standard concrete (~389 psi). This implies that

cracking could occur or will happen depending on the actual strength of the concrete wall. The summary below is concerned with the moderately expansive clay simulation as an approximation of the soil conditions in Amherst.

For the 20-foot wall (Figure 36), the unsupported 8- and 10-inch thick wall stresses are at or near the threshold needed to initiate cracking. In the 40-foot wall simulation (Figure 37), both unsupported top condition walls have stresses that exceed the tensile strength of wall and cracking may occur. Interestingly, if the soils are highly expansive, even an 8-inch supported 40-ft wall is near the cracking threshold.

Modeling was also used to help understand deflection related to the effect of lateral pressure at the top of the foundation walls. An unsupported foundation wall was modeled using GTSTRUDL. Expectedly, the deflection at the top of wall was greater for a thinner and longer wall for all the soil types modeled. In fact, an 8-inch thick, 40-foot long wall had almost double the deflection of a 10-inch thick, 40-footlong wall for the most expansive clay soil type.

The modeling results demonstrate that (1) granular backfills can reduce lateral pressures, (2) top wall support is a critical design and construction element, and (3) historical wall designs are at or near the threshold for cracking. In one home affected by lateral pressures, we observed as much as nine inches of deflection along the top of an 8" bowing wall (Photo 13).

3.5 Associative Factors

Besides quantified geotechnical evidence about causative factors, there are several associative causative factors that we speculate to be important in explaining foundation damage at some sites. These qualitative observations/findings are diverse and we generally have limited information about these factors.

Heterogeneous soil conditions or soil discontinuity beneath a house foundation can induce differential settlements if the compressibility of soils beneath the footings varies significantly across the footprint of the house (Diaz et al., 1994). For example, if one end of a strip footing is placed on stiff native clay and the other end on loose backfill material, then the end of the footing placed on loose backfill material could be expected to settle with respect to the end placed on stiff clay. A location where this commonly occurs is at the transition between the basement and crawl space. Near the basement wall, strip footings supporting crawl-space foundation walls often bear on loose backfill material placed against the basement wall. Even if house foundations are placed on initially homogeneous soils, areas of the foundation subgrade can be softened by water and frost, resulting in variable soil compressibility beneath the footprint of the house (Photo 10). Foundation subgrade soils are especially susceptible to softening by water and/or frost during construction activities when the subgrade soils are exposed for prolonged periods. Heterogeneous soil conditions with expansive and non-expansive soils are within the same excavation may also promote differential movements (Photo 8).

At locations where footings are placed near the soft stratum or atop relatively compressible soils, differential settlement can be induced by variable footing pressures. Heavily loaded areas with high footing pressure would be expected to compress the underlying soft soils more than lightly loaded areas.

Erosion of soils beneath footings could potentially contribute to differential settlement at some sites (Photo 14). It is hypothesized that water moving along foundation surfaces can potentially erode foundation soils. Foundation soils consisting of silts and fine sands are most susceptible to erosion. Although it is not a definitive symptom, accumulation of soil in the sump pit suggests potential foundation soil erosion.

Historically in Amherst, house foundations have been designed to limit footing contact pressures to an allowable bearing capacity to prevent bearing capacity failure of foundation soils. Bearing capacity failure occurs as the soil supporting the foundation fails in shear. House footings in Amherst are typically placed on stiff soils. Bearing capacity failures in stiff soils typically result in sudden and catastrophic downward movement shortly after a footing is loaded (Poulos et al., 2002). Foundation failures in Amherst do not typically occur during or shortly after construction. Therefore, although possible at some locations, bearing capacity failures are not suspected to be a significant contributing factor to foundation settlement problems in Amherst.

Hydrostatic pressure has likely contributed to uplift and cracking of floor slabs at some locations. Hydrostatic uplift pressures will develop beneath a floor slab whenever the foundation drainage system fails to keep the groundwater level below the base of the slab. Evidence of hydrostatic pressure buildup includes water entering through cracks in the basement walls and/or slab. Concrete basement floor slabs are not typically designed/constructed to withstand uplift pressures. At one inspection site, the sump pump had recently failed and the slab had clearly fractured, lifted, and hollow areas beneath the slab were detectable with a hammer.

The Town Building Department has robust inspection requirements for new construction (Section 1.6.3). By law, inspections may include but are not limited to building location, site preparation, excavation, foundation, framing, superstructure, electrical, plumbing, heating, ventilation and air conditioning (NYSDOS, 2003). In some cases, this inspection regime may not be sufficient to ensure compliance with the code. In addition, inspectors acknowledge the need for additional skills training to keep pace with new information and technologies.

