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Beyond the Building Code: Expansive Soils

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Abstract

As defined by ASTM, soils that are susceptible to significant volumetric changes from the addition and/or removal of external elements are deemed "expansive." Expansive soils associated with clay soil compositions are predominantly encountered throughout the central portion of the United States as well as portions of the southeast and west regions. Although it is not well documented, expansive soils are also encountered adjacent to coal deposits throughout the Appalachian coal region in the eastern United States. Depending on the mineralogy, clay soils comprised of expansive minerals can bond with moisture, causing the volume of the soil to increase with the addition of moisture and decrease with the withdrawal of moisture. This paper will explore tools for identifying expansive soils and factors to consider in the design and construction of ground-supported structures to mitigate the risk of post-construction differential foundation movement caused by expansive soils. It will also explore consequences to ground-supported structures not adequately designed and/or constructed for expansive soils as well as potential remedial measures to address adverse foundation performance.

Keywords

Active zone, chemical injection, deep foundations, expansive clay soils, expansive index (EI), expansive pyritic soils, expansive soil, foundations, geotechnical testing, moisture conditioning, montmorillonite, plasticity index (PI), potential vertical movement (PVM), potential vertical rise (PVR), slab-on-grade, soil survey, swelling capacity, water injection, forensic engineering

Introduction and Background

Susceptible to significant volumetric changes from the addition and/or removal of external elements, expansive soils are prevalent throughout the central portion of the United States as well as portions of the southeast and west regions. Although not well documented, expansive soils are also encountered adjacent to coal deposits throughout the Appalachian coal region in the United States. When expansive soils are identified through site-specific geotechnical tests or regional soil surveys, certain design and construction considerations should be used for ground-supported structures with foundations placed on or within the active zone of expansive soils to ensure that the structures will perform. Without using those design and construction considerations, ground-supported structures on expansive soils are subject to differential movement outside of specified performance standards and may require remediation to perform acceptably. Four case studies are presented to illustrate the effects of expansive soils on ground-supported structures as well as to illustrate performance evaluations and remediation options of ground-supported structures on expansive soils.

Three types of expansive soils will be discussed in this paper, including expansive clay soils, expansive carbonaceous soils, and expansive pyritic soils.

Definition of Expansive Soils

Expansive soils often contain minerals that easily mix and dissolve into water, such as montmorillonite and illite[1], and are susceptible to significant volumetric changes from the addition and/or removal of external elements, such as water. When introduced to moisture, expansive soils comprised of clay are susceptible to swell, whereas

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the removal of moisture causes expansive soils to shrink. Certain volumetric changes exceeding specified performance standards by a structural and/or geotechnical engineer can interfere with the usability and/or serviceability of a ground-supported structure, and, in some cases, cause structural damage and failure.

Expansive clay soils are often rich in montmorillonite (commonly referred to interchangeably as bentonite and smectite) and illite. Montmorillonite has a crystalline structure that is not tightly bound and allows for the intervention of water. Montmorillonite has a greater expansion capacity than other clays, including illite, due to its ability to allow water to penetrate the interlayer molecular spaces[2]. Illite minerals are contained in cyclical alumina and silica layers and have high absorption capacity. Montmorillonite has a similar molecular arrangement to illite[3].

The plasticity index (PI) of soil is defined as the difference between the liquid limit and the plastic limit during which the soil is in a semi-solid state. As documented by Fredlund and Rahardjo (1993)[4], as well as Lytton (1994)[5], the volume of a soil can increase with the addition of moisture and decrease with its withdrawal. A relationship between the PI of a soil and its inherent swelling capacity was documented and qualitatively categorized by Terzaghi, Peck, and Mesri (1996)[6], which is shown in **Figure 1**.

ASTM D4829-21 "Standard Test Method for Expansion Index of Soils" provides a standardized test method to compute the expansion index (EI), an indicator of a soil's swell capacity, of a soil sample[7].

According to ASTM D4829-21:

> *5.1 The expansion index, EI, value is used by engineers and other professionals as an indicator of the soil's swelling potential. It may also be used to determine the suitability of a soil to satisfy requirements set by specifying agencies.*

Plasticity Index (PI) Percent	Inherent Swelling Capacity
0-10	Low
10-20	Medium
20-35	High
35 and greater	Very high

Figure 1
Approximate relationship between plasticity index (PI) and inherent swelling capacity.

ASTM D4829-21 classifies a soil with EI ranging from 0-20, 21-50, 51-90, 91-130, and greater than 130 to have potential expansion of very low, low, medium, high, and very high, respectively.

Geographic Prevalence

Expansive soils are prevalent in the central portion of the United States as well as portions of the southeast and west regions. A map of the United States showing the distribution of soils based on their swelling potential is provided in **Figure 2**.

Other types of expansive soils are also encountered adjacent to coal deposits throughout the Appalachian coal region in the eastern United States, although their prevalence is not well documented. Two main types of coal-adjacent soils are expansive: carbonaceous and pyritic. Carbonaceous expansive soils are rich in organic matter, particularly carbon, and are often found in shales. Not only does the organic material characteristic of carbonaceous expansive soils increase the volume and duration of water retention, but it also resists compaction[9]. The upper limit of expansion for pyritic soils relies upon the depletion of the soil components[10]. Pyritic expansive soils contain large amounts of pyrite, which is reactive with both water and oxygen, resulting in the production of sulfuric acid. The

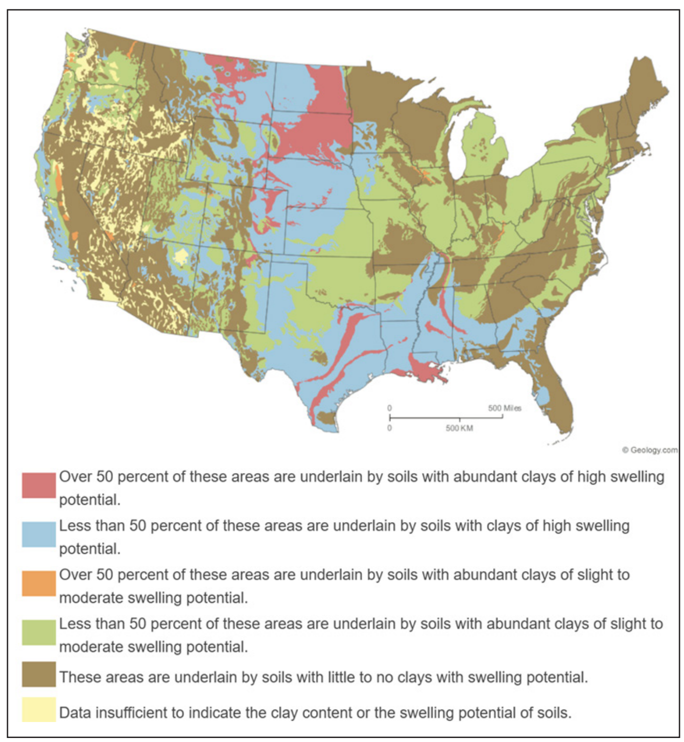

Figure 2
Distribution of soils in the United States based upon their swelling potential[8].

sulfuric acid can then react with minerals in the soil, causing swelling and shrinking; therefore, the expansion-contraction manifestation is a two-step process. Although it is outside the scope of this paper, it should be noted that the presence of sulfuric acid in soils supporting a structure can actually lead to deterioration of the structural materials, such as wood, concrete, and steel, over time. Furthermore, while other forms of expansive soils have a practical upper limit on their expansion capacity, the only upper limit on pyritic decay is depletion of components. Although the USGS map in **Figure 2** does not reflect coal-adjacent expansive soils, the coal deposit map in **Figure 3** and **Figure 4**[11] can serve as a predictor for the presence of both carbonaceous and pyritic expansive soils.

