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On the Move: Case Studies of Expansive Soils and Foundation Movement

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ABSTRACT

Foundation movement has the potential to cause extensive damage to buildings and other structures. One of the most common causes of foundation movement, and specifically differential foundation movement, are expansive soils. Expansive soils can place significant stresses on foundation systems, resulting in damage to the foundation, superstructure, and additional building components. For new buildings, the challenges presented by expansive soils must be considered during project planning and pre-construction site investigation, and must be accounted for in design and during construction. This paper discusses the authors' experiences regarding foundation movement caused by expansive soils. Case studies are utilized to illustrate the destructive potential of expansive soils and the implications of failing to understand or account for this potential at a given site.

INTRODUCTION

When designing a building or other type of structure, engineers must consider the factors that will affect the performance of the foundation over its service life, including those with the potential to result in damaging degrees of foundation movement. One factor that must be accounted for, and that often complicates the design process, is the presence of expansive soils. Expansive soils experience volumetric changes associated with changes in moisture content, expanding as moisture content increases and contracting as moisture content decreases. This behavior has the potential to place significant stresses on foundation systems, which may result in movement and associated damage to a structure's mechanical/electrical components, architectural elements, foundation, and/or superstructure.

In order to properly account for the behavior of expansive soils in the design of a structure, structural engineers must rely on the knowledge and expertise of geotechnical engineers for an analysis of the engineering properties of the soils at a given site. For this reason, structural design engineers must be able to interpret geotechnical recommendations and should also be aware of any limitations that exist with respect to the foundation design.

To limit foundation movement associated with expansive soils to an acceptable magnitude, site characteristics that can affect the moisture content of the soils must be considered during the design and site preparation phases of a project. Such characteristics include a site's natural climate; the frequency of rainstorm events or the potential lack thereof (i.e., periods of drought); grading and drainage conditions; the presence of and potential effects related to groundwater; the existence and location of trees and other large vegetation; and the effects of the proposed changes to the site on the moisture properties of the subgrade soils.

The Manifestation of Foundation Movement and Resulting Distress

When a structure is experiencing differential foundation movement, one of the first warning signs is often damage to less flexible and weaker finishes. Therefore, fractures and separations at interior and exterior finishes are typical early indications of differential foundation movement. These types of architectural distress are also some of the most common reported by a building's occupants. Superstructure framing tends to be more flexible than most architectural finishes and is not as readily compromised by differential foundation movement. Therefore, differential foundation movement is more likely to result in serviceability issues, such as sloped floors, inoperable doors/windows, and finish distress, rather than issues that compromise the structural integrity of a building. However, as the movement becomes more severe, structural framing components can experience distress.

Understanding where foundation movement has occurred and the mode of foundation movement (i.e., is it heave, settlement, or a combination of heave and settlement?), is one of the first steps in determining the primary cause(s) of the foundation movement. Differential heave is commonly caused by the addition of moisture to the expansive supporting soils, while settlement can be caused by a myriad of factors, including but not limited to overloading the bearing soils, poor compaction, or desiccation of expansive soils. Once the patterns and mode of foundation movement have been determined, the cause(s) of the movement may become more readily apparent.

CASE STUDIES

The following case studies illustrate some common issues faced when building on a site with expansive soils, as well as the potential for significant damages caused by differential soil movement.

Case Study 1 – Central Texas Office Building

The subject of the first case study is a two-story, commercial office building located in Central Texas. The building's superstructure consisted of concrete tilt-up panels at the perimeter walls and steel columns and beams supporting steel joist framing at the interior. The foundation consisted of concrete perimeter footings and interior piers located beneath the columns, with a concrete slab-on-grade foundation at the first floor. The scope of the authors' investigation was to determine the cause(s) and extent of the foundation movement and the extent of resulting distress.