3.6 Figures, Tables, Photos

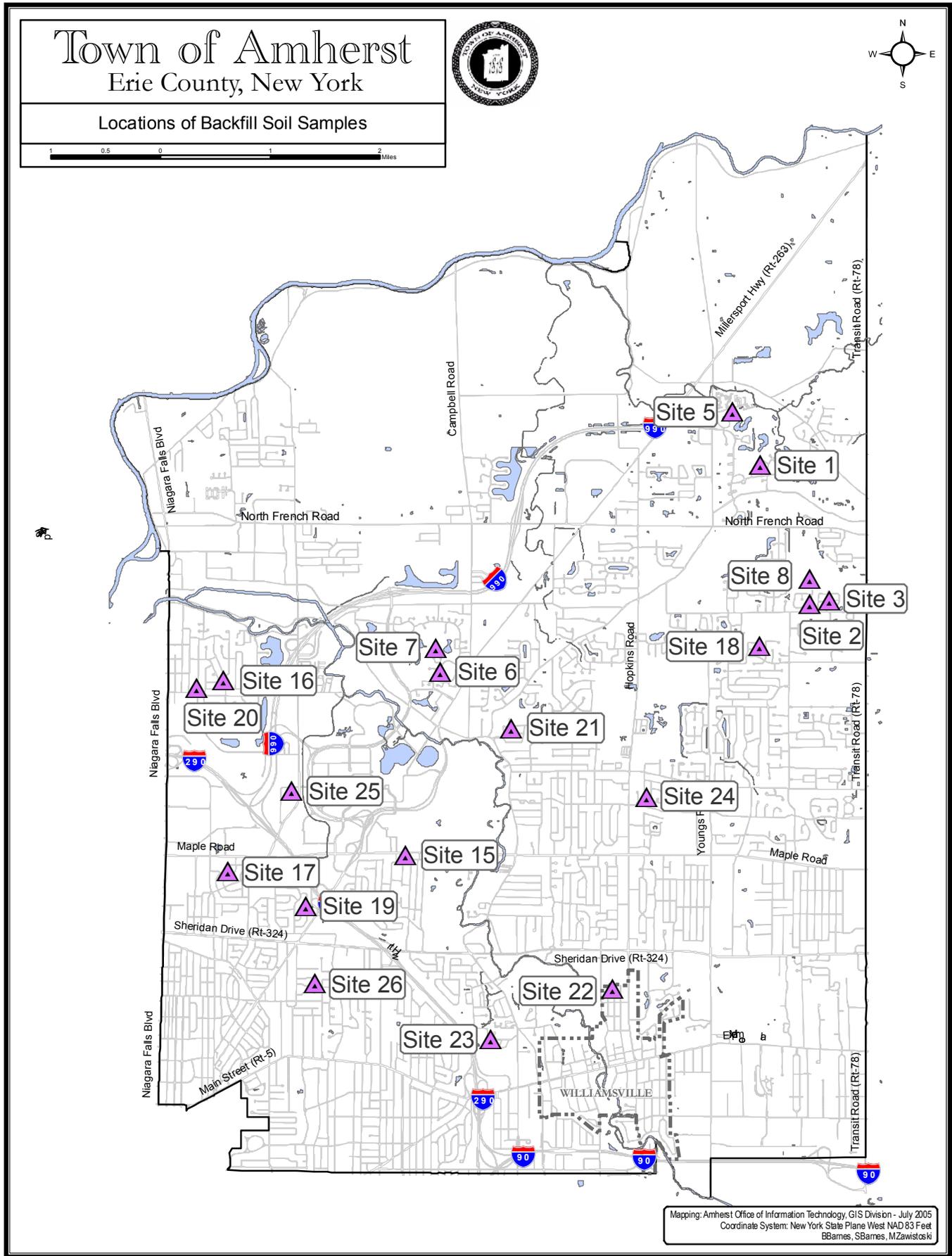


Figure 28: Backfill sampling locations in Amherst, NY. Seventeen of nineteen basement walls exhibited damage related to lateral pressure.

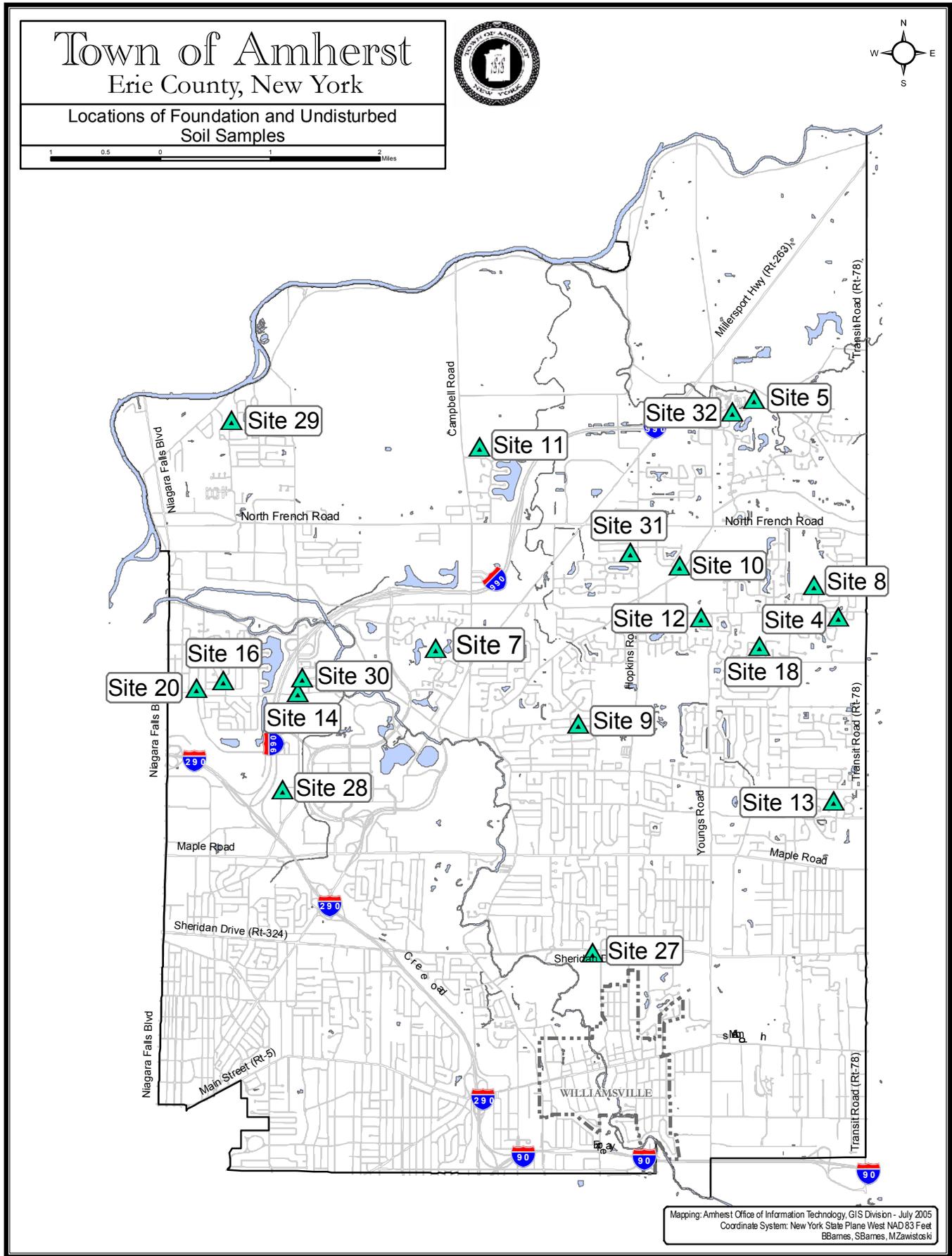


Figure 29: Foundation soil sampling locations.

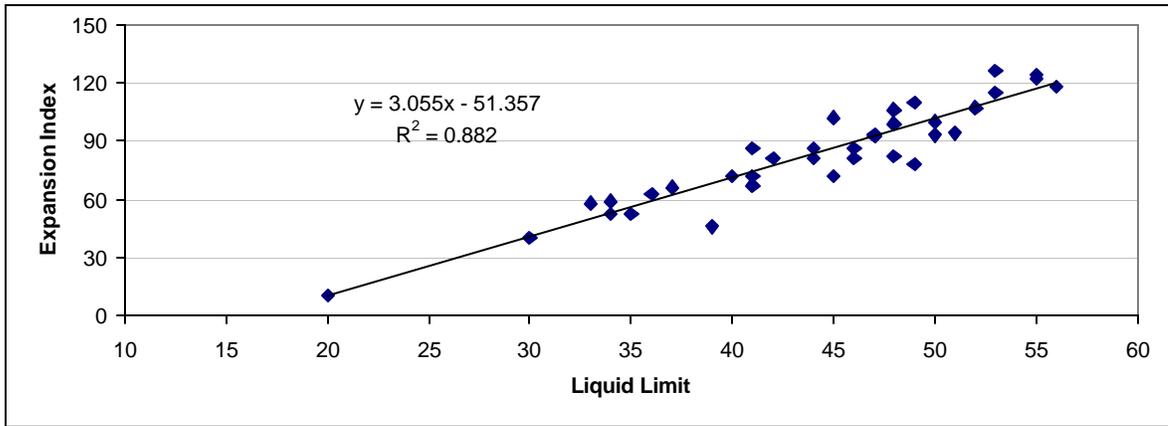


Figure 30. Regression analysis of expansion index (EI) and liquid limit (LL) for backfill and foundation soil samples in Amherst, NY.