There are adopted standards that define expansive soils based upon various size and expansion parameters. For example, the International Building Code (IBC), which is the building code standard that is widely adopted in the United States, specifies that soil materials shall be classified in accordance with ASTM D2487, provides additional requirements for areas that are likely to have expansive soil, and offers guidelines on how to classify a soil as expansive.

According to Section 1803.5.3 of the 2024 IBC[12]:

1803.5.3 Expansive soil.

... Soils meeting all four of the following provisions shall be considered to be expansive, except that tests to show compliance with Items 1, 2 and 3 shall not be required if the test prescribed in Item 4 is conducted:

1. Plasticity Index (PI) of 15 or greater, determined in accordance with ASTM D4318.

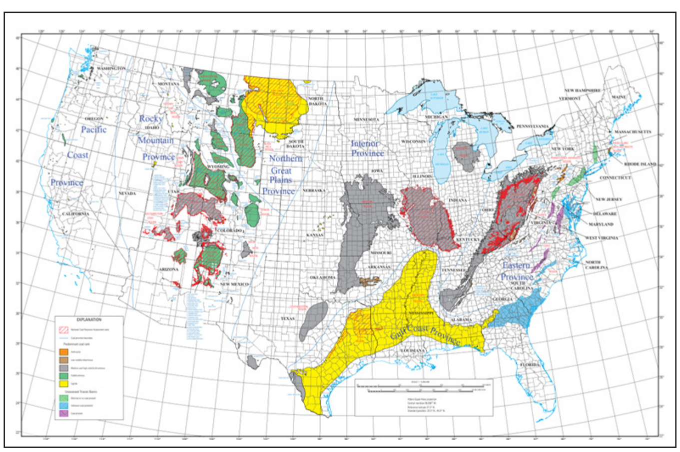

Figure 3
Map showing coal field of the conterminous United States (2013)[11].

2. More than 10 percent of the soil particles pass a No.200 sieve (75 µm), determined in accordance with ASTM D6913.

3. More than 10 percent of the soil particles are less than 5 micrometers in size, determined in accordance with ASTM D6913.

4. Expansion index greater than 20, determine in accordance with ASTM D4829.

Section R403.1.8.1 of the 2024 International Residential Code (IRC) includes a similar definition for expansive

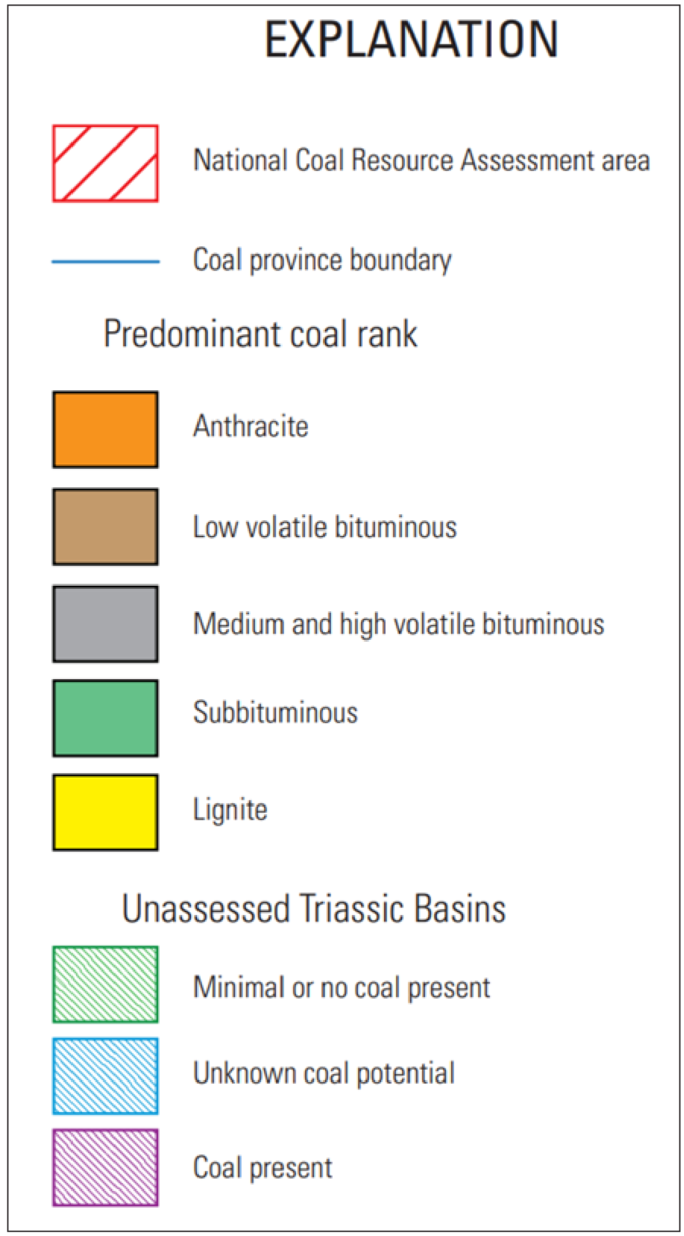

Figure 4
Enlarged "explanation" from Figure 3[11].

soils as the 2024 IBC; however, items 2 and 3 refer to ASTM D422 rather than ASTM D6913[13].

In addition, the National Building Code of Canada (NBCC), which is the building code standard that is widely adopted in Canada, provides guidelines for identifying expansive soils.

According to Section 4.2.4.11 of the 2020 NBCC, Volume 1[14]:

> ***4.2.4.11 Swelling and Shrinking Soils***
>
> *1) Where swelling or shrinking soils, in which movements resulting from moisture content changes may be sufficient to cause damage to a structure, are encountered or known to exist, such a condition shall be fully investigated and provided for in the design.*

For the purposes of this paper, soils that meet the requirements of 1803.5.3 of the 2024 IBC will be considered "expansive." To reiterate and summarize, according to the 2024 IBC, an expansive soil is defined as a soil that exhibits a PI of 15 percent or greater, where more than 10 percent of the soil particles pass a number 200 sieve, where more than 10 percent of the soil particles are less than 5 micrometers in size, and/or where the EI is greater than 20.

Identification Tools

There are various methods that can be used to identify expansive soils, including site-specific geotechnical testing and regional soil surveys. Site-specific geotechnical testing is not always required for construction at a subject site. The applicable building code specifies when site-specific geotechnical testing is required.

According to Section 1803.5.3 of the 2024 IBC[12]:

> ***1803.5.3 Expansive soil.*** *In areas likely to have expansive soils, the building official shall require soil tests to determine where such soils do exist…*

Similarly,

According to Section R401.4 of the 2024 IRC[13]:

> ***R401.4 Soil tests.*** *Where quantifiable data created by accepted soil science methodologies indicate expansive soils, compressible soils, shifting soils or other questionable soil characteristics are likely to be present, the building official shall determine whether to require a soil test to determine the soil's characteristics at a particular location. This test shall be done by an approved agency using an approved method…*

Site-specific geotechnical tests provide information regarding boring locations, boring logs, elevation of groundwater (if encountered in the borings), recommendations for foundation types, foundation design criteria, lateral pressures for below-grade structures, expected total and differential movements, and soil remediation recommendations (if warranted).

