Residential House Foundations on Expansive Soils in Changing Climates

Nafisa Tabassum
Rifat Bulut
School of Civil and Environmental Engineering, Oklahoma State University

Abstract

Today, communities are vulnerable to extreme weather events, natural disasters, and geologic hazards resulting from changing climates. The U.S. Department of Housing and Urban Development (HUD) aims to provide sustainable, resilient, energy efficient, and healthy homes to its stakeholders. HUD has a great opportunity to invest in climate resiliency to achieve the goal of advancing sustainable communities. Climate change has increased the risk of exacerbating geologic hazards, especially under extreme events like excessive precipitation and drought or shifting patterns of climatic extremes. Lightweight structures with shallow foundations, such as residential houses with slab-on-ground foundations built on expansive soils, are more vulnerable to climate-related challenges than those situated on sites with non-expansive soils (Diaz and Moore, 2017; Mostafiz et al., 2021). Therefore, current design codes and methods need to be improved to mitigate the problems of slab-on-ground foundations of residential houses constructed over expansive soils.

Expansive soils are well-known geologic hazards for residential homes. Even without the exacerbating effects of climate change, they can cause extensive problems to foundations due to their swelling and shrinking characteristics. Expansive soils swell when water enters the soil and shrink when the soil dries out. These swelling and shrinking cycles can lead to severe cracks in foundations and walls and can cause other damages. When foundations are not designed to withstand the movements of expansive soils, houses will begin to show signs of distress in the form of cracks. As the walls move, the cracks begin to appear and, thereafter, progressively, doors start to jam, floors tilt, and structural integrity may diminish. These damages, whether they are at cosmetic levels or more severe but not at a structural failure state, can have multiple consequences, such as reduced service life of the structure, reduction of energy efficiency caused by increased air leakage and heat exchange through cracks or voids in walls and foundations, and loss of durability due to water intrusion. These same consequences can also cause emotional distress, loss of property value with the prospect of costly repairs, and affect occupant health due to impaired indoor environmental and air quality.

In the United States, in addition to many locally supported and practiced design methods, the current Post-Tensioning Institute (PTI) design code DC10.5-19 is widely recognized across many states (Vann and Houston, 2021). PTI DC10.5-19, "Standard Requirements for Design and Analysis of Shallow

Abstract (continued)

Post-Tensioned Foundations on Expansive and Stable Soils," is a more rational method compared with its predecessor versions, and it is based partly on unsaturated soil mechanics principles. However, it still contains some major shortcomings. The use of unsaturated mechanics, climatic and other moisture boundary conditions, soil properties, and soil-structure interface can be used in a more rational way following current knowledge. With these improvements, it is possible to better predict the performance of houses and better manage the risk and potential consequences of building on expansive soils. With the financial support that HUD provided, this research study aimed at developing several design modules that use the principles of unsaturated soil mechanics and soil-structure interaction. These modules reflect the most recent advances and current thought.

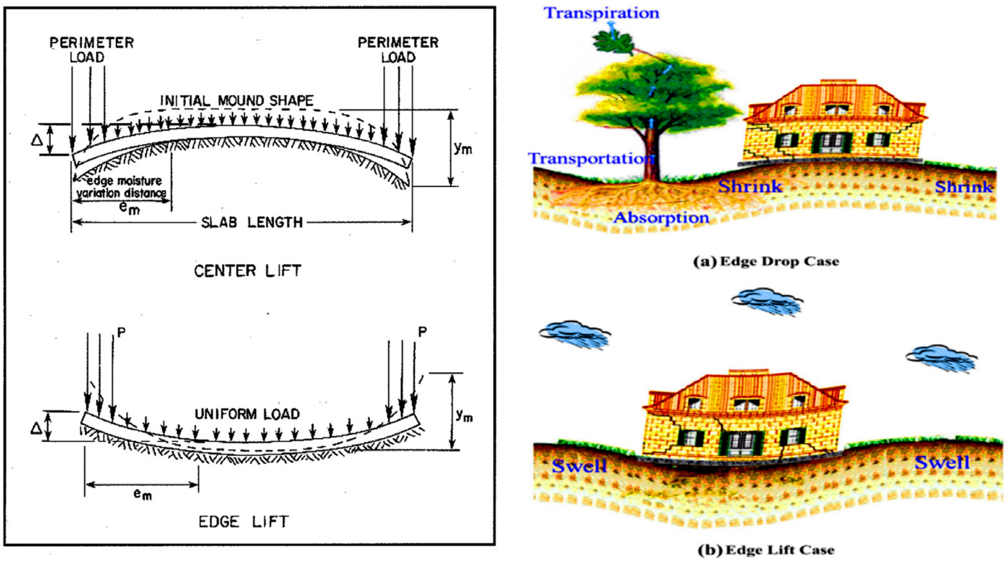
Introduction

A significant number of residential houses in the United States have been built on expansive soils, and among those houses, a considerably high number are likely to have performance issues (Mostafiz et al., 2021). In the early 1950s, the development of design procedures for slab-on-ground foundations followed an empirical approach based on experience. During the 1960s, the Federal Housing Administration, a HUD precursor, initiated a research study to develop design methods for slab-on-ground foundations. That study, in the literature, is known as the "BRAB Method" (BRAB, 1968). The BRAB method identified four basic slab-on-ground slab types based on soil properties, climatic conditions, and functional levels. After BRAB, several different approaches began to appear at the local and national levels. However, all these methods or standards were still mostly based on experience and did not contain many of the mechanics-based techniques. For the most part, many of them were inconsistent and very different from each other in terms of climatic and soil design parameters and types of structural slabs.