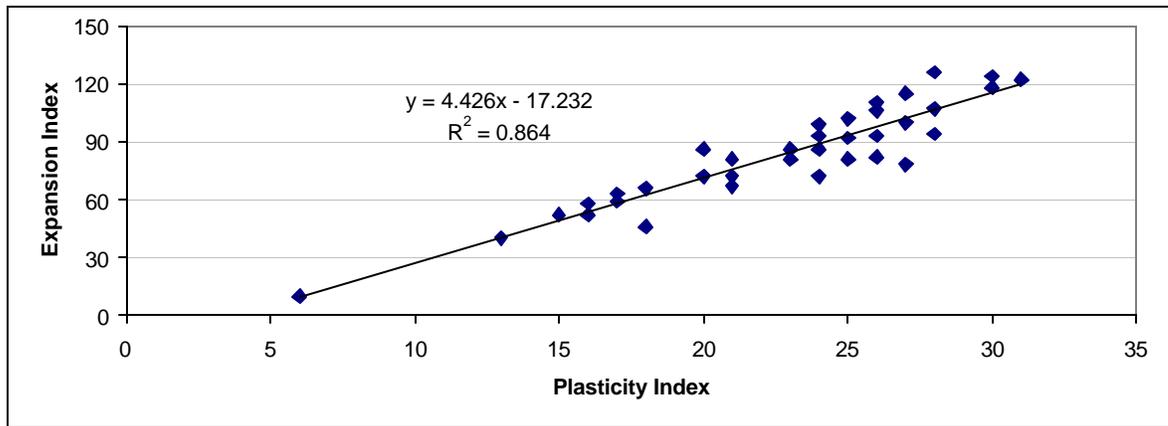


Figure 31. Regression analysis of expansion index (EI) and plasticity index (PI) for backfill and foundation soil samples in Amherst, NY.

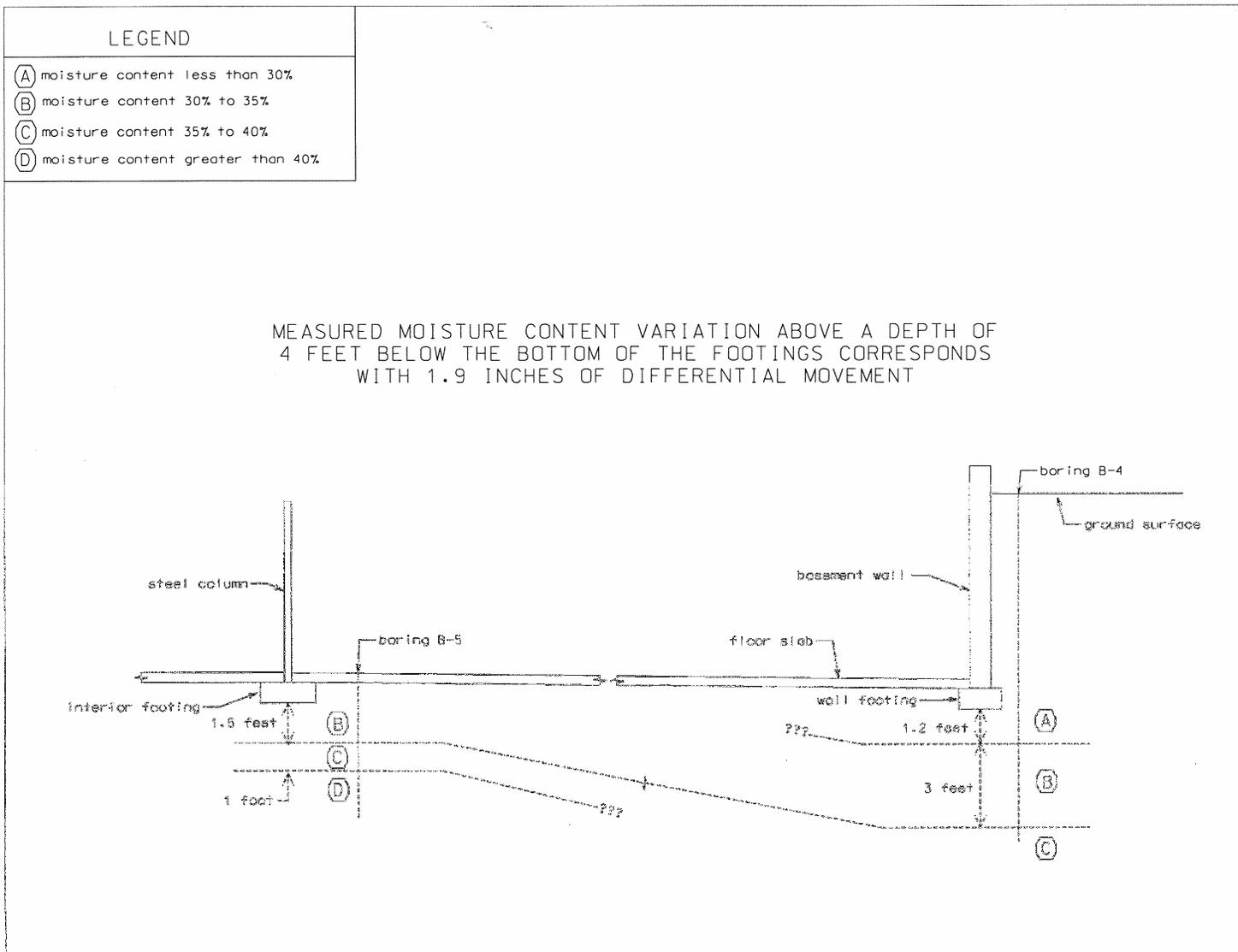


Figure 32. Foundation soil moisture content variation estimated from two boring at Site 7 in Amherst, NY (July, 2004). Gravel under slab is not shown.