In Texas, the Texas Department of Transportation (TXDOT) established a test procedure to empirically estimate the swell potential for natural subgrade soils. According to TXDOT's "Test Procedure for Potential Vertical Rise of Natural Subgrade Soils" (TXDOT Designation: Tex-124-E)[15], the potential vertical rise (PVR) is defined as the "potential of soils to swell in the vertical direction at a given density, moisture, and loading condition when exposed to capillary ground or surface water, and thereby increases the elevation of its upper surface, along with anything resting on it." Another empirical estimate for soil swell capacity is potential vertical movement (PVM), which is often considered when evaluating the soil properties for construction sites in Texas; however, PVM may not have a published basis. Typically, geotechnical reports in Texas include an estimate for PVR or PVM that may occur in the subgrade soil.

There are also regional organizations that specify recommended practices depending on the location of a project site. For example, the Texas Section of the American Society of Civil Engineers (TXASCE) "Recommended Practice for the Design of Residential Foundations – Version 2" provides recommendations for site-specific geotechnical testing used for the design of residential foundations[16].

According to TXASCE "Recommended Practice for the Design of Residential Foundations – Version 2":

> ***3.1 Geotechnical Services***
>
> *Prior to foundation design, a geotechnical investigation and report shall be completed by a geotechnical engineer….*

The TXASCE document also provides recommendations for how a geotechnical investigation should be conducted. For subdivisions, TXASCE recommends that borings be spaced at a maximum of 300 feet (91.44 meters) on center. For single lots, they recommend one to two borings. TXASCE recommends that borings shall be a minimum of 20 feet (6.10 meters) in depth, unless rock strata are encountered. In addition, TXASCE[16] recommends that borings shall extend through any known fill or potentially compressible materials.

Section 1803.6 of the 2024 IBC includes a list of information that shall be included in a geotechnical report. According to Section 1803.6 of the 2024 IBC, the information required to be included in a geotechnical report includes provisions to mitigate the effects of expansive soils as well as special design and construction provisions for foundations of structures founded on expansive soils.

According to Section 1803.6 of the 2024 IBC[12]:

> ***1803.6 Reporting.***
>
> *Where geotechnical investigations are required, a written report of the investigation shall be submitted to the building official by the permit applicant at the time of permit application. This geotechnical report shall include, but need not be limited to, the following information:*
>
> *1. A plot showing the location of the soil investigations.*
>
> *2. A complete record of the soil boring and penetration test logs and soil samples.*
>
> *3. A record of the soil profile.*
>
> *4. Elevation of the water table, if encountered.*
>
> *5. Recommendations for foundation type and design criteria, including but not limited to: bearing capacity of natural or compacted soil; provisions to mitigate the effects of expansive soils; mitigation of the effects of liquefaction, differential settlement and varying soil strength; and the effects of adjacent loads.*
>
> *6. Expected total and differential settlement.*
>
> *7. Deep foundation information in accordance with Section 1803.5.5.*
>
> *8. Special design and construction provisions for foundations of structures founded on expansive soils, as necessary.*
>
> *9. Compacted fill material properties and testing in accordance with Section 1803.5.9.*
>
> *10. Controlled low-strength material properties and testing in accordance with Section 1803.5.9.*

In addition, TXASCE's "Recommended Practice for the Design of Residential Foundations – Version 2"[16] includes recommendations for information that should be included in a geotechnical report. At a minimum, TXASCE recommends that geotechnical reports include the following information:

a. Dry density

b. Moisture content

c. Atterberg limits

d. Pocket penetrometer estimates of cohesive strength

e. Torvane

f. Strengths tests

g. Swell and/or shrinkage tests

h. Hydrometer testing

i. Sieve size percentage

j. Soil suction

k. Consolidation

TXASCE recommends that all laboratory testing be performed in accordance with ASTM standards or other recognized standards.

Similarly, for Ontario, the Association of Professional Engineers of Ontario (APEO) published a guideline in 1993 titled Professional Engineers Providing Geotechnical Engineering Services, which outlines the extent of geotechnical services provided, the methodology to be followed, the reporting standards, and the normal range of recommendations that may be included in the report[17].

According to APEO, normal standard sampling is done at 0.75-meter (2.46-feet) intervals initially and may be increased to 1.5 meters (4.92 feet) below the 4.5-meter (14.76-feet) or 6-meter (19.69-feet) depth, if warranted. In addition, APEO recommends that geotechnical reports include details of the field investigation, field testing results, records of groundwater observations (if encountered), laboratory test results, a site plan, infrared soil stratigraphy, and recommendations.

Particularly in residential construction, developers and/or general contractors opt out of site-specific geotechnical testing and rely instead on regional soil surveys. An example of a regional soil survey that is often referred to in residential construction in the United States is the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) Web Soil Survey[18], which is an online service that provides general information about soil types and their characteristics depending on the geographical location of a site. Similarly, Canada has an online resource for soil surveys for many provinces and territories provided by the Canadian Soil Information Service (CanSIS)[19].

Design Considerations

Many design options can be implemented to reduce the potential vertical movement of soils on a site, which depend on a geotechnical investigation, existing site conditions, and the owner/developer's acceptable level of risk with respect to differential movement of a ground-supported structure.

It is worth noting that the IRC[13] refers to the IBC[12] for design methods for foundations on expansive soils.

According to Section R403.1.8 of the 2024 IRC[13]:

> ***R403.1.8 Foundations on expansive soils.***
>
> *Foundations and floor slabs for buildings located on expansive soils shall be designed in accordance with Section 1808.6 of the International Building Code.*

According to Section 1808.6.1 of the 2024 IBC[12]:

> ***1808.6.1 Foundations.***
>
> *Foundations placed on or within the active zone of expansive soils shall be designed to resist differential volume changes and to prevent structural damage to the supported structure. Deflection and racking of the supported structure shall be limited to that which will not interfere with the usability and serviceability of the structure…*

The depth in a soil to which periodic changes of moisture occur is usually referred to as the active zone[20].

According to the IBC[12], foundations placed on expansive soils are designed to prevent structural damage, usability, and serviceability of the structure. Therefore, foundations designed in accordance with the IBC are not designed to prevent cosmetic distress.

General consensus within the local industry (Texas) is that 4.5 inches is the maximum allowable PVR/PVM for a slab-on-grade foundation system. In general, if the PVR/PVM of the soils on a specific site exceeds 4.5 inches, the soil can be remediated to lower the PVR/PVM, or a different foundation type can be selected such that it is not supported by the expansive soils.

Frequent sub-slab plumbing failures in expansive soil conditions triggered a response from the International Code Council (ICC). The International Plumbing Code (IPC) was updated in 2024 to include new regulations regarding plumbing penetrations through foundations on expansive soils.

According to Section 305.8, Section 305.8.1, and Section 305.8.2 of the 2024 IPC[24]:

> ***305.8 Expansive soil.*** *Where expansive soil is identified under buildings in accordance with Section 1803.5.3 of the International Building Code, but not removed in accordance with Section 1808.6.3 of the International Building Code, plumbing shall be protected in accordance with Section 305.8.1 or 305.8.2.*
>
> ***305.8.1 Nonisolated foundations.*** *Under foundations with slabs that are structurally supported by a subgrade, buried plumbing shall be permitted.*
>
> ***305.8.2 Isolated foundations.*** *Under foundations with a slab or framing that structurally spans over an under-floor space that isolates*

the slab or framing from the effects of expansive soil swelling and shrinking in accordance with 1808.6.1 of the International Building Code, the plumbing shall be suspended so that plumbing, hangers and supports are isolated, by a void space, from the effects of expansive soil swelling and shrinking.