Designing foundations on expansive soils has always been a great challenge for any geotechnical engineer due to its unique swelling and shrinkage characteristics. It is essential to examine buildings these soils affect to grasp the behavior of their foundations. Expansive soils contain very fine clay minerals (smaller than 2μm) that swell when they absorb moisture and shrink when they lose moisture. This moisture cycle is a key factor for volume changes in expansive soils. Differential soil movement takes place as a result of nonuniform moisture distribution within the soil beneath the foundation, causing significant damages to lightweight structures, particularly shallow residential slabs-on-ground. If the soil below the slab undergoes a change in its moisture content after the construction of the slab, it will twist into one of two worst-case modes—center lift or edge lift. The center lift, or edge drop, condition occurs when the moisture level of the soil surrounding the slab perimeter slowly drops, and the soil shrinks, or compresses, by comparison with the soil underneath the interior of the slab. On the contrary, the edge lift case arises when the soil below the perimeter of the house becomes wetter than the soil beneath the interior of the slab, causing it to expand, or swell. Exhibit 1 illustrates both center lift and edge lift modes of a shallow slab-on-ground situated on expansive soils.

Exhibit 1

Center Lift and Edge Lift Modes of Slabs on Expansive Soils (Left) and Damage Caused by Expansive Soils (Right)



Sources: Post-Tensioning Institute, 2004; Zhang and Briaud, 2015

Each year, residential homes across the United States are exposed to adverse and extreme climatic events (Jones and Jefferson, 2012; Mostafiz et al., 2021). The extreme events are exacerbating the potential for geologic hazard of expansive soils. The building standards are designed to ensure an acceptable level of safety during the life of the structure. However, many residential houses are still at risk of bearing performance issues. Although these structures have an increasingly high potential for experiencing problems, the designs can also be compromised in an effort to reduce the construction cost, in addition to other issues like poor construction and maintenance (Mostafiz et al., 2021; Vann and Houston, 2021). The building codes must always emphasize striking an appropriate balance between cost and performance, including safety and durability (Vann and Houston, 2021). The responsibility of a designer is to select the best economical design strategies, using building standards that serve satisfactory performance in its lifespan, as locally adopted and legally required minimum building code regulations govern.

With these issues at hand, the Wire Reinforcement Institute (WRI) and the Post-Tensioning Institute (PTI) have advanced existing design codes in recent decades. The WRI and PTI versions are currently well recognized in the construction industry and used by design engineers (PTI, 1980, 1996, 2004; WRI, 1981, 1996). However, in these standards, some areas lack current knowledge in implementing unsaturated soil mechanics principles and soil-structure interaction modeling. In essence, the building codes must provide the most up-to-date engineering and technical knowledge and contain all necessary design information and methodologies that are easy for design engineers to follow and implement. A building code must also offer the homebuilding industry state-of-the-art developments that could result in more economical, durable housing with minimum construction costs.

This article presents a brief discussion about the ongoing project at the School of Civil and Environmental Engineering at Oklahoma State University with HUD-provided financial support. The project aims at developing several design modules using the principles of unsaturated soil mechanics and soil-structure interaction. The developed modules will reflect the most recent advances relating to current knowledge that will be able to predict more realistic stresses and deformations in the slab and to determine practical soil design parameters that characterize the performance of the foundation soil under applied loads, various climatic events, and other moisture boundary conditions.