It was reported that a few years after the structure was built, the occupants began to notice distress at interior finishes throughout the building and doors that did not properly open/close. Many of the occupants reported feeling as though there were uneven spots in the floor, and noticed that the chairs at their desks would roll on their own. By the time the authors arrived on site, extensive distress was present at the structure, including fractures and separations at interior finishes throughout the building (**Figures 1** and **2**); displaced acoustical ceiling panels and displaced/buckled ceiling grids (**Figures 3** and **4**); separations at the tilt-up wall panel joints at the exterior walls that extended all the way to the roof (**Figure 5**); and buckled cold-formed steel studs at the plenum spaces (**Figure 6**). The extent of distress was consistent with significant differential foundation movement.

Figure 1: Gypsum board separations and fractures

Figure 2: Gypsum board separation and fracture

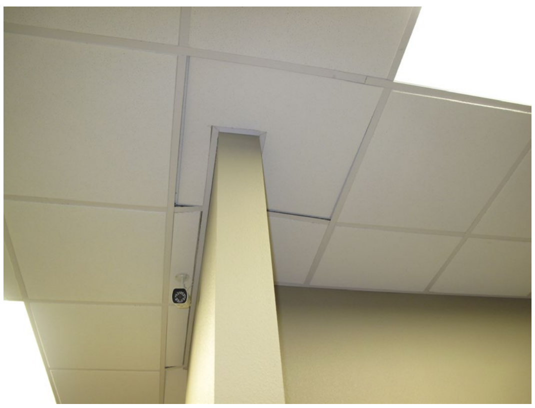

Figure 3: Displaced ceiling panels and displaced/buckled ceiling grid

Figure 4: Displaced ceiling panels

Figure 5: Tilt-up wall panel joint separations

Figure 6: Buckled cold-formed steel stud

To determine the patterns and extents of the differential foundation movement occurring at the structure, relative elevation surveys of the first and second floors were performed. The results of the surveys indicated that each floor was out-of-level by approximately 5", with relative high points located at the north portions of both floors and relative low points located in the vicinity of an elevator at the southeast portion of the structure (**Figures 7** and **8**).