Exception: *Plumbing shall be permitted to be buried where it provides drainage of an under-floor space.*

To protect the voidspace, soil shall be sloped, benched or retained in accordance with an approved design methodology. Plumbing, hangers and supports below the slab or framing shall not be permitted to be in contact with the soil or any assemblage of materials that is in contact with soil in the active zone. A slab and plumbing shall not be permitted to be lifted as an assembly to create a voidspace unless the under-floor space is a crawlspace with access to allow inspection of plumbing after lifting.

Organic materials subject to decay shall not be used for hangers, supports and soil retention systems. Materials subject to corrosion shall not be used for hangers, supports and soil retention systems unless protected in an approved manner. Where plumbing transitions to a buried condition beyond the perimeter of the foundation, an adequately flexible expansion joint shall be provided in the plumbing system to accommodate the effects of expansive soil swelling and shrinking.

Soil Remediation Methods

Expansive soil remediation options typically include water injection, chemical injection, moisture conditioning, and/or removal and replacement of the in-situ soils with select fill.

Water injection was developed in the Dallas/Fort Worth area of Texas in the 1950s and early 1960s and is a popular option to reduce the swell capacity of in-situ soils[21]. Water injection involves the controlled introduction of water into in-situ soils to increase the moisture content of the soil, which initially swells the soil and reduces the residual swell potential of the soil. Water injection is accomplished by pushing injection rods vertically downward into expansive soil strata, typically 10 to 15 feet deep from the ground surface, in stages that range from approximately 12 to 18 inches in depth. The injection rods have tips on the ends that allow water to be injected horizontally.

Water is typically injected until it is observed directly at the ground surface (referred to as refusal) or until a minimum time requirement is met. There are specialized injection rigs utilized for water injection, which typically have a maximum injection depth of 18 feet. The injection rods are typically spaced at 5 feet on center across the rig. Once the injection is complete, the rig will move 5 feet, resulting in a 5 foot by 5 foot grid. Most of the time, multiple passes are required, which are offset from the initial grid, resulting in tightening the grid across the site. Most of the time, the injection area is defined as the footprint of a structure plus a nominal distance beyond the footprint of the structure — commonly between 5 and 10 feet outside the footprint of the structure.

Chemical injection is similar to water injection, but rather than injecting water, a chemical solution (lime, bitumen, cement, oils, potassium, etc.) is injected into the soil[22]. The chemicals permeate into the soil and fill in cracks or fissures, which can help improve the volumetric stability of the in-situ expansive soils.

Moisture conditioning of in-situ expansive soils typically requires the removal and re-work of the in-situ soils such that a specified water content and density are achieved through the addition of water and placement of soil in prescribed, compressed lifts. The water content and density are determined by performing appropriate field density-moisture measurements based on a Proctor test for the soils. The resultant soil mixture will have reduced shrink-swell capacity if the design requirements are met.

Finally, a common soil remediation option is the removal and replacement of site soils with select fill materials. Select fill materials have parameters that are defined by the design professional in responsible charge. This option requires the removal of the site soils throughout the footprint of the structure to a specified depth (typically 5 to 10 feet beyond the foundation footprint). The removed soil is then replaced with new select fill materials that have a lesser degree of shrink-swell capacity than the removed soils.

While this is a commonly used method, it also poses a risk for a phenomenon known as the “bathtub effect.” This occurs when water is collected in the excavation zone and highly permeable fill is utilized, which allows water to flow freely and create a reservoir within the fill material[23]. The water can then permeate into the surrounding in-situ expansive soils over time.

To avoid the bathtub effect, it is recommended to install a clay cap or moisture barrier, such as geomembrane, between the in-situ soils and the select fill material as well as between the finished grade surface and the select fill materials. If the bathtub effect occurs, post-construction measures may have to be implemented to restore the moisture content of the fill material and adjacent in-situ expansive soils to a more uniform composition, such as water and/or chemical injection, modified watering, installation of vertical/horizontal moisture barriers, and/or a sub-surface drainage system.

Foundation Types

If soil remediation is not preferred, other foundation types may be considered that reduce/eliminate the impact of shrink/swell of underlying expansive soils on the structure.

Slab-on-grade foundations with piers are commonly designed for areas where soil settlement is a concern. If properly designed and constructed, portions of a slab-on-grade foundation supported on deep foundation elements (i.e., piers/piles) will be prevented from downward movement; however, portions of a slab-on-grade foundation with deep foundation elements (i.e., piers/piles) are still susceptible to heave from the underlying expansive soils.

Sometimes slab-on-grade foundations are only partially supported on deep foundation elements (i.e., piers/piles), and, in such cases, portions of the slab-on-grade foundation that are not supported on deep foundation elements (i.e., piers/piles) are susceptible to both heave and settlement from underlying expansive soils. With any kind of ground-supported foundation, it is important to maintain uniform/consistent soil moisture content, typically achieved by irrigation around the perimeter of the foundation, as well as positive drainage grades to prevent the accumulation of moisture that creates uneven moisture conditions in the soil.

Elevated foundation systems (pier-and-beam, structural concrete slab on void cartons, and proprietary systems) can be used to create a void between the slab and expansive soils to prevent the slab from interacting directly with the underlying soils.

Pier-and-beam foundations are those where the piers (typically wood, concrete, and/or steel) are constructed, ideally, to a bearing stratum, and the grade beams and/or framing members (typically wood, steel, and/or wood/steel composites) are designed to span between the pier supports. If a pier is properly designed and constructed, it will not be susceptible to vertical displacement from the underlying soils. In addition, when concrete-grade beams are designed, a void form may be specified below the grade beams to prevent soil from having a direct impact on the concrete grade beams. The required design depth of piers in expansive soils is often controlled by the uplift force exerted on the pier by expansive soil in the active zone and the resultant required penetration depth into a deeper stratum to resist such uplift.

Structural concrete slabs on void cartons are comprised of piers and grade beams. Before the concrete is formed, void boxes, which are decomposable forms, are placed below the slab and the beams. Once the concrete is placed, it sits upon the void boxes, which decompose over time to ultimately provide a void between the supporting soil and the grade beams and slabs, which prevents the grade beams and slabs from being directly impacted by soil shrinkage and swell. Certain types of void boxes have been found to perform better than others.

It should be noted that trapezoidal void boxes have been found to be problematic as they allow concrete to flow down along the sides of the void boxes, which can result in a portion of the grade beam bearing on the expansive soil beneath the void forms. In addition, although counterintuitive, certain waterproofing methods do not work well with void boxes. In many cases, designers specify — or installers construct — moisture barriers around the void boxes in an effort to protect the void boxes during construction. However, by encapsulating the void box with a weather barrier, it is prevented from decomposing and will remain in place, transferring any pressure from the underlying shrinking and swelling soils below to the foundation structure above.

Finally, there are various proprietary elevated foundation systems that are commonly encountered. In some instances, proprietary systems may not account for all critical details of a foundation structure, including plumbing and gas penetrations. The performance evaluation of these proprietary foundation systems is considered outside the scope of this paper.

Site Conditions

Existing site conditions prior to construction may also affect design considerations for a site and structure, including the presence of a body of water, large vegetation (trees), prior site use, site slopes, and fill depth. For the purposes of this paper, only filled-in bodies of water and vegetation will be discussed.

If a large body of water was previously filled in on a site prior to construction, the fill material installed may have been uncontrolled fill. Therefore, it may not be representative of the site soils outside the perimeter of the prior body of water. In this case, it is important to understand the history of the site and sample soils inside the prior body of water as well as outside the fill area. In addition, if the body of water was naturally occurring due to the location of the water table, ground water may still exist below the fill material, which could impact the performance of the ground-supported structure if not identified and mitigated.