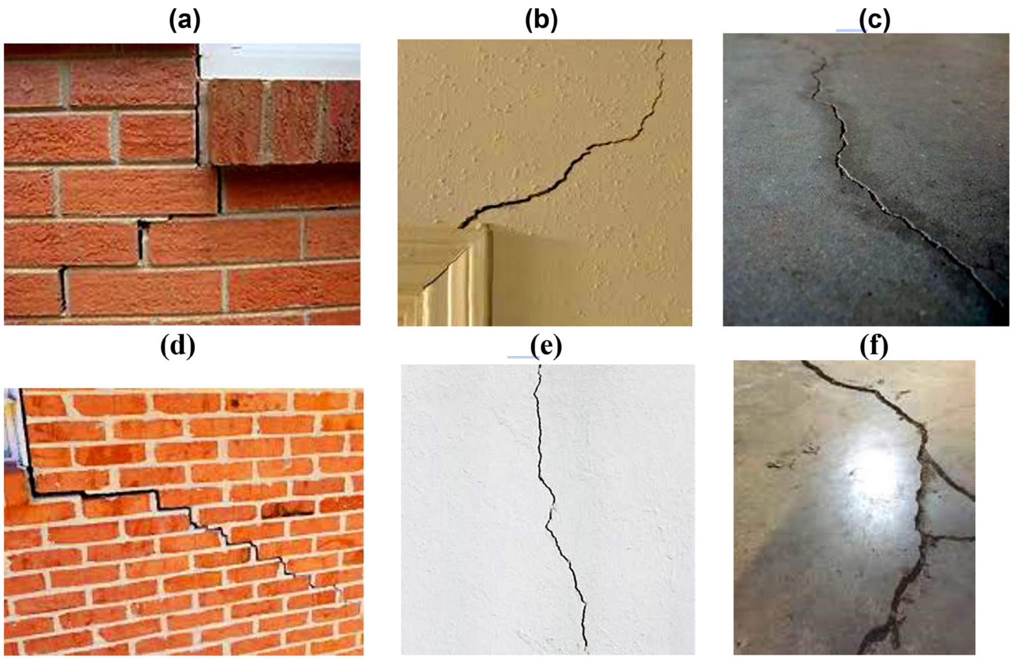
Background

The problems with expansive soils are global. Expansive soils are considered the most common geologic hazard. These soils cause billions of dollars worth of destruction to building foundations and structures annually. According to the American Society of Civil Engineers, one in every four residences in the continental United States has experienced disturbances by expansive soils, with the yearly cost of damages to buildings and infrastructure surpassing $15 billion, which is more than twice the amount of destruction that all other natural disasters cause combined, including earthquakes, hurricanes, tornadoes, and floods (Jones and Jefferson, 2012). For instance, Witherspoon (2000) indicates that Dallas, Texas, listed more than 120 foundation repair companies in the phonebook. During the same period, approximately 15 geotechnical engineering firms were conducting foundation designs for residential homes. These numbers illustrate the severity of the problem.

Residential homes will begin to show signs of distress in the form of cracks if the foundation has not been designed properly. As the walls move, the cracks begin to appear, doors start to jam, floors tilt, and structural integrity may be in jeopardy. These damages can reduce the design life of the structure, reduce its energy efficiency, and cause psychological stress to its occupants. These cracks allow for rapid infiltration of heat and cold, thus reducing energy efficiency and creating pathways for the penetration of moisture and other harmful substances. The cracks also compromise the structural integrity of the house, making it more vulnerable to damages during other disaster events, such as earthquakes. Exhibit 2 illustrates some practical cases of structure damage due to expansive soils.

Exhibit 2

Typical Damages that Expansive Soils Cause



Sources: (a), (d) https://www.jeswork.com/resources/foundation-repair/reasons-why-your-homes-foundation-is-cracking/ (b), (e) https://www.dawsonfoundationrepair.com/best-sugar-land-foundation-repair-company/ (c) https://garagetransformed.com/garage-floor-cracks/ (f) https://inspectaproperty.com/blog/f/expansive-soil-what-you-should-know

Slab-on-ground foundations became common in the early 1950s. The Building Research Advisory Board (BRAB) developed an empirical design procedure in the United States in the 1960s (BRAB, 1959, 1962, and 1968). The main objective, at that time, was simply to put the basis for designing a stiffened slab foundation on expansive soils. The Federal Housing Administration approved the BRAB procedure in 1968. In the procedure, design loads are assumed to be uniformly distributed across the slab. A support index is defined by climatic rating and plasticity index of soil. Irregular slab shapes are split into overlapping rectangular shapes and design values for maximum moment, maximum shear, and maximum deflection are calculated (BRAB, 1968). Among some engineers, the BRAB method is not considered a realistic design approach, because it does not contain a theoretical basis. Instead, a slab type is chosen among a set of empirically developed slab shapes based on the soil properties and a climatic index.

The WRI developed a method in 1981 that is very similar to the BRAB approach. In 1996, WRI updated its design methodology. WRI also considers climatic index, plasticity of soil, and soil-climate support index. The beam spacing and cantilever length are calculated from the support index, and the maximum bending moment, maximum shear, and maximum deflection are then determined (WRI, 1981, 1996).

The Wray and Lytton research served as a basis for the PTI design methodology, which has been continuously modified through the years (Wray, 1978). For structures built on expansive soils, Wray (1978) introduced the parameter edge moisture variation distance, which is based on a climatic factor called the Thornthwaite Moisture Index. The edge moisture variation parameter represents the distance from the edge of the slab inward. PTI afterward embraced this approach and introduced its first edition of the design guidelines in 1980 (PTI, 1980). In 1996, PTI published its second edition of the PTI design procedure. This edition focused on the design of both ribbed and uniform thickness foundations (PTI, 1996).

With the inclusion of several amendments during the years by the PTI's DC-10 Slab-on-Ground Committee, PTI released its third edition of design guidelines in 2004. Major adjustments were made in the assessment of geotechnical parameters (PTI, 2004). The edition includes an updated relationship between soil suction (moisture stress in soil) and the Thornthwaite Moisture Index. In the procedure, the soil analysis relies on the soil index properties. The suction compression index, a parameter that defines the magnitude of soil volume change, is calculated from both clay type and soil index properties adjusted for gradation. The unsaturated soil moisture diffusion coefficient, which determines the rate of moisture movement in the soil, is computed using the suction compression index and the slope of the soil-water characteristic curve, a relationship between the suction and soil water content. Further, the soil-water characteristic curve, which laboratory testing ideally determines, is instead derived from empirical correlations to soil index properties and gradation. Later, PTI updated the third edition with a supplement in 2008 (PTI, 2008). Whereas these parameters and concepts are heavily representing the principles of unsaturated soil mechanics, most of them are determined indirectly through some other factors and experience.