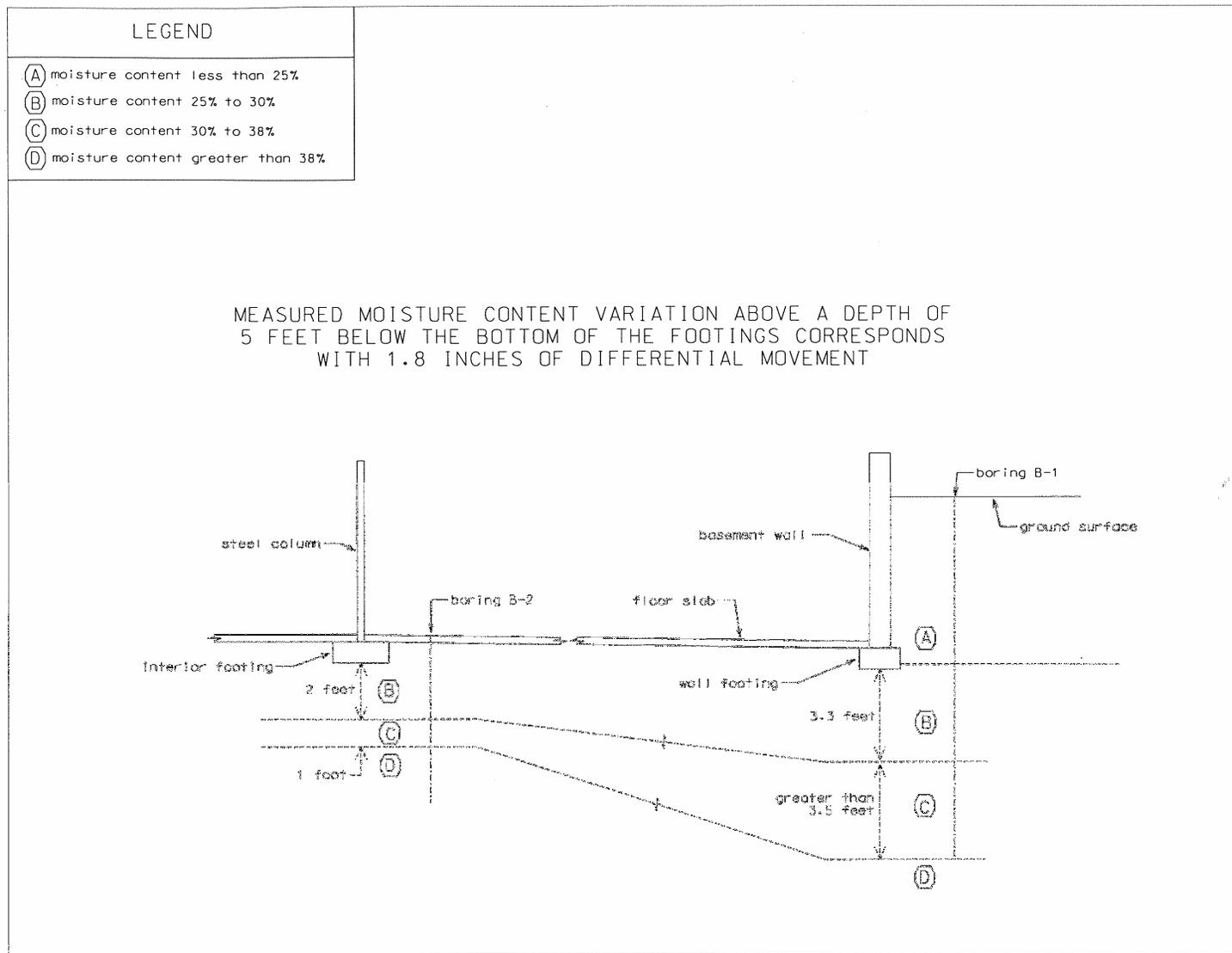


Figure 33. Foundation soil moisture content variation estimated from two borings at Site 4 in Amherst, NY (July, 2004).

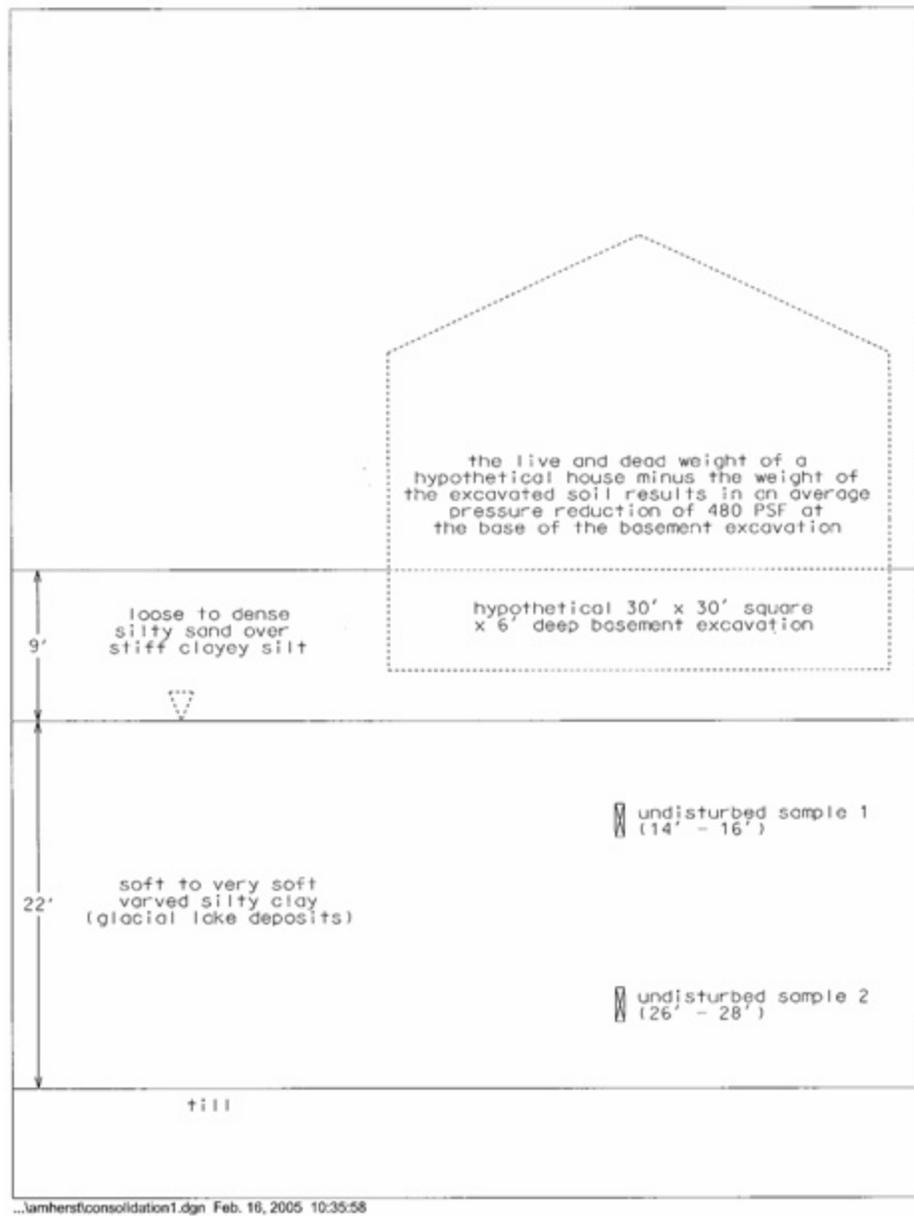


Figure 34. Schematic of hypothetical square house located within a 30' x 30' x 6' deep basement excavation (Section 3.4.3.2).