Existing trees removed from a site can also trigger a soil-structure interaction mechanism through natural equilibration of soil moisture. Typically, geotechnical reports should include information about how to properly treat soil adjacent to removed trees to minimize the effect of natural equilibration of soil moisture. Trees possess root systems that withdraw moisture from the soil through the process of transpiration, and the moisture content of soil located near an area of mature vegetation is typically lower than the moisture content of soil not located in proximity to mature vegetation; therefore, previously removed trees at a site would have contributed to moisture withdrawal and relatively drier conditions in a bowl of soil material below and around the location of the trees' root systems for many years prior to construction of a structure.

Construction Considerations

There are construction considerations that can be implemented to ensure the performance of a ground-supported structure on expansive soils. Depending on the design recommendations for soil remediation, the geotechnical engineer and/or civil/structural engineer may specify construction material testing (CMT) methods and testing frequency to monitor the moisture content and/or densities of the soils. If directed to do so, it is the responsibility of the general contractor and their earthwork subcontractor to adhere to the requirements set forth in the geotechnical report and/or civil/structural engineering plans with respect to CMT for site soils.

For example, for re-working soil, a geotechnical engineering report will usually provide requirements for excavation depth, depths for soil lifts for the re-worked soils, compaction density requirements for each lift of soil, an acceptable range for moisture content of the re-worked soil, and a frequency for testing the density and moisture content of soil samples in each lift.

Certain regions and municipalities may require inspections to be conducted during the construction process for portions of ground-supported foundations, such as pier inspections to document the pier depth and bearing capacity for drilled piers, concrete sampling to ensure that the concrete strength meets the minimum requirements of the design, and visual inspections of post-tensioned cable reinforcing and conventional steel reinforcing to ensure proper spacing and cover. While these types of inspections may not be required, they are recommended to ensure that the ground-supported structure meets the minimum requirements of the design specifications.

Documentation of as-built relative elevations for a slab-on-grade foundation, or any type of concrete foundation, can be beneficial for future evaluation of the structure's performance over time. While not commonly documented, original construction elevations (OCEs) can be measured and documented soon after a foundation is constructed, and future relative elevation surveys can be compared with the OCE survey to evaluate potential impacts of the supporting expansive soils.

As previously discussed, the IBC[12] specifies that foundations on expansive soils be designed to prevent structural damage and negative impacts to the usability and serviceability of the structure; however, they are not designed to prevent cosmetic damage. "Slab-on-Ground Foundation Performance Evaluation"[25] by Brian Eubanks, Dean Reed, and Robert Pierry, Jr. discusses foundation performance evaluation methods in accordance with TXASCE "Guidelines for Evaluation and Repair of Residential Foundations"[26] and the Post-Tensioning Institute (PTI) DC10.8-18 "Guide for Performance Evaluation of Slab-on-Ground Foundations,"[27] which provide guidelines for the relative elevations of the foundation to be measured and analyzed for two criteria limits: tilt and deflection.

Tilt is defined as the planar variation from a level condition to one that slopes across the entire foundation[26]. Deflection is defined as the maximum deviation from a straight line between two points[26]. When deflection is referred to as "global" or "overall," the deflection profile is analyzed across the overall foundation dimension in a given direction; whereas "local" deflection is analyzed over a shortened length. Tilt and global deflection are analyzed by taking elevation profiles edge-to-edge of the subject foundation and comparing the maximum values for tilt and deflection against limiting criteria. TXASCE and PTI also require local deflection profiles to be analyzed. In conjunction with tilt and deflection, TXASCE and PTI require distress to be evaluated to determine if the foundation has failed.

It is also recommended that general contractors clearly indicate in their contract documents and/or warranty documents what specific performance standards will be referred to if a structural claim is made regarding differential movement of a ground-supported structure. Some general contractors and owners purchase third-party warranties that may have different evaluation criteria. For example, in Texas, many residential construction contracts utilize the Texas Association of Builders (TAB)[28] templatized contracts, which typically reference the TXASCE "Guidelines for the Evaluation and Repair of Residential Foundations"[26] for performance guidelines for residential slab-on-grade foundations.

Some custom contracts limit the applicability of the TXASCE performance standards by not requiring the evaluation of local deflection profiles. In addition, many third-party warranty standards consider tilt and deflection of a foundation and have requirements for minimum occurrences of distress based upon their severity.

An in-depth discussion of the performance evaluation of ground-supported structures on expansive soils is beyond the scope of this paper; however, some performance evaluation concepts will be presented in the case studies herein.

Potential Remediation Options

It is worth noting that differential movement of ground-supported structures does not "settle out" over time without intervention. As previously discussed, the performance of a ground-supported structure is dependent on the relative moisture content of the supporting soils. Certain mechanisms, such as soil hysteresis and large vegetation, can worsen the performance of a foundation over time due to the lasting and worsening impacts on the soils supporting the structure.

Soil hysteresis is permanent deformation in the soils as a result of cycling of the moisture conditions of a soil over time, which can result in subsequent downward movement of the ground-supported structure. In addition, large vegetation has a lasting impact on soils. As the vegetation and root systems grow over time, more water is extracted by the vegetation, which causes shrinkage of the soils and subsequent downward movement of any ground-supported structure in proximity of, or above, the root system.

The TXASCE "Guidelines for Evaluation and Repair of Residential Foundations" includes various potential remediation options for foundations that exhibit differential movement causally related to expansive soils[26]. Remediation options for foundations exhibiting differential movement due to expansive soil include non-structural and structural measures. Non-structural remedial measures may include a conscientious irrigation regimen/program, vegetation alteration, root barriers, gutters and downspouts, surface grading, sub-surface drainage, and/or moisture barriers. Structural remedial measures may include underpinning, grouting, mudjacking, crack injection, and/or tendon stressing (if the foundation is post-tensioned). The repair of pier and beam foundations typically includes floor shimming, framing repairs, additional support, and/or crawl space moisture control.

Whenever a foundation is lifted or lowered as part of a structural foundation remediation plan, plumbing tests should be performed after completion of the lifting/lowering process to verify whether leaks are present, and any leaks should be repaired. Further, it is recommended to perform a baseline relative elevation survey shortly thereafter for future evaluation purposes if any additional signs of differential foundation movement arise.

Expansive Soils Case Studies

In the following sections, this paper will explore four case studies to illustrate the effects of expansive soils on ground-supported structures and the performance evaluations and remediation options of ground-supported structures on expansive soil. As previously noted, an in-depth discussion of the performance evaluation of ground-supported structures on expansive soils is beyond the scope of this paper.

Case Study #1: Negative Drainage Grades

The owners of a two-story, wood-framed, single-family residence reported distress throughout the interior and exterior of a residential structure. The residence was reportedly constructed circa 2005. An investigation was performed to evaluate the performance of the foundation and to determine the cause of the reported distress and movement. The residence was located in a suburb of Dallas, Texas, which is in the northeast portion of Texas in a region that is well known for exhibiting the presence of expansive clay soils.

Prior to construction, a geotechnical engineer investigated the soil at the site to provide recommendations for the site preparation and foundation design. The geotechnical report indicated potential vertical movements in excess of 6 inches and soil with plasticity indices ranging approximately between 8 and 53. The geotechnical engineer recommended to excavate, moisture-condition, and replace the upper 9 feet of soil below the building pad in order to reduce the estimated potential vertical movement to 4.5 inches or less. The foundation engineer provided the design for a cast-in-place, concrete, slab-on-grade foundation system with auger-excavated cast-in-place concrete piers.