In 2019, PTI published the latest version of the design guidelines named "PTI DC10.5-19 Standard Requirements for Design and Analysis of Shallow Post-Tensioned Concrete Foundations on Expansive and Stable Soils," which is an update to the "PTI DC10.5-12 Standard Requirements for Design and Analysis of Shallow Post-Tensioned Concrete Foundations on Expansive Soils" (PTI, 2012, 2019). The newest version mainly highlights stable soils, PTI foundation types, noncompliant rectangles, shape factor recommendations, rib continuity, and edge drop moment calculation requirements (PTI, 2019).

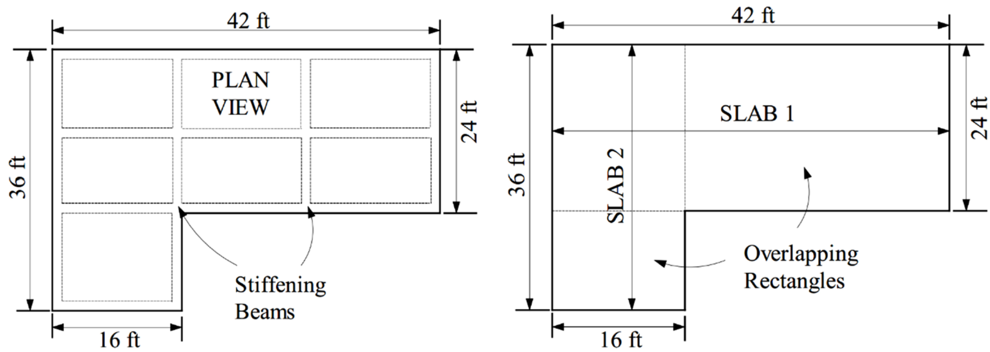
Many states permit local authorities with jurisdiction to use or amend building codes to meet their unique requirements or, in a few exceptional cases, to build their own codes. HUD is in favor of implementing regulations that consider both regional and local interests that will minimize risks to communities in the long run. HUD has prioritized funding for the invention, adoption, and use of the latest and most robust building codes to guarantee that buildings constructed within an area can survive any potential future threats.

Shortcomings of Current Design Methods

Design methods currently used (that is, PTI, WRI, BRAB, and others) have significant shortcomings for structural analysis of slabs and do not possess a rational approach for establishing and modeling deformed ground surfaces due to swelling and shrinking of soils. The frequently used PTI method and some other methods assume an overlapping approach for residential house slabs that are not square or rectangular in shape, as exhibit 3 depicts. In other words, the methods simply cannot handle a nonrectangular shape slab for structural analyses to obtain deformations, moments, and shear forces. The overlapping rectangle approach is simply not realistic and misses stress concentrations at critical locations in the slab due to the nonrectangular nature of the slab geometry and various loading and boundary conditions. Studies show that current methods result in sharp and discontinuous stresses over a very short distance in the slab that cannot be explained (Bulut and Lytton, 2002). The current procedures also make unrealistic assumptions by assigning only uniform foundation soil parameters around the perimeter of the slab, as well as uniform loading patterns, as exhibit 4 shows. A complete edge lift or edge drop case is considered to produce the worst-case scenario for design; however, whether the combination of the edge lift and edge drop would generate other critical stress concentration areas is unknown.

Exhibit 3

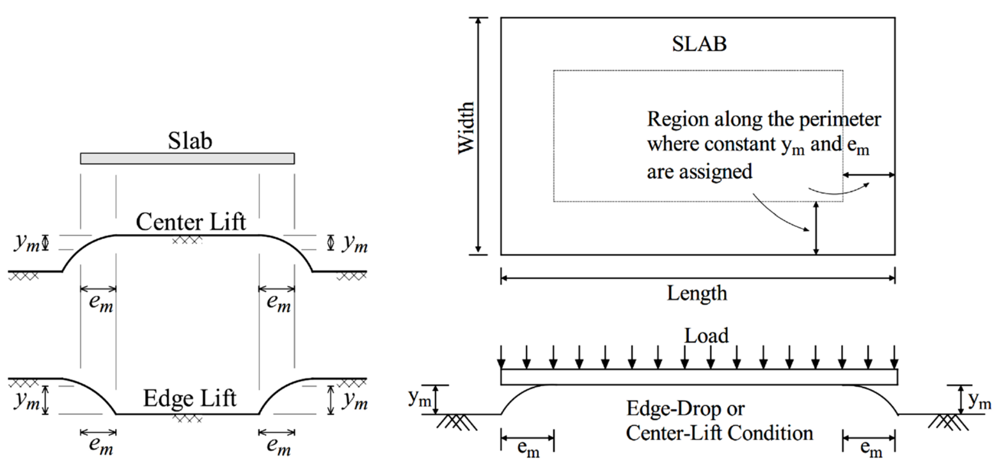
An L-Shaped Slab with Stiffening Beams (Left) and Overlapping Rectangles Assumption for Structural Analysis (Right)