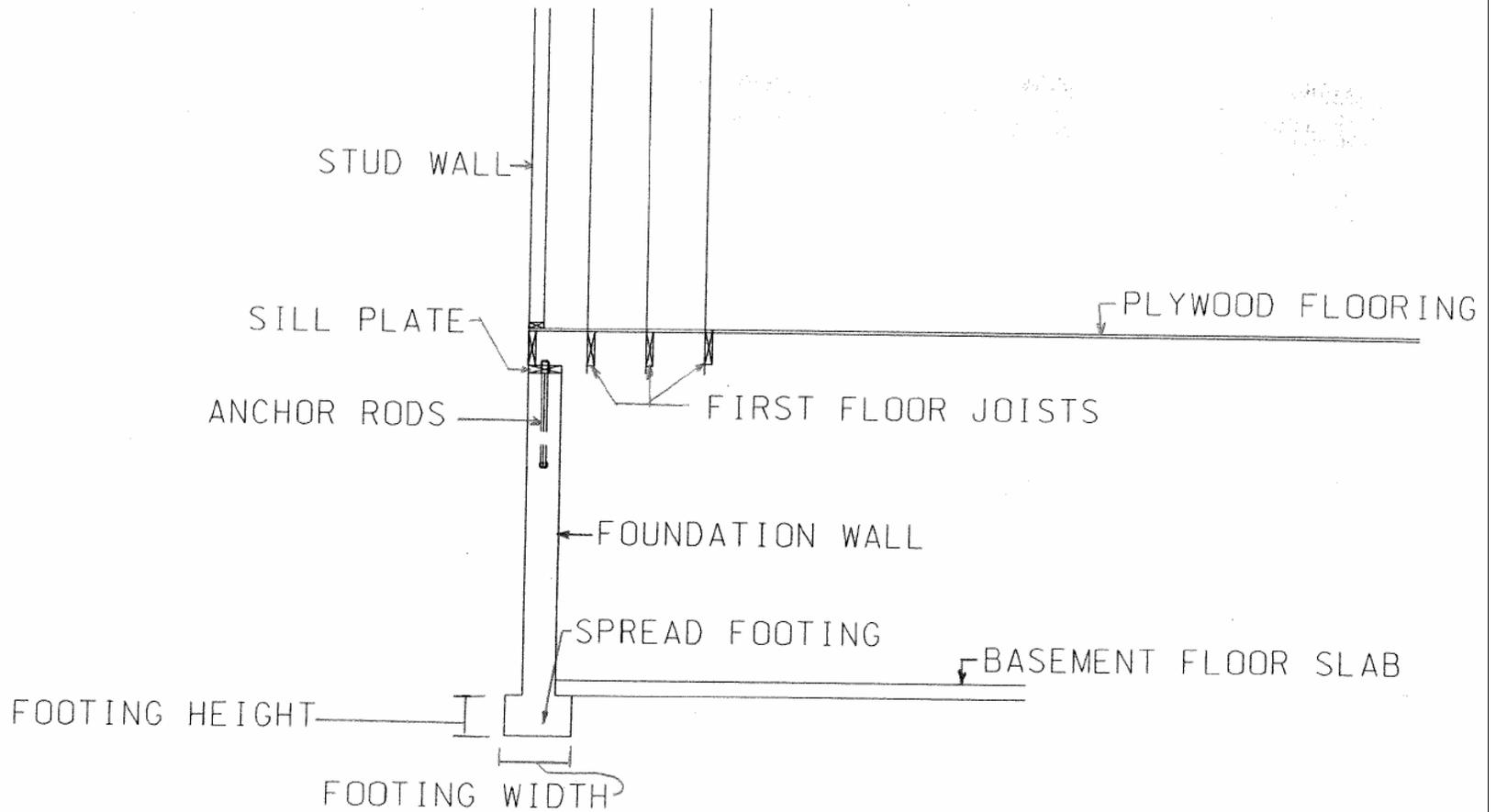


Figure 35. Typical structural components of foundation.

GTSTRUDL Model -- Lateral Load on 20 Ft Basement Wall

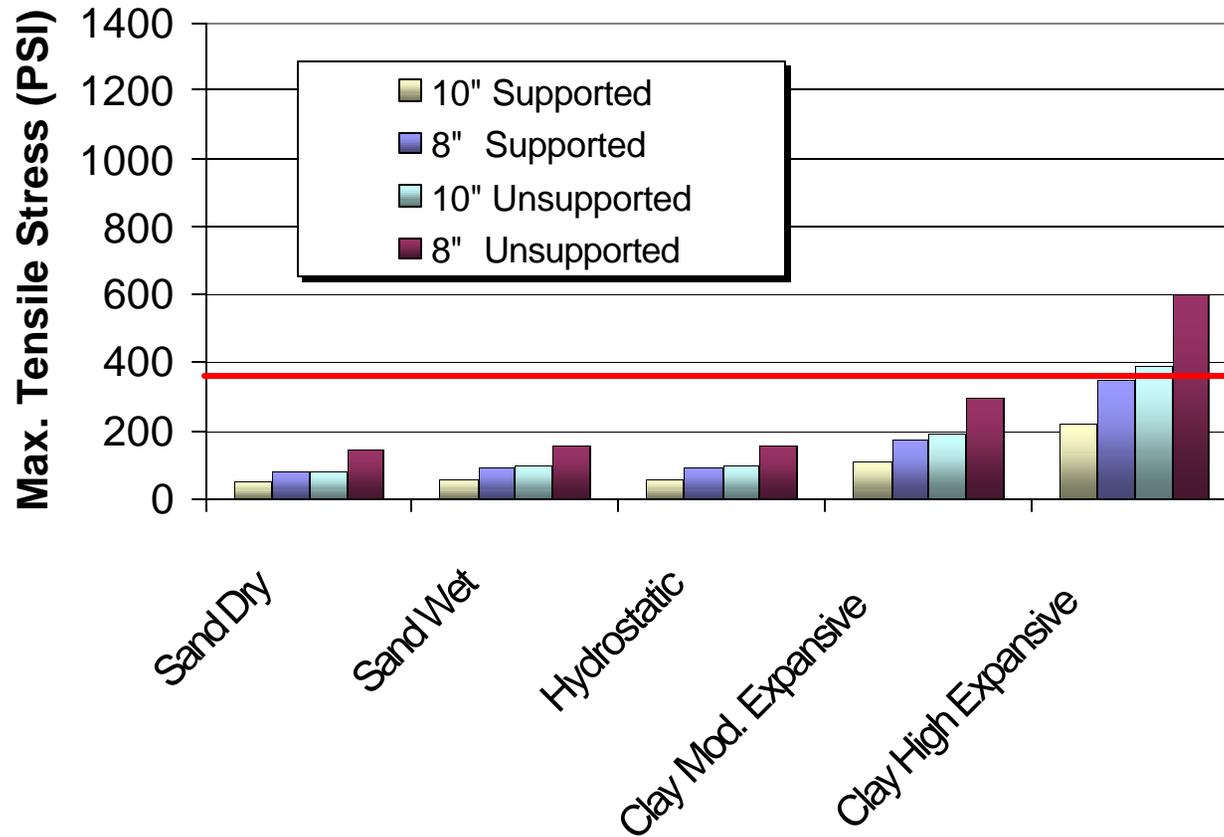


Figure 36. Modeling results of 20 ft basement wall with different backfill conditions, thickness, and support conditions. Red line indicates approximate maximum tensile strength of standard concrete (~389 psi). See Appendix 6.5 for model parameters.