The geotechnical investigation report also provided recommendations for site grading and drainage conditions such that the lot drainage within 6 feet of the foundations should slope a minimum of 10 percent away from the foundations, and, beyond 6 feet, the lots should slope a minimum of 3 percent away from the foundation.

As previously discussed in the Design Considerations section, if properly designed and constructed, portions of a slab-on-grade foundation supported on deep foundation elements (i.e., piers/piles) will be prevented from downward movement (settlement); however, portions of a slab-on-grade foundation with deep foundation elements (i.e., piers/piles) are still susceptible to heave from underlying expansive soils.

Documentation during the construction of the subject residence indicated that the site soils were prepared in general accordance with the geotechnical report, and the foundation was constructed in general accordance with the engineered foundation plans.

On October 17, 2011, a relative elevation survey of the finished floor surfaces was conducted by an engineer utilizing a Zip-Level Pro-2000. According to the equipment manufacturer, the elevation measuring instrument has a tolerance of ±0.1 inch over a range of 200 feet.

The referenced surveying method is relative in that it does not reference a permanent benchmark. Adjustments for differences in floor covering thickness and built-in elevation changes (i.e., step ups/downs) were made for this relative elevation survey. Sloped areas, such as porches, patios, and garages, are typically excluded from the survey because they are typically constructed with built-in slopes to facilitate drainage. However, the garages were included due to the distress located in those areas and to compare with future elevation surveys, if needed. It is important to note that foundations are not constructed perfectly level; therefore, an elevation survey will reflect as-built variances in addition to any net post-construction movements of the foundation system. Furthermore, any zero-inch contour lines or elevations are not intended to indicate the foundation's original elevation, but are used as a reference to compare other relative elevation points. The location of the 0-inch reference point (datum) is generally arbitrary; however, experience and/or previous elevation information may assist in the selection of the reference datum location.

The survey datum was selected in the northwest corner of the living room. The highest relative elevation was +3.9 inches. Excluding the as-built slopes of the patio and garage, the lowest relative elevations were -0.6 inch. Subsequently, these relative elevations indicate a foundation levelness variance of approximately 4.5 inches (absolute difference between minimum and maximum elevation) across the interior portions of the foundation. In general, the foundation of the subject residence exhibited relatively higher elevations in the northeast portion of the structure and relatively lower elevations in the southwest and west portions of the structure.

At the time of the investigation, the site grading and drainage characteristics were documented. It was observed that the subject property exhibited adverse drainage conditions at the northeast corner of the site with water flow directed toward the foundation.

The relative elevation survey for the subject residence and a photograph of the negative drainage grades in the northeast portion of the property are included in **Figure 5** and **Figure 6**, respectively.

Although the site soils were reportedly remediated, the geotechnical report indicated that the subject residence could still be susceptible to potential movements up to 4.5 inches after soil remediation. The as-built site drainage conditions did not adhere to the recommendations of the geotechnical investigation report nor the provisions of the building code, and alternative approved drainage methods were not implemented at the northeast corner of the subject lot. As a result, surficial water was directed toward the northeast corner of the residence, which induced differential heave of the foundation at that location.

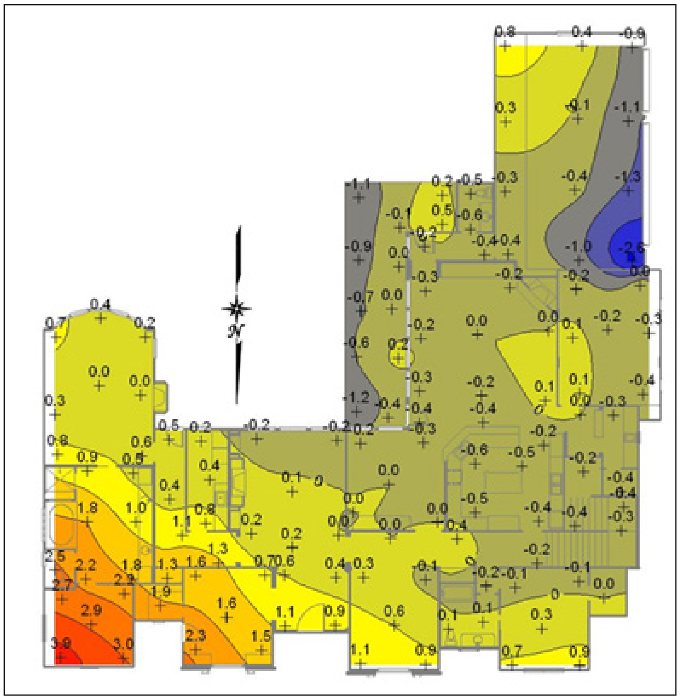

Figure 5
Relative elevation survey of subject residence (October 17, 2011).

Figure 6
Photograph of drainage grades in
northeast portion of the subject property.

Based upon the investigation, distress in the northeast portion of the subject residence was determined to be causally related to moisture-related soil heave under a portion of the foundation adjacent to negative drainage grades in the northeast portion of the subject property.

Case Study #2: Pre-Existing Vegetation

The owners of a two-story, wood-framed, single-family residence reported distress throughout the interior and exterior of the house. An investigation was conducted to evaluate the foundation's performance and determine the cause of the reported distress and movement. The residence was located in a suburb of Dallas, Texas, which is in an area in the northeast portion of Texas that is well known for its expansive clay soils.

Prior to construction, a geotechnical engineer investigated the soil at the site to provide recommendations for the site preparation and foundation design. The geotechnical report indicated potential vertical movements on the order of 1 to 3 inches and soil with plasticity indices ranging approximately between 20 and 39. The foundation engineer provided the design for a cast-in-place, concrete, slab-on-grade foundation system with auger-excavated cast-in-place concrete piers.

As a note in the foundation plans, the structural engineer of record provided specifications for tree removal, indicating that where trees are to be removed within the footprint and extending 10 feet away from the foundation, the area where the tree bulbs are removed should be continuously filled with water for five days before commencement of the foundation construction.

A relative elevation survey of the finished floor surfaces was conducted by an engineer utilizing a Zip-Level Pro-2000. Refer to Case Study #1 for additional information regarding how relative elevation surveys are performed and documented.

The survey datum was selected in the central portion of the foundation. The highest relative elevation was +1.0 inch, recorded in the south-central portion of the structure. Excluding the as-built slopes of the porch, patio, and garage, the lowest relative elevation was -3.2 inches, recorded along the west perimeter of the structure. Subsequently, these relative elevations indicate a foundation levelness variance on the order of 4.2 inches (absolute difference between minimum and maximum elevation) across the interior portions of the foundation. In general, the foundation of the subject residence exhibited a band of relatively higher elevations oriented in the northwest-southwest direction through the central portion of the structure, and it exhibited areas of relatively lower elevations near the interior east-central portion of the structure as well as toward the southwest portion of the structure.

Following the site investigation, historic aerial imagery was reviewed to determine the pre-development conditions of the site. The historic imagery revealed that various trees were previously located within the footprint of the residence.

Trees possess root systems that withdraw moisture from the soil through the process of transpiration, and the moisture content of the soil located near an area of mature vegetation is typically lower than the moisture content of a soil not located in proximity to mature vegetation. Therefore, the previously removed trees at the site would have contributed to moisture withdrawal and relatively drier conditions in a bowl of soil material below and around the location of the tree's root system for many years prior to the construction of the relatively new residence.