Source: Bulut, 2001

Exhibit 4

Typical Worst-Case Conditions for Design (Left) and Uniform Foundation Soil Parameters Around the Perimeter of the Slab and Uniform Loading Condition for Design



Source: Bulut, 2001

No cases of partial or combined loadings can be considered. Such approaches may not describe accurate service environments. With these limitations, it is not possible to consider various foundation boundary and slab loading conditions for an optimum (that is, resilient and sustainable) design. The current design methods have been around for a very long time, but a systematic study of the performance of distressed foundations in different geographical areas has not checked and validated the methods. As the professionals working in this field already know, these foundations have been underperforming in many different situations and have been causing billions of dollars each year for consumers to fix their homes due to poor foundation performance on expansive soils (FEMA, 1982; Jones and Jefferson, 2012).

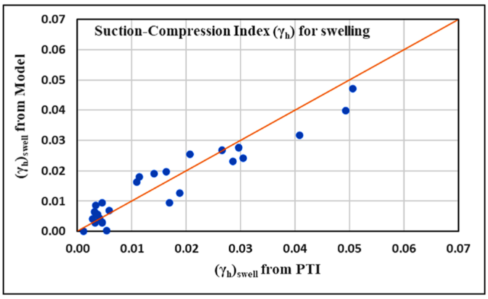
Analysis of Slab and Expansive Soil Foundation

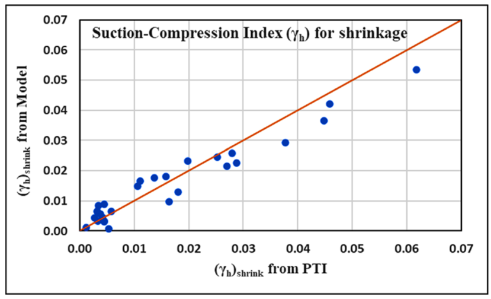
Current building codes are deficient, with respect to the structural analysis of slab-on-ground foundations on expansive soils, due to the overlapping slab rectangles assumptions. Improvement is needed in structural analysis of the slab for predicting deformations, moments, and shear forces in the slab. Similarly, a need exists for practical prediction of foundation soil design parameters in response to variations in climatic boundary conditions. It is equally, and probably more, important to have a realistic yet practical model that results in a rational expansive soil-foundation slab interaction interface. This study focuses on the problem for developing a rational soil structure interaction approach that can be used in modeling (or coupling) the slab with expansive soil foundation in a realistic and practical manner.

One objective of this study is to use the unsaturated soil mechanics principles applied to expansive soils for determining and assigning more rational, yet practical, soil and moisture boundary condition parameters for analysis and design. The most widely used PTI design guide uses two parameters (for example, e_m and y_m), representing the behavior of the expansive soils under climatic boundary conditions. Other design guides (for example, BRAB and WRI) also use similar parameters in their codes. The y_m parameter depends on the suction compression index (a potential volume change indicator) that is a function of the type of soil and its clay content. This value is different when the soil is swelling compared with when it is shrinking. The current tables and figures in the PTI method listing this index need to be critically evaluated. Those numbers were derived indirectly from soil index properties. A more practical and realistic approach needs to be provided in obtaining and determining these indices. The evaluation will be based on the existing and currently used data in the PTI manual that are available in the literature and the U.S. Soil Survey Conservation Services database for the United States (USDA-Natural Resources Conservation Service). The current PTI design guide uses one figure as a mineral classification chart and six figures representing six zones for the suction-compression index, γ_h. The extraction of γ_h from these figures is tedious and prone to user error. Exhibit 5 depicts only two figures, one for swelling and one for shrinkage condition. This study used a machine learning (that is, artificial intelligence) technique to construct the figures in exhibit 5. The soil index properties (liquid limit, plasticity index, clay, and silt fractions) were extracted from the U.S. Soil Survey Conservation Services database for predicting γ_h values using the machine learning method. A comparison is shown between γ_h values predicted by the model and the PTI method in exhibit 5.

Exhibit 5

A Comparison of Suction-Compression Index (γ_h) for Swelling and Shrinkage Condition Between Post-Tensioning Institute (PTI) Method and Model