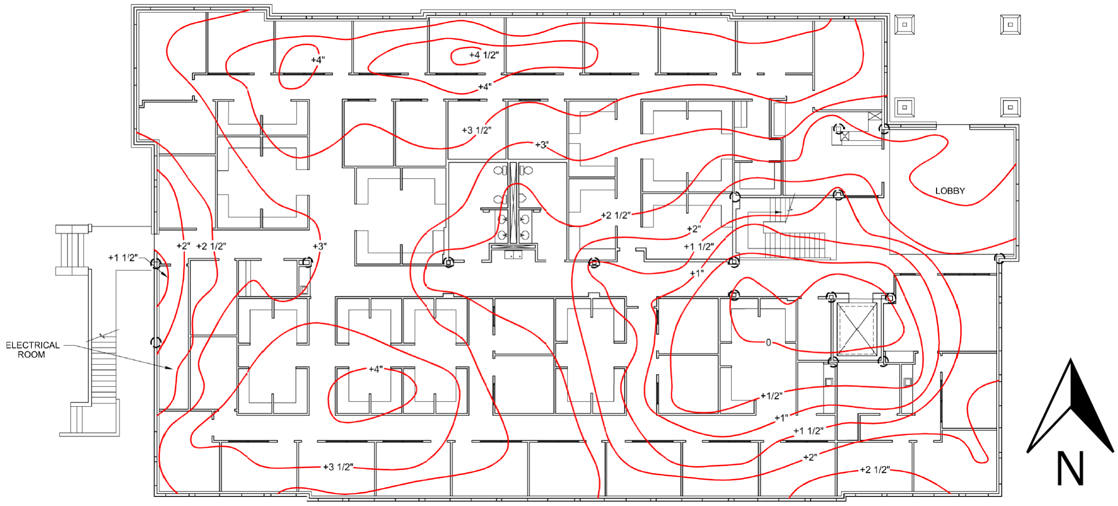

Figure 7: Topography of the structure's first floor

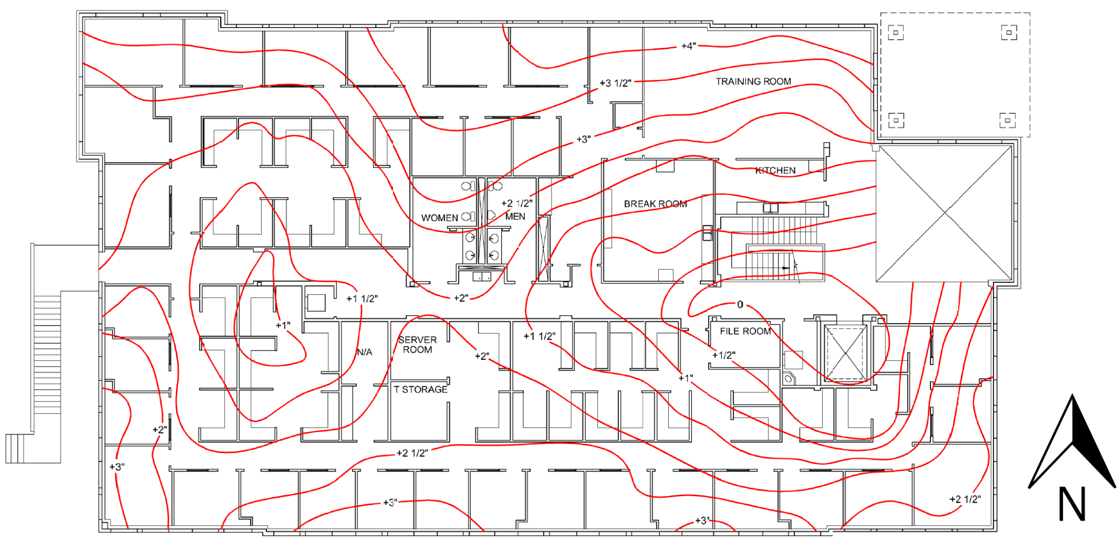

Figure 8: Topography of the structure's second floor

In order to determine the mode of foundation movement that had occurred at the structure, an analysis of the topographic maps obtained from the surveys, and the patterns and nature of the distress observed at the structure's components, was conducted. The most severe distress was located at the south portion of the structure, in the vicinity of the stairwell and the elevator, where the most significant angular distortion of the foundation had occurred. The appearance and patterns of this distress indicated that interior finishes had moved upward relative to the low point located near the elevator. The buckling of cold-formed steel studs at the plenum spaces was also consistent with upward movement of the foundation. Based on the measurements and observed conditions, it was determined that the primary mode of foundation movement that had occurred at the structure was differential heave. The patterns of differential foundation movement were also consistent at both floors, and distress was present at structural components, including at the perimeter tilt-up wall panels. This indicated that the foundation movement was not limited to the foundation slab, but that it had also affected the piers and concrete perimeter footings, and caused movement of the superstructure.

The pattern and degree of upward movement occurring at the structure were consistent with a significant source, or sources, of moisture influencing the underlying expansive soils. Grading and drainage conditions at the site were poor, allowing surface water to collect near the perimeter of the structure. The topography of the site and the surrounding areas was also such that surface water flowed downhill from the adjacent properties toward the structure, increasing the amount of moisture available to accumulate and migrate beneath the structure, where it could then influence the supporting soils and cause the observed differential heave. The poor performance of the structure so early in its service life raised significant questions related to the causes of the differential foundation movement.