When mature vegetation is removed, the soil moisture content of the affected soil is allowed to equilibrate with that of the surrounding soils. The equilibration process involves a natural migration of water or moisture from areas of higher moisture content to areas of lower moisture content. Desiccated root bowls can take several years to rehydrate. The volumetric changes that occur in soil during the equilibration process can cause differential movement in ground-supported foundation structures.

It was determined that a soil-structure interaction causally related to a majority of the differential foundation movement at the subject residence was due to natural soil equilibration in an area of removed trees. Based on the investigation, it was clear that the general contractor and/or their subcontractor associated with site grading had not properly wetted the soil in accordance with the foundation plans at the locations of the removed trees. Aerial imagery of the subject property/residence before and after development is included as **Figure 7**.

Based on the correlation of the location of previously removed mature trees and areas of relatively higher elevations along a northwest/southeast band across the central portion of the residence — and in the southwestern portion of the residence — it was concluded that the relatively higher foundation elevations were causally related to moisture-related soil heave from re-hydration of desiccated soil in proximity to the location of the removed trees.

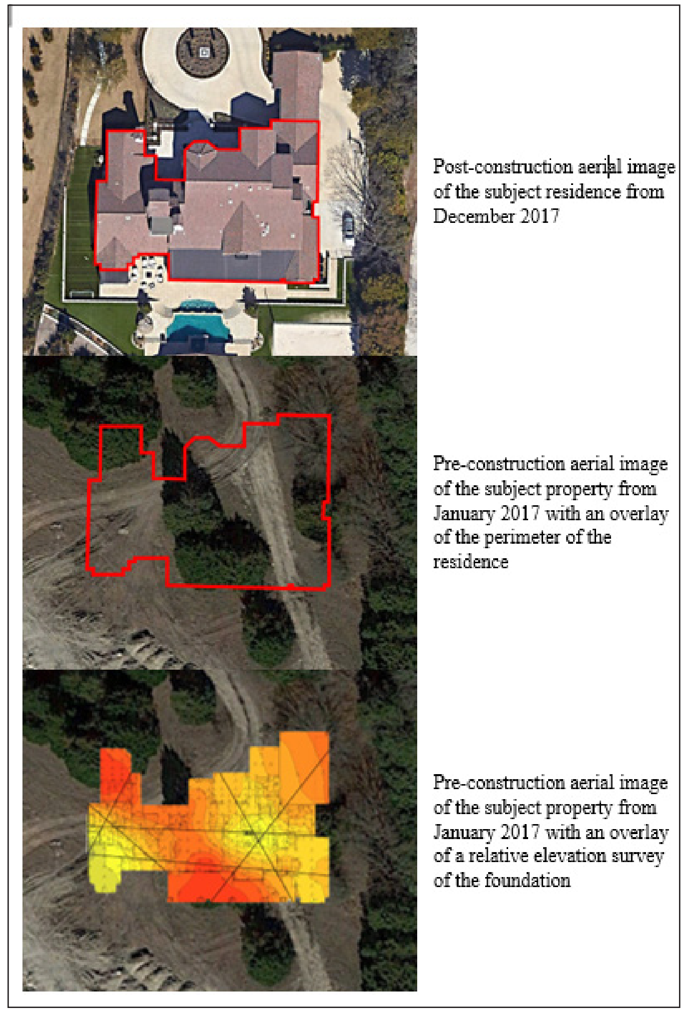

Figure 7
Pre-development and post-development aerial imagery with residence outline overlay and relative elevation survey overlay.

Figure 8
General view of subject site topography.

Case Study #3: Basement Wall Failure

Prior to the development of a complex of duplex carriage homes and single-family homes in McMurray, Pennsylvania, carbonaceous expansive soils were identified through geotechnical investigative testing directed by the developer. Development of the sites in the complex began in approximately 1999, and construction of residential structures began in 2001 (starting at the bottom of a steep hill and working up). A photograph of the site, illustrating the site topography, is included in **Figure 8**.

The owner of a residential unit of one of the duplex structures reported ongoing distress and rotation of a basement wall. According to the owner, the subject residential unit was purchased in 2009. At the time of purchase, there was no visible distress and/or rotation to the basement wall. According to county records, the residential structure in question was among the first to be built in the development. The subject residence has a front-entrance garage, with the dwelling area to the side and rear. A photograph of the subject unit is included in **Figure 9**.

The basement of the subject residence was contained within the footprint of the living area of the main level, and it did not extend below the garage. Schematics illustrating the general layouts of the main and basement levels are included in **Figure 10**.

During construction, carbonaceous expansive soils encountered during excavation of the basement were reportedly removed; however, based on the investigation, the builder did not excavate or remove the corresponding carbonaceous expansive soils beneath the garage or driveway. As those soils expanded, pressure was exerted along the 21-foot-long, front load-bearing wall of the basement and along the 11-foot projecting, load-bearing wall of the basement.

The 11-foot wall appeared to be relatively unaffected by the pressure of the expansive soil due to the short span and additional stiffness from the adjacent wall structures; however, the 21-foot, front load-bearing wall was not as stiff and experienced distress due to the expansive soil pressure. The pressure was highest at the interior corner, and the 21-foot wall broke free from the 11-foot wall and began to rotate, reaching a maximum displacement of 14 inches. **Figure 11** illustrates the movement of the basement wall.

The developer initially denied liability; however, immediately upon filing a writ of summons (initiating litigation), the developer agreed to install temporary jacks, to excavate the expansive soils beneath the garage and driveway and replace them with clean, non-expansive, compacted fill, to re-build the displaced 21-foot wall and the damaged corner formed by the 21-foot and the 11-foot walls — all under the supervision of a 3rd-party inspector — and to provide an assignable extended structural warranty.

Although the reported damage was extensive, the subject residential unit suffered less damage than some other units in the same development due to improperly mitigated carbonaceous expansive soils. Another single-family residential unit in the development experienced such extensive damage that the entire residential structure was rendered unsafe and had to be demolished. The owners

Figure 9
Front elevation of the subject unit.

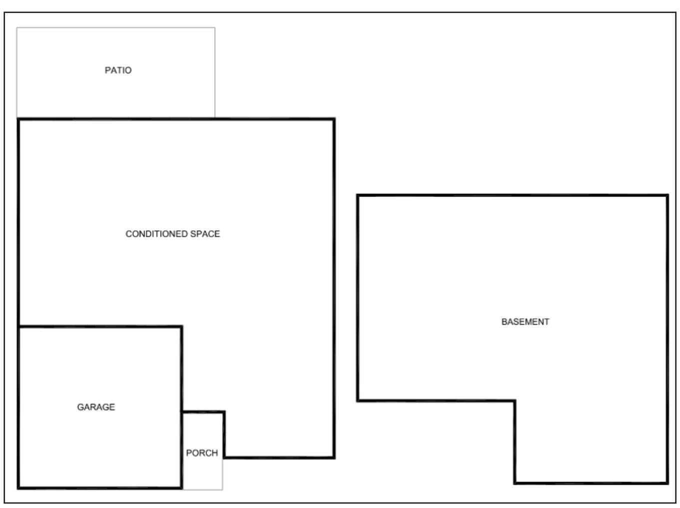

Figure 10
Schematic of the main level (left) and the basement level (right).