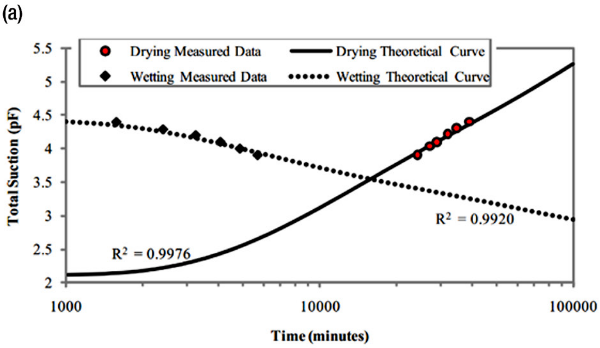
Source: Authors' research

The e_m parameter depends on the unsaturated soil moisture diffusion coefficient, which must be carefully considered. Exhibit 6(a) depicts a suction hysteresis curve for drying and wetting processes for predicting drying and wetting unsaturated soil diffusion coefficient measurements (Mabirizi and Bulut, 2010). It is well known that soils exhibit hysteresis during wetting and drying, and thus the corresponding diffusion coefficients must be used for predicting moisture movement in unsaturated expansive soils and edge moisture variation. In this study, a model was developed using the weighted average of modified unsaturated diffusion coefficient (α') and soil index properties (liquid limit, plasticity index, clay, and silt fractions) from the U.S. Soil Survey Conservation Services database for predicting edge moisture variation distance (e_m) for drying and wetting processes. Exhibit 7 shows the correlation between the PTI method and the model developed in this study. The graph for shrinkage in exhibit 7 is based on data at larger values of e_m due to limited number of datapoints.

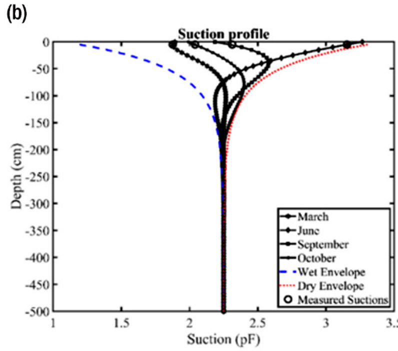
Exhibit 6

(a) Hysteresis in Unsaturated Diffusivity Coefficient and (b) Suction Envelope Prediction Using a Single Suction Measurement Based on Modified Mitchell (1979) Model

(a)



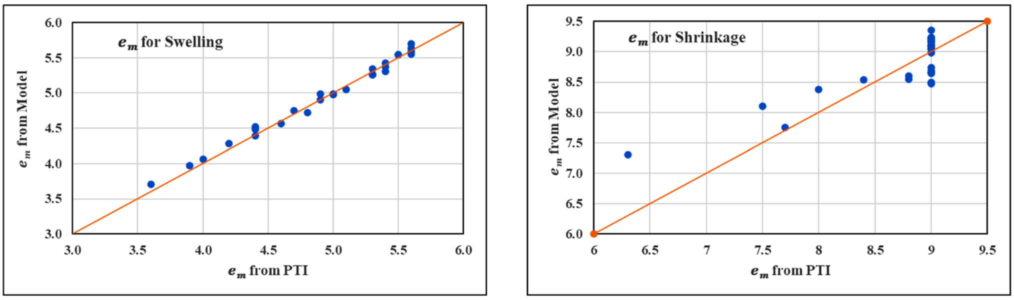
(b)



Sources: (a) Mabirizi and Bulut, 2010; (b) Javid and Bulut, 2019

Exhibit 7

A Comparison of Edge Moisture Variation Distance e_m for Swelling and Shrinkage Condition Between Post-Tensioning Institute (PTI) Method and Model

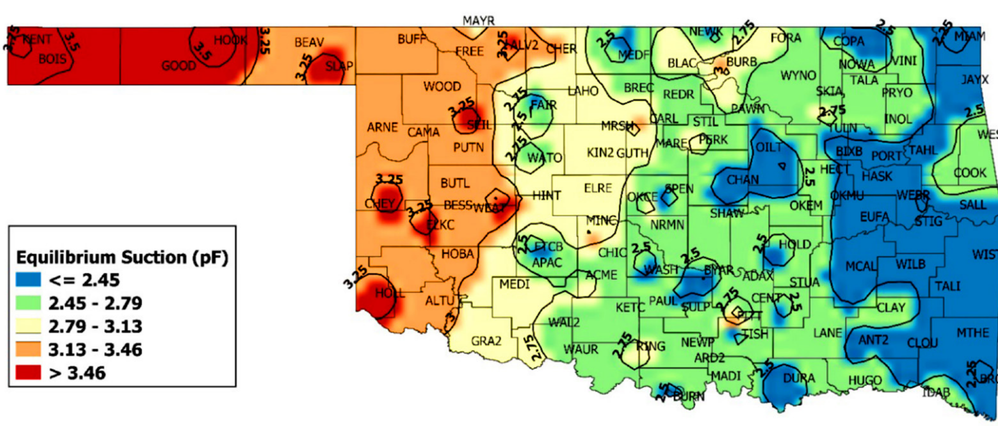


Source: Authors' research

Soil suction profile given in exhibit 6(b) and the equilibrium suction contour map depicted in exhibit 8 are needed for predicting both the differential soil movement, y_m, for swelling and shrinkage (using γ_h from exhibit 5) and the edge moisture variation distance, e_m, for swelling and shrinkage (using exhibit 7). Exhibit 6(b) shows a suction profile envelope based on the modified Mitchell model (Mitchell, 1979). To make such predictions, only one suction measurement is sufficient. Exhibit 8 demonstrates the equilibrium suction contour lines for the state of Oklahoma. These maps are generated using the modified Mitchell (1979) model for suction variation with depth and time, and actual climate data were obtained from Oklahoma Mesonet weather stations. This model, developed by Javid and Bulut (2019), can be used to create similar maps for regions with the expansive soil problems across the United States. For instance, the current PTI method uses a simple chart developed by Russam and Coleman (1961) that utilizes data from different parts of the world. Therefore, the curve may not represent site-specific equilibrium suctions.