GTSTRUDL Model -- Lateral Load on 40 Ft Basement Wall

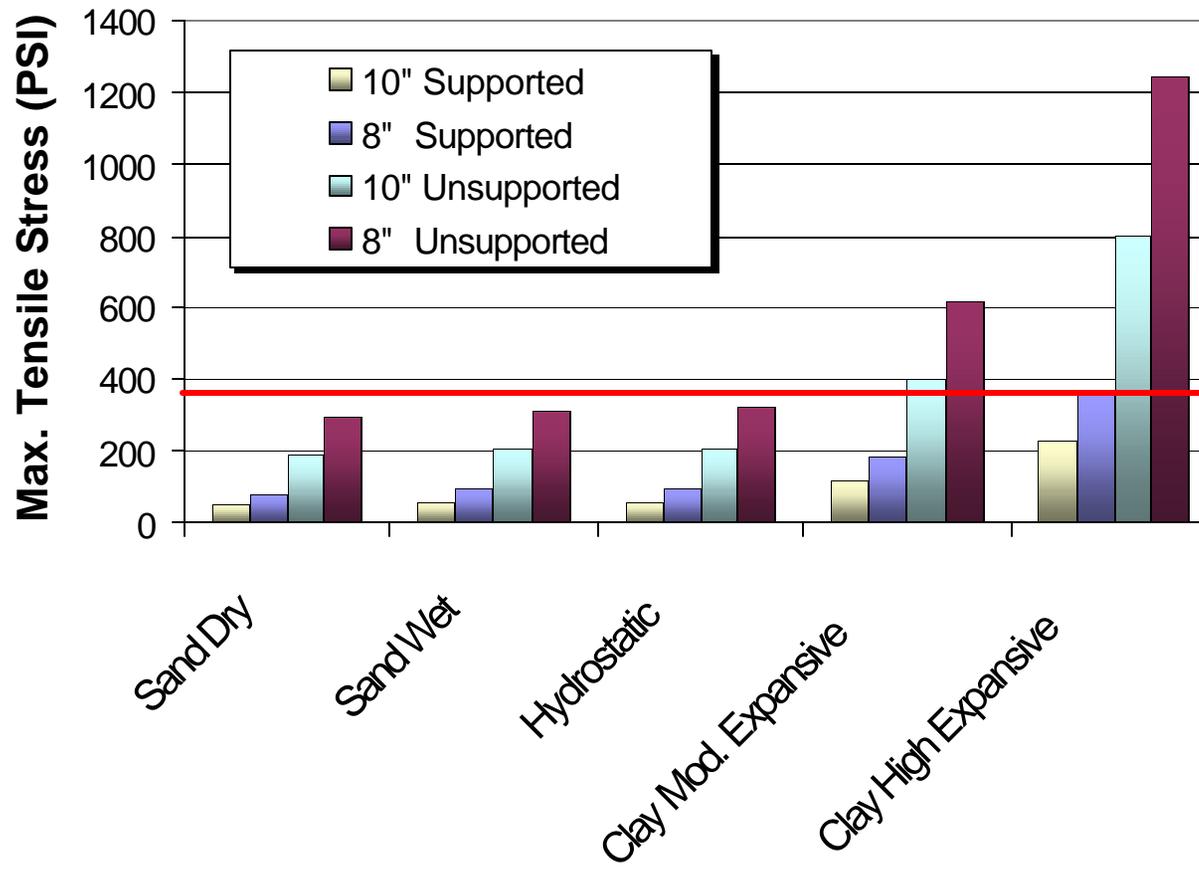


Figure 37. Modeling results of 40 ft basement wall with different backfill conditions, thickness, and support conditions. Red line indicates approximate maximum tensile strength of standard concrete (~389 psi). See Appendix 6.5 for model parameters. Results suggest unsupported walls may yield in the moderately expansive case similar to Amherst.

Table 8. Laboratory test results for basement wall backfill soils in Amherst, NY (2004)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SITE	COMPOSITE SAMPLE DEPTH (FEET)	CLAY FRACTION – PERCENT FINER THAN 0.002 mm	PERCENT FINER THAN 0.005 mm	PERCENT FINER THAN #200 SIEVE	LIQUID LIMIT (ASTM D4318)	PLASTICITY INDEX (ASTM D4318)	UNIFIED CLASSIFICATION (ASTM D2487)	SHRINKAGE LIMIT (ASTM D427)	SPECIFIC GRAVITY (ASTM D854)	EXPANSION INDEX (ASTM D4829)	POTENTIAL EXPANSION (ASTM D4829)	NUMBER OF NATURAL MOISTURE CONTENT TEST SAMPLES ¹	HIGHEST MEASURED NATURAL MOISTURE CONTENT (%)	LOWEST MEASURED NATURAL MOISTURE CONTENT (%)	EXPANSIVE? (Residential Code of NYS, Section R403.1.8.1)
1	1 – 3	36	47	80	39	18	CL	14	2.65	46	LOW	7	23.7	8.9	YES
2	0 – 4.5	36	48	76	34	17	CL	13	2.67	59	MEDIUM	3	26.6	22.6	YES
3	2 – 4.7	35	47	83	37	18	CL	15	2.68	66	MEDIUM	5	25.8	20.2	YES
5	0.5 – 4	52	71	96	46	24	CL	17	2.72	86	MEDIUM	6	25.3	22.3	YES
6 ²	1.5 – 4.2	36	42	76	33	16	CL	13	2.65	58	MEDIUM	1	25.5	25.5	YES
7	1 – 4.2	48	62	88	40	20	CL	17	2.71	72	MEDIUM	8	28.6	22.6	YES
8 ³	1 – 5	35	47	81	36	17	CL	14	2.69	63	MEDIUM	6	26.7	21.1	YES
15	1 – 4	56	70	93	48	26	CL	17	2.76	106	HIGH	6	31.8	13.1	YES
16	1 – 4	44	56	81	41	21	CL	14	2.71	72	MEDIUM	6	27.3	20.9	YES
17	1.5 – 4.5	58	73	100	50	27	CH	18	2.75	100	HIGH	6	26.3	21.7	YES
18	1 – 5	52	71	95	44	23	CL	15	2.75	81	MEDIUM	6	21.9	19.9	YES
19	1 – 4	60	75	95	52	28	CH	17	2.75	107	HIGH	6	27.1	21.5	YES
20	2 – 4	45	57	86	45	25	CL	15	2.72	102	HIGH	4	20.3	18.1	YES
21	1 – 4	48	64	92	44	23	CL	19	2.74	86	MEDIUM	6	22.1	19.2	YES
22	1 – 4	46	60	97	41	20	CL	15	2.73	86	MEDIUM	5	28.5	20.1	YES
23	2.5 – 4.5	33	45	88	34	15	CL	14	2.73	52	MEDIUM	4	18.4	14.2	YES
24	1 – 4.9	52	68	94	47	24	CL	15	2.74	93	HIGH	5	25.6	23.6	YES
25	1 – 3.2	56	75	100	48	24	CL	16	2.73	99	HIGH	3	30.4	25.7	YES
26	0 – 3.5	50	63	91	42	21	CL	15	2.72	81	MEDIUM	0	NA	NA	YES
MAX		60	75	100	52	28		19	2.76	107			31.8	25.7	
MIN		33	42	76	33	15		13	2.65	46			18.4	8.9	
AVERAGE		46	60	89	42	21		16	2.72	80			25.7	20.1	
STANDARD DEVIATION (+/-)		9	11	8	6	4		2	0.03	19			3.4	4.3	
Residential Code Criteria Defining Expansive Soils			> 10	> 10		≥ 15				> 20					