To attempt to answer these questions, a review of the pre-construction geotechnical engineering report was undertaken. This review indicated that, while expansive soils were identified at the site, the geotechnical engineer estimated the Potential Vertical Rise (PVR) to be only 1-1/2", maximum, for the expansive soils supporting the structure. PVR is a value that communicates the latent or potential ability of a soil material to swell and is commonly used as a measure of the expansive characteristics of the soil at a given site. Given the differential vertical heave of approximately 5" experienced by the structure, the original PVR appeared to be significantly underestimated. An independent forensic geotechnical engineering investigation was performed, and it was determined that there had been an inaccurate assessment of the types of soils present at the subject site, and an underestimation of the soil's potential for moisture-induced volume changes. This error resulted in greater-than-expected differential soil movement, beyond that anticipated in the design of the structure's foundation, and ultimately resulted in the associated building damage.

The expansive characteristics/potential of the site soils far exceeded the amount originally anticipated by the geotechnical engineer and communicated to the structural engineer for the design of the foundation. The failure to identify the true expansive nature and potential of the subgrade soils resulted in significant differential foundation movement, including differential heave of the piers and superstructure framing, and failure of the foundation system. This case study is an illustration of the potential for significant ramifications of excessive differential soil movement. If the true potential for differential foundation movement had been identified during the geotechnical investigation phase of the project, the construction of this project would have required more extensive site preparation, and likely would have changed the foundation design.

Case Study 2 – Central Texas Entertainment Facility

The subject of the second case study is a sprawling entertainment facility located in Central Texas. The superstructure consisted of concrete tilt-up perimeter wall panels and steel columns and beams supporting steel joist framing at the interior. The foundation was constructed with perimeter footings supporting the concrete tilt-up panels, piers supporting the interior columns, and a concrete slab-on-grade. The scope of the authors' investigation was to determine the cause(s) and extent of the foundation movement and the extent of resulting distress.

It was reported that the facility began to exhibit evidence of foundation movement within approximately a year of construction. Facility managers noticed ever-worsening separations, fractures, and shifting finishes; low spots and visible sloping in the floors; and doors that did not close properly. Notably, the facility's bowling alley had experienced movement such that a portion of the lanes had reversed slope, leading to bowling balls stopping midway down the lanes or rolling backwards. Additionally, excessive amounts of surface water were accumulating at the perimeter of the structure, which resulted in water intrusion at multiple entry doors. Due to these conditions, remedial site drainage work was initiated. The remedial work included removing portions of the concrete flatwork and installing a subsurface drainage system.

By the time the authors arrived on site, extensive evidence of differential foundation movement was present at the facility. Vertical offsets and separations were observed between the flatwork and the foundation at the structure's perimeter; the exposed concrete slab-on-grade and tile flooring exhibited fractures with vertical offsets (**Figures 9** and **10**); and many of the doors were either inoperable or had required adjustment in order to continue to function properly. The stairs and risers inside the theaters had separations and buckled carpet (**Figure 11**), and many of the gypsum board finishes throughout the interior were separated, buckled, and/or fractured (**Figure 12**), particularly at beam-to-wall interfaces and around the windows. However, the tilt-up wall panels at the structure's perimeter did not exhibit patterns of fractures or separations.

Figure 9: Fractured concrete slab-on-grade exhibiting vertical offsets

Figure 10: Fractured tile floor; visibly sloping floor

Figure 11: Separation at a movie theater platform riser

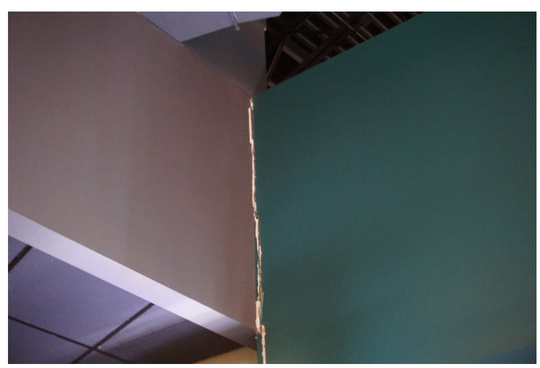

Figure 12: Gypsum board separation at a beam-to-wall interface

The results of a relative elevation survey of the floor surface indicated distinct areas of higher elevations (i.e., "domes") located at the interior of the foundation, while the relative elevation measurements at the perimeter were relatively consistent (**Figure 13**). Notably, the slope of the floor surface did not exhibit discrete elevation changes, indicating that the interior piers and slab-on-grade had moved (heaved) somewhat synchronously, while the perimeter grade beams experienced much less differential movement and remained relatively flat (i.e., exhibited relatively consistent elevations).