Exhibit 8

Contour Maps of Equilibrium Suction for Oklahoma Based on Modified Mitchell (1979) Model and Actual Climate Data from Oklahoma Mesonet Weather Stations



Source: Javid and Bulut, 2019

Slab-Foundation Soil Interaction

It is important that a more realistic soil-structure interface exists for understanding the behavior of slabs on expansive soil foundations. Although the BRAB and WRI design codes do not have such interaction features, the PTI method has an interface model based on the Elastic half space foundation model (that is, elastic foundation). The interface model must be based on the entire slab shape, not the overlapping slabs assumption used in the PTI method, to capture the true behavior of the coupled slab and expansive soil foundation. Such an interface would probably be achieved through finite element modeling, which can handle various slab shapes. This study aims at setting an interface algorithm module to accommodate two foundation models, such as the elastic half space and Winkler models. The Winkler model considers vertical, independent, closely spaced elastic springs generating only vertical reaction. In other words, the area directly underneath the applied load experiences deformation, whereas displacements beyond the loaded area are zero. The elastic half space soil foundation model is considered more realistic, simulating the elastic behavior of the soil in the field. In this approach, the force applied at that point, in addition to the forces adjacent to that area, influence deflection at any point.

Verification of Developed Modules with Commercially Available Software

Two commercially available software packages, PTISlab 3.5 and CORD, are used to test the soil-structure interface module proposed in this study. The PTISlab 3.5 code is widely used in the United States, and the CORD code is widely used in Australia. Both codes are quite similar and use similar assumptions in their analysis of slabs on expansive soil foundations. The comparison is accomplished by running the commercial codes and the module developed in this study, using the same input parameters (that is, applied load and soil design parameters). Currently, commercially available software (that is, PTISlab 3.5 and CORD) cannot provide the required information for rational, practical, and theoretical-based design of residential house slab foundations due to the major assumptions mentioned previously. Each computer program has its own deficiency in addressing all the needed parameters for analysis and design. A one-to-one comparison will not be possible, because the existing computer programs have their own limitations in handling various e_m and y_m values and other boundary conditions.

Two example problems in the second edition of the PTI design manual were used for the comparison study. Exhibit 9 lists soil design parameters (e_m and y_m) for both example problems. The slab dimensions for both examples are in the left panel of exhibit 3.

Exhibit 9

Soil Design Parameters (e_m and y_m)

Example 1			Example 2		
	Center Lift	Edge Lift		Center Lift	Edge Lift
y_m (inch)	3.61	0.75	y_m (inch)	0.90	0.706
e_m (feet)	5.5	2.5	e_m (feet)	4.5	5.5

Source: Authors' research

It must be noted that both PTISlab 3.5 and CORD analyze only a rectangle in the given L-shaped slab. However, the module SLAB computer program developed in this study handles the whole L-shaped slab. In example 1 of exhibit 9, for the 42-by-24-foot rectangle slab for PTISlab 3.5 and CORD and the whole slab for the SLAB program for the center lift analysis, the moments and shear forces in long and short directions are relatively comparable (not large variations from each other). However, in the edge lift analysis, CORD underpredicts the moments and shear forces in long and short directions by significant margins, relative to the results the PTISlab 3.5 gives. On the other hand, values by the PTISlab 3.5 are significantly less than the values the SLAB gives. In all other rectangular and L-shaped slabs in examples 1 and 2, trends of the results are similar.

These results indicate that, for the edge lift cases, the SLAB program gives conservative values relative to PTISlab 3.5 and CORD. This result is probably because the SLAB module can analyze the whole L-shaped slab and, therefore, can capture stress concentration points, like the reentrant corner.

Conclusions

This article outlines the need for improving the current method for analysis and design of slab foundations on expansive soils under changing climate conditions. It is important that modern houses are sustainable, resilient, energy-efficient, and affordable. The current methods that major building codes have adopted for foundation design have significant shortcomings that are not realistic and rational. These codes have major deficiencies by assuming overlapping slabs that are not able to handle various loading conditions and not able to accommodate various soil foundation models (Bulut and Lytton, 2002). This work provides an analytical approach, several modules, and computer code algorithms that engineers and researchers can use in improving the current codes for designing foundations to withstand natural hazards that expansive soils under changing climate conditions cause.

Future Research Needs

A residential house slab can be instrumented with moisture, temperature, and displacement sensors over an entire weather cycle to validate the models developed in this study, in terms of capturing actual movement of the slab vs. the model predictions.

Acknowledgments

The authors gratefully acknowledge the financial support that HUD provided for this research under grant number H-21692 CA. Furthermore, we thank Mike Blanford for managing and coordinating this work on HUD’s behalf. Finally, the authors thank the editors and two referees for helpful comments.

Authors

Nafisa Tabassum is a graduate student in the School of Civil and Environmental Engineering at Oklahoma State University. Rifat Bulut is a professor in the School of Civil and Environmental Engineering at Oklahoma State University.