¹ Discrete samples were collected within the depth range listed in column 2; ² No significant damage observed at Site 6; ³ No significant damage observed at Site 8

Table 9. Laboratory test results for stiff foundation soil samples in Amherst, NY (2004)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SITE	COMPOSITE SAMPLE DEPTH (FEET)	CLAY FRACTION – PERCENT FINER THAN 0.002 mm	PERCENT FINER THAN 0.005 mm	PERCENT FINER THAN #200 SIEVE	LIQUID LIMIT (ASTM D4318)	PLASTICITY INDEX (ASTM D4318)	UNIFIED CLASSIFICATION (ASTM D2487)	SHRINKAGE LIMIT (ASTM D427)	SPECIFIC GRAVITY (ASTM D854)	EXPANSION INDEX (ASTM D4829)	POTENTIAL EXPANSION (ASTM D4829)	NUMBER OF NATURAL MOISTURE CONTENT TEST SAMPLES ¹	HIGHEST MEASURED NATURAL MOISTURE CONTENT (%)	LOWEST MEASURED NATURAL MOISTURE CONTENT (%)	EXPANSIVE? (Residential Code of NYS, Section R403.1.8.1)
4	6 – 9	62	81	100	50	26	CH	19	2.74	93	HIGH	14	30	23	YES
8 ²	6 – 7.5	62	82	97	51	28	CH	19	2.74	94	HIGH	3	27	28	YES
9	≈ 7	53	76	100	45	24	CL	18	2.71	72	MEDIUM	1	25	25	YES
10	≈ 7	43	60	100	35	16	CL	16	2.72	52	MEDIUM	1	23	23	YES
11	≈ 6	54	74	100	41	21	CL	16	2.69	67	MEDIUM	1	26	26	YES
12	≈ 6	62	83	100	48	26	CL	17	2.75	82	MEDIUM	1	30	30	YES
13 ³	≈ 6	18	21	64	20	6	CL - ML	12	2.76	10	VERY LOW	1	14	14	NO
14	≈ 7	53	68	90	46	25	CL	17	2.76	81	MEDIUM	1	26	26	YES
16	7 – 7.5	No test	No test	No test	57	33	CH	No test	No test	No test	No test	2	29	28	No test
18	5.5 – 7.5	64	83	95	49	27	CL	17	2.76	78	MEDIUM	7	30	23	YES
20	7 – 10	69	90	100	55	31	CH	20	2.78	122	HIGH	6	34	24	YES
27 ⁴	≈ 6.5	35	49	94	30	13	CL	14	2.73	40	LOW	1	16	16	NO
28	≈ 1.5	67	83	95	56	30	CH	18	2.75	118	HIGH	1	30	30	YES
31	8 – 10	No test	No test	No test	46	25	CL	No test	2.69	No test	No test	1	25	25	No test
MAX ⁵		69	90	100	56	31		20	2.78	122					
MIN ⁵		43	60	90	35	16		16	2.69	52					
AVERAGE ⁵		59	78	98	48	25		17	2.74	86					
STANDARD DEVIATION (+/-)		8	9	3	6	4		1	0.03	22					
Residential Code Criteria Defining Expansive Soils			> 10	> 10		≥ 15				> 20					

¹ Discrete samples were collected within the depth range listed in column 2; ² No significant damage observed at Site 8; ³ Soil consisted of glacial till; ⁴ Soil consisted of glacial till; ⁵ Excludes sites 13, 16, 27, and 31

Table 10. Laboratory test results for undisturbed samples of stiff foundation soils in Amherst, NY (2004)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SITE	SAMPLE DEPTH (FEET)	CLAY FRACTION – PERCENT FINER THAN 0.002 mm	PERCENT FINER THAN #200 SIEVE	LIQUID LIMIT (ASTM D4318)	PLASTICITY INDEX (ASTM D4318)	UNIFIED CLASS.	DISTURBED SHRINKAGE LIMIT (ASTM D427)	EXPANSION INDEX (ASTM D4829)	POTENTIAL EXPANSION (ASTM D4829)	DRY UNIT-WEIGHT (POUNDS PER CUBIC FOOT)	EXPANSIVE? (Residential Code of NYS, Section R403.1.8.1)	NATURAL MOISTURE CONTENT (%)	INITIAL SATURATION (%)	UNDISTURBED SHRINKAGE LIMIT ¹	S _v ²	S _{v(theor)} ³
9	≈7	53	100	45	24	CL	18	72	MEDIUM	100	YES	25.1	100	18	0.53	0.54
10	≈7	43	100	35	16	CL	16	52	MEDIUM	106	YES	22.6	100	20	0.59	0.57
11 ^a	≈6	54	100	41	21	CL	16	67	MEDIUM		YES					
a	≈6									101		25.1	100	17	0.66	0.54
b	≈6									100		26.0	100	19	0.59	0.53
12	≈6	62	100	48	26	CL	17	82	MEDIUM	94	YES	29.7	100	19	0.68	0.50
14	≈7	53	90	46	25	CL	17	81	MEDIUM	100	YES	25.8	100	17	0.63	0.53
MAX		62	100	48	26		18	82		106		29.7		20	0.68	0.57
MIN		43	90	35	16		16	52		94		22.6		17	0.53	0.50
AVERAGE		53	98	43	22		17	71		100		25.7		18	0.61	0.54
STANDARD DEVIATION (+/-)		7	4	5	4		1	12		4		2.3		1	0.05	0.02

