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Introduction

The design of foundations for structures constructed on expansive soils is a major challenge for geotechnical engineers practicing in areas where such soils are prevalent. The forces exerted by expansive soils and the movements that they cause to even heavily loaded structures can be well in excess of those experienced by ordinary soils. Also, the costs associated with development of expansive soil sites are much higher than those for nonexpansive soil sites. The site investigation and design phase requires more extensive testing and analyses, and the construction phase requires more inspection and attention to detail. Special considerations must be addressed during their occupancy with regard to the maintenance of facilities constructed on expansive soils. Furthermore, the cost to repair the problems caused by expansive soils may be prohibitive. There are many examples where repair costs exceed the original cost of construction.

The nature of expansive soils and the magnitude of costs associated with shortcomings in design, construction, and operation are such that there exists little margin for error in any phase of a project. In that regard, the following quote is appropriate (Krazynski 1979):

> To come even remotely close to a satisfactory situation, trained and experienced professional geotechnical engineers must be retained to evaluate soil conditions. The simple truth is that it costs more to build on expansive soils and part of the cost is for the professional skill and judgment needed. Experience also clearly indicates that the cost of repairs is very much higher than the cost of a proper initial design, and the results are much less satisfactory.

In the initial phases of a project, the owner or developer is faced with costs that may be significantly higher than initially estimated. They generally are intolerant of shortcomings and demand that the foundations be designed and constructed such that the movements are within tolerable limits. At the same time, they are reluctant to undertake the required additional cost for something that exists below ground and cannot be seen. One large foundation contractor, Hayward Baker, has as part of its motto, “You never see our best work.” An important task of the engineer is to convince the client that the additional cost is not merely justified, but is critical. This is especially true for critical structures such as hospitals and public buildings, where failure could have serious consequences.

Expansive soils problems exist on every continent, with the exception perhaps of Antarctica. Expansive soils have been encountered in almost every state and province of the United States and Canada, but they are more troublesome in the western and southwestern areas because areas of low precipitation often tend to be more problematic.

In spite of the fact that expansive soils have been designated a geologic hazard, public awareness is lacking. Few universities offer formal courses relating to geotechnical applications for expansive soils. There is a shortage of continuing education courses in the subject, and research is limited to a relatively small number of institutions. As a result, few practicing foundation engineers have received formal education in this area. It is intended that this book will provide a service for awareness, education, and technical reference in this important area.

1.1 PURPOSE

This book is intended to provide the background and principles necessary for the design of foundations for expansive soils. The nature of expansive soil is described from an engineering perspective to develop an appreciation as to how the microscopic and macroscopic aspects of soil interact to affect expansive behavior. Tools that are necessary to use in the practice of expansive soil foundation design are developed in a fashion that can be easily implemented. The application of these tools to the design of foundations is demonstrated.

An important underlying theme of the book is the ability to predict ground heave and structural movement caused by expansive soil. This is a fundamental part of foundation design. Rigorous calculations of slab heave and potential movement of deep foundations should be a part of every design. Several chapters in this book are devoted to that important subject.

1.2 ORGANIZATION

The organization of this book is designed to first present the fundamental nature of expansive soil and then address the factors that influence expansion. Those tools provide the means for the design of foundations based on the concept of minimizing structural movement. The first eight chapters present the nature of expansive soil and the tools needed to perform the analyses for foundation design. The remaining chapters apply these tools.

Chapter 2 begins with a microscopic view of the molecular structure of the clay particle and the chemistry of the surrounding water. The concept of a clay micelle is introduced and used to explain the nature of expansive soil and the formation of an expansive soil deposit. That concept is extended to show the manner in which macroscopic factors such as density and water content influence the expansion potential. The distribution of expansive soil throughout the world and representative expansive soil profiles are discussed.