References

Building Research Advisory Board (BRAB). 1968. "National Research Council Criteria for Selection and Design of Residential Slabs-on-Ground." U. S. National Academy of Sciences Publication 1571. Washington, DC: National Academies Press.

———. 1962. "National Research Council-Design Criteria for Residential Slabs-on-Ground." U.S. National Academy of Sciences Publication 1077. Washington, DC: National Academies Press.

———. 1959. "National Research Council-Design Criteria for Residential Slabs-on-Ground." U.S. National Academy of Sciences Publication 657. Washington, DC: National Academies Press.

Bulut, Rifat. 2001. "Finite Element Method Analysis of Slabs on Elastic Half Space Expansive Soil Foundations." Ph.D. diss., Department of Civil Engineering, Texas A&M University.

Bulut, Rifat, and Robert L. Lytton. 2002. "Slab-on-Ground—A Finite Element Method Analysis." In *The Proceedings of Texas Section American Society of Civil Engineers*.

Diaz, Delavane, and Frances Moore. 2017. "Quantifying the Economic Risks of Climate Change," *Nature Climate Change* 7: 774–782.

Federal Emergency Management Agency (FEMA). 1982. "Special Statistical Summary–Death, Injuries, and Property Loss by Type of Disaster 1970–1980." https://apps.dtic.mil/sti/pdfs/ADA127645.pdf.

Javid, Amir H., and Rifat Bulut. 2019. "Evaluating Equilibrium Matric Suctions Under Pavement System Based on Thornthwaite Moisture Index (TMI)." *Airfield and Highway Pavements 2019: Testing and Characterization of Pavement Materials*: 511–521.

Jones, Lee D., and Ian F. Jefferson. 2012. "Expansive Soils." In *ICE Manual of Geotechnical Engineering, Volume I*. London: Institution of Civil Engineers.

Mabirizi, Daniel, and Rifat Bulut. 2010. "A Unified Testing Method for Measuring Unsaturated Soil Drying and Wetting Diffusion Coefficients in Laboratory," *Journal of the Transportation Research Board* 2170 (1): 109–118.

Mitchell, Peter W. 1979. "The Structural Analysis of Footings on Expansive Soil," Kenneth W. G. Smith and Associates, Research Report No. 1. Adelaide, Australia: Webb and Son.

Mostafiz, Rubayet B., Carol J. Friedland, Robert V. Rohli, Nazla Bushra, and Chad Held. 2021. "Property Risk Assessment for Expansive Soils in Louisiana," *Frontiers in Built Environment* 7: 1–10.

Post-Tensioning Institute (PTI). 2019. "Standard Requirements for Design and Analysis of Shallow Post-Tensioned Concrete Foundations on Expansive and Stable Soils." Farmington Hills, MI: Post-Tensioning Institute.

———. 2012. "Standard Requirements for Design and Analysis of Shallow Post-Tensioned Concrete Foundations on Expansive Soils." Farmington Hills, MI: Post-Tensioning Institute.

———. 2008. *Design of Post-Tensioned Slabs-on-Ground, 3rd Edition with 2008 Supplement (PTI DC10.1-08)*. Phoenix: Post-Tensioning Institute.

———. 2004. *Design and Construction of Post-Tensioned Slabs-on-Ground, 3rd Edition*. Phoenix: Post-Tensioning Institute.

———. 1996. *Design and Construction of Post Tensioned Slabs-on-Ground, 2nd Edition*. Phoenix: Post-Tensioning Institute.

———. 1980. *Design and Construction of Post-Tensioned Slabs-on-Ground, 1st Edition*. Phoenix: Post-Tensioning Institute.

Russam, Kenneth, and J. D. Coleman. 1961. "The Effect of Climatic Factors on Subgrade Moisture Conditions," *Géotechnique* 3 (1): 22–28.

U.S. Department of Agriculture (USDA)-Natural Resources Conservation Service. "U.S. Soil Survey Conservation Services Database." https://websoilsurvey.sc.egov.usda.gov/App/WebSoilSurvey.aspx.

Vann, J. D., and S. L. Houston. 2021. "Field Soil Suction Profiles for Expansive Soil," *Journal of Geotechnical and Geoenvironmental Engineering* 147 (9): 1–10.

Wire Reinforcement Institute (WRI). 1996. *Design of Slab-on-Ground Foundations*. Findlay, OH.

———. 1981. *Design of Slab-on-Ground Foundations*. Findlay, OH.

Witherspoon, W. T. 2000. *Residential Foundation Performance: A Study of Repaired Foundations*. Dallas: The International Association of Foundation Drilling.

Wray, Warren K. 1978. "Development of a Design Procedure for Residential and Light Commercial Slabs-on-Ground Constructed over Expansive Soils." Ph.D. diss., Department of Civil Engineering, Texas A&M University.

Zhang, Xiong, and Jean-Louis Briaud. 2015. "Three Dimensional Numerical Simulation of Residential Building on Shrink-Swell Soils in Response to Climatic Conditions," *International Journal for Numerical and Analytical Methods in Geomechanics* 39 (13): 1369–1409.