¹ Determined via shrink test; ² Vertical shrink-swell coefficient determined via shrink test; ³ Theoretical vertical shrink-swell coefficient; ⁴ One grab sample and two undisturbed samples, samples a & b, were collected at Site 11

Table 11. Laboratory test results for upper portion of soft stratum in Amherst, NY (2004)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SITE	COMPOSITE SAMPLE DEPTH (FEET)	CLAY FRACTION – PERCENT FINER THAN 0.002 mm	PERCENT FINER THAN 0.005 mm	PERCENT FINER THAN #200 SIEVE	LIQUID LIMIT (ASTM D4318)	PLASTICITY INDEX (ASTM D4318)	UNIFIED CLASSIFICATION (ASTM D2487)	SHRINKAGE LIMIT (ASTM D427)	SPECIFIC GRAVITY (ASTM D854)	EXPANSION INDEX (ASTM D4829)	POTENTIAL EXPANSION (ASTM D4829)	NUMBER OF NATURAL MOISTURE CONTENT TEST SAMPLES ¹	HIGHEST MEASURED NATURAL MOISTURE CONTENT (%)	LOWEST MEASURED NATURAL MOISTURE CONTENT (%)	EXPANSIVE? (Residential Code of NYS, Section R403.1.8.1)
4	9 – 13	70	90	100	53	27	CH	21	2.76	115	HIGH	10	46	30	YES
5	8 – 11	62	85	100	47	25	CL	18	2.76	92	HIGH	10	39	30	YES
7	8 – 12	70	94	100	55	29	CH	20	2.76	128	HIGH	14	43	29	YES
8 ²	9 – 12	70	93	100	53	28	CH	20	2.79	126	HIGH	4	48	34	YES
18	7 – 8.5	58	76	90	49	26	CL	18	2.77	110	HIGH	3	35	28	YES
20	10 – 11.5	72	96	100	55	30	CH	21	2.78	124	HIGH	2	37	35	YES
MAX		72	96	100	55	30		21	2.79	128			48	35	
MIN		58	76	90	47	25		18	2.76	92			35	28	
AVERAGE		67	89	98	52	28		20	2.77	116			41	31	
STANDARD DEVIATION (+/-)		6	7	4	3	2		1	0.01	14			5	3	
Residential Code Criteria Defining Expansive Soils			> 10	> 10		≥ 15				> 20					

¹ Discrete samples were collected within the depth range listed in column 2; ² No significant damage observed at Site 8

Table 12. Laboratory test results for consolidation test samples obtained from soft stratum in Amherst, NY

1	2	3	4	5	6	7	8	9	10
SITE	SAMPLE DEPTH (FEET)	NATURAL MOISTURE CONTENT (%)	LIQUID LIMIT (ASTM D4318)	PLASTICITY INDEX (ASTM D4318)	UNIFIED CLASSIFICATION (ASTM D2487)	APPROXIMATE IN- SITU EFFECTIVE STRESS (POUNDS PER SQUARE FOOT)	APPROXIMATE PRECONSOLIDATION STRESS (POUNDS PER SQUARE FOOT)	COMPRESSION RATIO ¹	RECOMPRESSION RATIO ²
29	14 – 16	49	51	29	CH	1400	2600	0.26	0.025
30	15 – 17	38	48	26	CL	1500	3000	0.20	0.021
31	20 – 22	48	52	29	CH	2000	2000	0.17	0.020
32	20 – 22	46	39	24	CL	2000	2000	0.22	0.018
29	26 – 28	49	49	29	CL	2000	2000	0.15	0.015
MAX		49	52	29				0.26	0.025
MIN		38	39	24				0.15	0.015
AVERAGE		46	48	27				0.20	0.020
STANDARD DEVIATION (+/-)		5	5	2				0.04	0.004

¹ Slope of strain vs. log pressure for virgin portion of consolidation test curve; ² Slope of strain vs. log pressure for reloading portion of consolidation test curve

Table 13. Calculated post-construction settlement/rebound due to strain response of soft stratum at Site 29 in Amherst, NY

LOCATION IN BASEMENT	CASE I (INCHES)	CASE II (INCHES)	CASE III (INCHES)	CASE IV (INCHES)
Center	0.3 upward	0.2 upward	0.2 downward	0.8 downward
Wall Midpoint	0.2 upward	0.1 downward	0.6 downward	1.3 downward
Corner	0.1 upward	0.5 downward	0.8 downward	1.7 downward

I 50% of excavation rebound occurs after house construction

II 50% of excavation rebound occurs after house construction and lot is raised with 2 feet of fill placed around the perimeter of the house after construction

III 50% of excavation rebound occurs after house construction and water table drops 4 feet after construction

IV 50% of excavation rebound occurs after house construction, lot is raised with 2 feet of fill placed around the perimeter of the house after construction, and water table drops 4 feet after construction

Table 14. Calculated post-construction angular distortion due to strain response of soft stratum at Site 29 in Amherst, NY

LOCATIONS IN BASEMENT	CASE I	CASE II	CASE III	CASE IV	ALLOWABLE
Between Center and Corner	1 / 1030	1 / 386	1 / 383	1 / 280	1/240 ^a
Between Wall Midpoint and Corner	1 / 2260	1 / 463	1 / 707	1 / 551	1/1500 ^b

I 50% of excavation rebound occurs after house construction

II 50% of excavation rebound occurs after house construction and lot is raised with 2 feet of fill placed around the perimeter of the house after construction

III 50% of excavation rebound occurs after house construction and water table drops 4 feet after construction

IV 50% of excavation rebound occurs after house construction, lot is raised with 2 feet of fill placed around the perimeter of the house after construction, and water table drops 4 feet after construction

^a Allowable angular distortion between footings supporting wood framing (Meehan and Karp, 1993); ^b Allowable angular distortion along 30' long x 7' high unreinforced basement wall (Poulos et al., 2002).



Photo 5. Lateral pressure affecting basement wall in central Amherst, NY. Wall has deflected inward nearly 3 inches from grounding rod.



Photo 6. Lateral pressure causing vertical fracture in mid-span of basement wall in north-central Amherst, NY.



Photo 7. Undisturbed sampling of stiff stratum in north Amherst, NY.



Photo 8. Heterogeneity in shallow soil conditions in north Amherst, NY. Darker soils are clay and lighter brown are fine sand. Note baking of footing soils (c.f., Photo 12).



Photo 9. Root hairs penetrating into sump pit in central Amherst, NY.



Photo 10. Construction of interior and perimeter footings on stiff stratum in north-central Amherst, NY.



Photo 11. Perimeter loading of house with 3 to 4 feet of fill in northAmherst, NY.



Photo 12. Winter foundation site in East Amherst showing potential for softening from frozen and saturated conditions (March, 2004).



Photo 13. Inward deflection of basement wall (and pilasters) in central Amherst NY. Plum-bob indicates 9" of inward movement. Pipes are damaged and/or relocated.



Photo 14. Erosion of strip footing during construction.