Chapter 3 concentrates on the factors of a site investigation for an expansive soil site that may not be included in the investigation of a non-expansive soil site. Chapter 4 is devoted to a discussion of soil suction and its role in defining the state of stress. Soil suction is an important parameter that relates to negative pore water pressure and is a major factor influencing the behavior of expansive soil. The state of stress and the stress state variables for unsaturated soils are presented in chapter 5. The nature in which they relate to the classical effective stress concept for saturated soil is discussed, and important constitutive relationships for expansive soils are presented.

Chapter 6 is devoted to the oedometer test. This is the principal method for measuring the expansion potential of a soil and is used extensively in predicting heave. The migration of water through soil is presented in chapter 7. Methods of analysis are presented for the determination of water content profiles to be used in computation of heave and the design of foundations. Chapter 8 discusses methods for computing predicted heave. Two basic methods of predicting heave are presented. One method is based on the application of oedometer test results and the other uses measurements of soil suction.

Chapter 9 introduces the design of foundations and other structural elements for expansive soil sites. Shrink-swell of soils is also considered. This chapter presents general considerations for foundation design and discusses those factors that are unique to expansive soils.

One approach to foundation design on expansive soil is to mitigate their effects by treating the soil or by controlling the water content regime around the structure. Methods of accomplishing those measures are presented in chapter 10. Chapters 11 and 12 present methods of design for shallow and deep foundations to accommodate the forces and movement of expansive soils. Centered on those designs is the computation of predicted foundation movement. This is the fundamental parameter that must guide a successful design. A discussion of several foundation repair options is also provided in these chapters to guide the reader to a successful rehabilitation of distressed structures.

A part of the foundation design must consider the floors and slabs and their interaction with foundation elements. This is addressed in chapter 13. The use of slab-on-grade floors is discouraged in lieu of structural floor systems. Consideration is given to the effect of soil heave on exterior flatwork. Again, repair options for slab-on-grade floors are also provided at the end of this chapter.

Finally, chapter 14 addresses lateral loads that are exerted on foundations and retaining walls by expansive soils. Lateral earth pressure from expansive backfill is generally of such a magnitude as to preclude the use of expansive soil as backfill.

The concepts and design methods that are presented in the previous chapters are demonstrated by several examples that are provided to help guide the reader through the calculations. Case studies of actual sites investigated by the authors have been presented as well. The case studies show applications of the principles presented in this book, not just from a study of the failure to properly apply expansive soil theory, but also from a research perspective that has been gained during development of many of the design methods provided herein.

This book presents design methods in both English and SI units. SI units are presented within the parentheses shown immediately after the English units. There are two exceptions to this. Chapter 4 on soil suction uses SI units primarily. Because most of the data that are used in the examples have been collected from projects in the United States, examples and case studies use only English units.

1.3 TERMINOLOGY

Many of the terms used in geotechnical practice with expansive soils are either new or have been used in different contexts by different engineers around the world. The following definitions and discussion explain the different terms used in this book. It is suggested that the engineering community adopt this terminology.

Expansive soil is generally defined as any soil or rock material that has a potential to increase in volume under increasing water content. In some cases, it is necessary to present a quantitative description of expansive soil. In those cases, expansive soil is described in terms of the following parameters: (1) the percent swell that a soil exhibits when inundated under a prescribed vertical stress and (2) the swelling pressure of the soil. These parameters are typically measured by one-dimensional consolidation-swell tests or constant volume tests conducted in the laboratory on representative samples of soil.

Soil suction is the magnitude of the tensile stress in the pore water of an unsaturated soil. It consists of two components, matric suction and osmotic suction. For purposes of general engineering practice, changes in matric suction are most important.

Oedometer test is a one-dimensional test in which a soil sample is confined laterally and subjected to vertical stress while being wetted. In the consolidation-swell (CS) test, the sample is wetted under a prescribed inundation stress and allowed to swell. In the constant volume (CV) test the sample is restrained from swelling while it is being wetted.

Consolidation-swell swelling pressure, σ''_{cs}, is the load required to compress the soil to its original thickness after it has been inundated and allowed to swell in a consolidation-swell (CS) test.