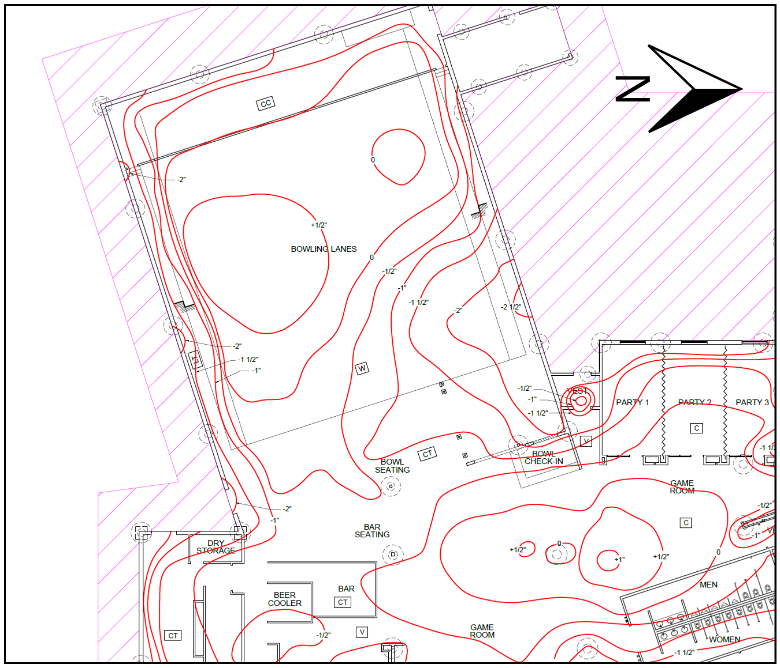

Figure 13: Localized domes in the topography of the facility

The geotechnical documentation included a pre-construction evaluation and a follow-up forensic evaluation performed by the geotechnical engineer of record approximately one year after construction. The pre-construction geotechnical investigation included nine borings, up to 60' deep, revealing fat clay over limestone. The geotechnical recommendations advised that the soils had a moderate to very high potential for volumetric changes if changes in water content occurred. No subsurface water was encountered during the borings. In order to determine the PVR of the soils, the geotechnical engineer performed two tests: a Texas Department of Transportation method and a free swell test. Using the Texas Department of Transportation method, the calculated PVR was 3-1/2" to 4-1/2", while the free swell test indicated a PVR of 7-1/4" to 11". Based on these results, the geotechnical engineer recommended that measures be taken to prevent the soils that support the structure's foundation from experiencing significant changes in moisture content. In order to reduce the PVR to 1", the geotechnical engineer recommended placing select fill to a depth of 3-1/2', and moisture conditioning to a depth of 10' below the building, as well as providing grading and drainage provisions generally in line with model building codes. Moisture management systems were also recommended to help mitigate the flow of surface water at the building's perimeter and to help maintain a consistent water content in the soils below the structure.