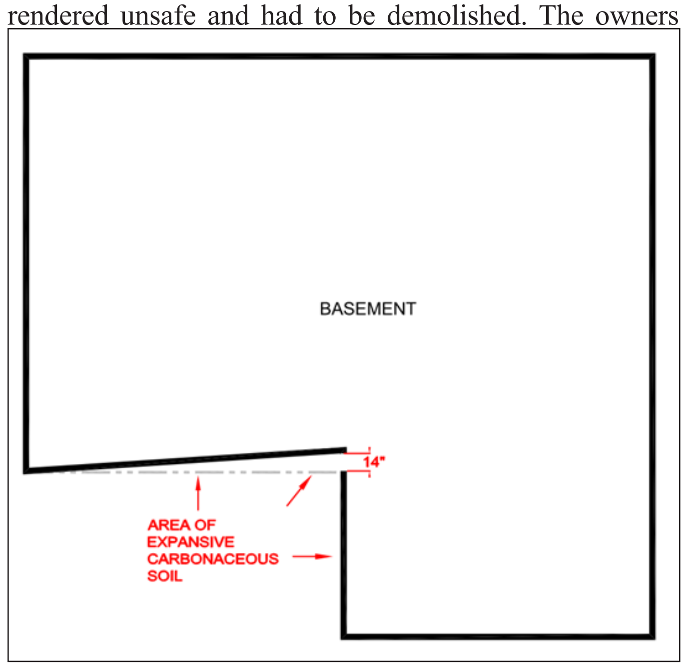

Figure 11
Schematic of the resultant movement to the basement wall.

of the demolished residence were temporarily relocated and subsequently provided with a completely different unit, and the design of the residence was strengthened and rebuilt, according to more robust design and construction methods. However, the carbonaceous expansive soils were not removed. Over time, the previously demolished and rebuilt residential structure experienced distress and structural damage considered severe enough to warrant a second demolition. To the best of the authors' knowledge, the lot remains green space in the development.

Case Study #4: School on Pyritic Soil

The authors were informed that an elementary school structure in southwestern Pennsylvania had experienced differential vertical movement, which had reportedly been ongoing since 2010. The authors were able to access the most recent monitoring report as well as several of the background source documents.

Prior to construction, a geotechnical investigation was completed in 1992. According to the geotechnical investigation report, the existing soils at the site contained expansive pyritic soils. The geotechnical engineering report recommended that pyritic soils be "sealed" when encountered. In the construction and design documents, no reports related to construction material testing of the site soils were identified; therefore, it is unknown whether the general contractor followed the specifications and recommendations outlined in the geotechnical report.

Based upon the reviewed documentation, the construction of the subject school commenced in 1995 and was completed in 1996. The foundation of the subject school is comprised of shallow spread footers with a 4.5-inch concrete slab-on-grade over a 6-inch gravel subbase. Based upon the as-built elevations, the overall slab had moved upward between 1.250 and 2.625 inches since original construction. The as-built drawings included a detail requiring a 1-inch compressible filler to be installed between the non-load bearing CMU masonry walls and steel floor structure above. The inspecting engineer believed this measure was sufficient to prevent some or all of the vertical movement from being transmitted to the floors above.

It was reported that adjustments had been made to the entry doors in order to remain functional. Based on measurements of modifications to the front entry doors, the center of the vestibule floor appeared to have moved upward approximately 2 inches since original construction (**Figure 12**).

Floor cracking and unlevel floor surfaces could be observed throughout the subject school. There was no apparent movement of the columns themselves; however, the surrounding slab-on-grade appeared to have heaved up to 0.5 inches.

Distress to the walls, in the form of cracking and displacement, was observed in some masonry walls of the building, primarily within the electrical room (**Figure 13**). At the northernmost portion of the west masonry wall, a level-line was drawn across a vertical expansion joint on November 20, 2009. The masonry wall to the north is an exterior wall on a shallow spread footer, and the western wall is an interior, non-load-bearing CMU wall on the slab-on-grade. Since that level-line was drawn in 2009, the southern portion of the non-load bearing western wall has risen approximately 0.5 inch. Nearby stairstep cracking was later observed, and follow-up survey data gathered in this area indicated that the southern (interior) wall was rising at a greater rate than the eastern (interior) wall.

The footers, coupled with the weight of the exterior wall loads, appeared to be sufficient to resist expansive forces. Heaving was isolated to the slab-on-grade and non-load-bearing masonry walls, which suggested that expansive pyritic soils remained beneath many portions of

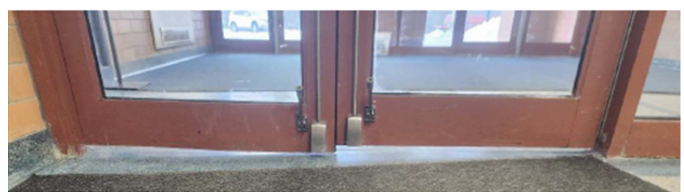

Figure 12
Photograph of the front entry doors.

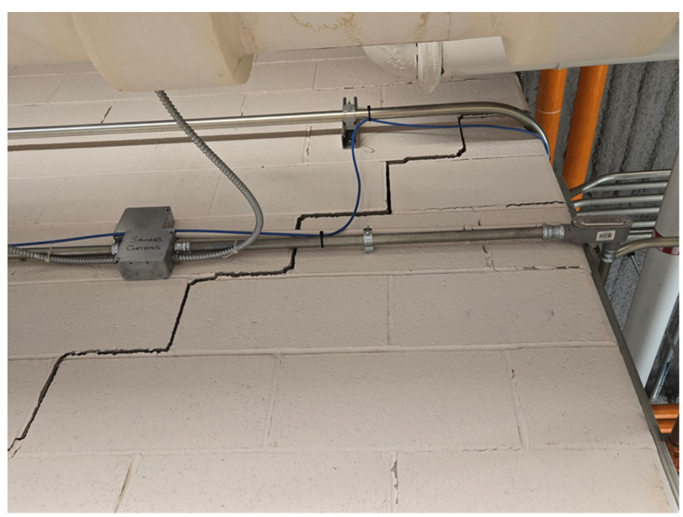

Figure 13
Photograph of cracking in masonry wall.

the slab on grade and were not remediated by removal or “sealing.”

The inspecting engineer recommended interior test borings to verify the depth of the suspected expansive materials beneath the slab on grade, enabling a more accurate prediction of potential future performance. Furthermore, it was recommended to install access ports in the architectural finishes to facilitate expansion joints inspections over time.

Summary

Understanding the prevalence and implications of expansive soils in development and construction is paramount for providing proper design and construction methodologies to mitigate the movement potential of expansive soils to an acceptable level. ASTM standards as well as adopted building codes offer guidance for how to define the expansiveness of a soil. Site-specific geotechnical testing can be performed to classify the in-situ soils at a site, determine the potential movements of the soils, and provide recommendations for soil remediation (if needed) and foundation design options.

Engineered foundation designs may consider the recommendations of a geotechnical report, if available, or, if not, may rely on regional soil surveys. Performing different tests and quality control/assurance measures can ensure that the subject site and structure are prepared in accordance with the engineered plans. After original construction, the performance of ground-supported structures can be evaluated. When not performing as intended, various remediation options, both structural and non-structural, can be implemented to restore the structure’s intended functionality.

Conclusion

Identifying the presence of expansive soils on a construction site prior to design and construction is critical to minimize the risks associated with potential soil movement and the resultant damages to ground-supported structures. Various cases have been presented that illustrate the potential damages that can occur when expansive soils are encountered and not properly planned for in design, construction, and site maintenance phases.

While these studies focus on the impacts of expansive soils on foundations and basement walls, the same principles can be applied to other ground-supported structures, including, but not limited to, in-ground swimming pools, retaining walls, tunnel structures, and trenches. Failure to identify and mitigate the risks associated with the construction of ground-supported structures on expansive soils can not only pose a risk to the appearance and serviceability of a structure, but may also pose a life-safety risk when the movement potential is substantial enough.

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