Constant volume swelling pressure, σ''_{cv}, is the load required to prevent swell, and thus maintain a constant volume of the soil after it has been inundated in a constant volume (CV) test.

Design life of a foundation is the useful lifespan of a foundation assumed for design purposes. Different elements of a structure are designed for different design lives. For example, the design life of a shingle roof is much less than that of a foundation. The design life for a foundation generally ranges from about 50 years to 200 years. A typical design life for a residential structure is 100 years, but for commercial structures it could be less.

Zone of seasonal moisture fluctuation, z_s, is the depth to which the water content fluctuates in the soil due to changes in climatic conditions at the ground surface. The zone of seasonal moisture fluctuation does not take into consideration the effect of water being introduced to the soil profile by other sources such as landscape irrigation or water introduced below the ground surface by leaking pipes or drains, or off-site sources of groundwater.

Active zone, z_A, is the zone of soil that contributes to heave due to soil expansion at any particular point in time (Nelson, Overton, and Durkee 2001). Thus, the depth of the active zone can vary with time. Historically, this zone has been considered to be the depth to which climatic changes can influence the change in water content in the soil (i.e., the "zone of seasonal moisture fluctuation"). That concept, however, is correct only if external influences such as grading, surface drainage, or irrigation are not present.

Zone (depth) of wetting, z_w, is the zone of soil in which water contents have increased due to the introduction of water from external sources, or due to capillarity after the elimination of evapotranspiration. The zone of wetting was originally defined in Nelson, Overton, and Durkee (2001). In the case where a wetting front is moving downward from the surface, the depth of this zone is the *zone of wetting*. The soil above the wetting front represents the zone in which heave is taking place, and hence, represents a time-varying active zone.

Depth of potential heave, z_p, is the greatest depth to which the overburden vertical stress equals or exceeds the swelling pressure of the soil. This represents the maximum depth to which the soil can heave, and, thus, is the deepest depth possible for the active zone.

Design active zone, z_{AD}, is the zone of soil that is expected to become wetted by the end of the design life. This is the active zone for which the foundation is to be designed.

Free-field heave is the amount of heave that the ground surface will experience due to wetting of the soils with no surface load applied. The surface load applied by slabs-on-grade and pavements is very small relative to the swelling pressure. Therefore, the heave of slabs and pavements is essentially the same as the free-field heave. The term *free-field heave* has been used for many years by various researchers and practitioners worldwide in the fields of expansive soil and frozen soil (O'Neill 1988; Rajani and Morgenstern 1992, 1993, and 1994; Ferregut and Picornell 1994; Venkataramana 2003; Miao, Wang, and Cui 2010; Ismail and Shahin 2011 and 2012). This term is also commonly called *free-field soil movement* (Poulos 1989; Ong 2004; Ong, Leung, and Chow 2006; Wang, Vasquez, and Reese 2008; and Ti et al. 2009). The free-field heave is also the heave to be expected for infrastructure, such as slabs-on-grade and pavements, where very low surface loads are applied.

Current heave is the heave that has occurred at the time being considered. This is the heave that has been produced by the current degree of wetting that has occurred in the active zone, taking into account whether the soil has been fully wetted or partially wetted.

Ultimate heave is the maximum amount of heave that a soil profile can exhibit if it were to become fully wetted throughout the entire zone above the depth of potential heave.

Future maximum heave is the amount of future heave expected to occur since the time of investigation. Generally this calculation assumes that the entire depth of potential heave will become fully wetted.

Design heave is the amount of heave that will be experienced during the design life of the foundation. Design heave is calculated based on the change in the subsurface water content profile in the design active zone. Water migration modeling can be used to predict the final water content profile at the end of the design life of the foundation. Calculations of the design free-field heave should also take into account the degree of wetting in the design active zone. It is also the amount of heave that the foundation must be designed to tolerate within its design life.

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