After the facility occupants noticed distress consistent with differential foundation movement, about one year after construction, the geotechnical engineer of record performed a forensic evaluation. During this evaluation, groundwater was encountered at seven of the ten forensic boring locations, consistently between 3' and 4' below final grade. It should be noted that the borings performed during the pre-construction geotechnical evaluation did not indicate any groundwater down to 60' below final grade. The forensic borings indicated three layers of stratum: the top layer of select fill, a middle layer of moisture-conditioned soils, and the bottom layer of in-situ, unconditioned soils. The middle and bottom stratums had very high plasticity indices, consistent with the properties of the site soils determined during the pre-construction geotechnical evaluation. Based on the forensic geotechnical evaluation, it was concluded that the moisture content of the site soils had increased significantly since the initial evaluation. Swell tests performed at the middle stratum revealed limited swell potential, as the soils had already experienced the majority of the potential water-related expansion. The geotechnical engineer identified several possible causes for the groundwater encountered during the forensics evaluation, including a possible plumbing leak and poor drainage of the flatwork at the perimeter of the structure.

Considering the relative elevation survey data obtained by the authors, additional water at the perimeter of the structure due to poor subsurface drainage did not, by itself, account for the significant amount of heave occurring throughout the interior of the building. The pattern of differential movement throughout the foundation system was indicative of a "global" phenomenon. The plumbing systems were tested, with no indication of a leak. Further, the domes at the interior of the structure did not correlate to the locations of plumbing lines. Based on the forensic geotechnical evaluation, it was apparent that groundwater conditions had changed significantly since construction of the building, and that these changes had resulted in an unexpected increase in moisture within the subgrade soils. These significant changes and the severity of the resultant damages begged the question: what caused the groundwater characteristics of the site to change and affect the soils supporting the foundation?

The authors reviewed drought data maintained by the National Drought Mitigation Center. The data showed that the area of Central Texas where the facility was constructed was in a severe drought for approximately one year prior to the pre-construction geotechnical site investigation. Additionally, the area had been abnormally dry or in a drought condition for the four years preceding construction. Essentially, the pre-construction geotechnical site investigation and construction of the facility had occurred following a long dry period, which resulted in abnormally dry soil conditions. The dry condition of the soils at the site accounts for the high swell potential determined by the geotechnical engineer and the lack of groundwater within the borings during the initial site investigation. Rainfall data from the National Oceanic and Atmospheric Administration indicated that the site experienced twice as much rain in the year after the facility was completed than in the years prior to and during construction, and was no longer experiencing drought conditions as of the time of the author's evaluation. While soil preparation, including moisture conditioning, was performed at the site, the changes in the subsurface moisture characteristics were beyond what was anticipated in the pre-construction site preparation recommendations.

The zone of soil that influences heave is commonly called the "active zone". An increase in the depth of the active zone at a site can result in significant heave and resultant distress at a structure. The significant variance from the anticipated moisture conditions at the site soils resulted in global heave of the structure's piers and slab-on-grade foundation system.

The climatic conditions preceding construction may have contributed to a significant increase in the depth of the actual active zone of soils compared to that which was anticipated in the original evaluation and design recommendations. The failure to identify the potential for significant subsurface moisture changes, in combination with poor as-built site drainage, resulted in significant differential movement and failure of the facility's foundation. This not only created ongoing serviceability problems for the entertainment facility, but also created potentially serious egress issues due to inoperable doors in a crowded building.

CONCLUSIONS

Expansive soils present many challenges for the design, construction, and long-term serviceability of buildings and other structures. As presented by the case studies included herein, when the expansive potential of the soils has been estimated and considered in the design of the foundation, it is still not always possible to account for the patterns and degree of subgrade movement that may occur at a site with expansive soils. As a result, some amount of differential movement should always be expected. Thankfully, such movement will not necessarily result in damage (or significant damage) to a structure, as long as the serviceability and strength limits of the structure's components are not exceeded. However, significant variations in subgrade soil conditions in comparison with the conditions assumed during the pre-construction evaluation and foundation design can result in excessive differential foundation movement and damage to a structure. To mitigate such damage, engineers must remain vigilant when designing a building on expansive soils. Underestimation of moisture changes in the site soils due to climate variability over the life of a building can have serious detrimental effects o the building's serviceability and may necessitate expensive repairs, which may be intrusive or difficult to implement.