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Review

Review of collapse triggering mechanism of collapsible soils due to wetting

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ABSTRACT

Loess soil deposits are widely distributed in arid and semi-arid regions and constitute about 10% of land area of the world. These soils typically have a loose honeycomb-type meta-stable structure that is susceptible to a large reduction in total volume or collapse upon wetting. Collapse characteristics contribute to various problems to infrastructures that are constructed on loess soils. For this reason, collapse triggering mechanism for loess soils has been of significant interest for researchers and practitioners all over the world. This paper aims at providing a state-of-the-art review on collapse mechanism with special reference to loess soil deposits. The collapse mechanism studies are summarized under three different categories, i.e. traditional approaches, microstructure approach, and soil mechanics-based approaches. The traditional and microstructure approaches for interpreting the collapse behavior are comprehensively summarized and critically reviewed based on the experimental results from the literature. The soil mechanics-based approaches proposed based on the experimental results of both compacted soils and natural loess soils are reviewed highlighting their strengths and limitations for estimating the collapse behavior. Simpler soil mechanics-based approaches with less parameters or parameters that are easy-to-determine from conventional tests are suggested for future research to better understand the collapse behavior of natural loess soils. Such studies would be more valuable for use in conventional geotechnical engineering practice applications.

1. Introduction

Loess soils are widely distributed and constitute about 10% of the total land area of the world. Several countries including China, Russia, United States, France, Germany, New Zealand and Argentina, have a large area of loess soil deposits (Phien-wej et al., 1992; Rogers et al., 1994; Rogers, 1995; Al-Rawas, 2000; Nouaouria et al., 2008; Ryashchenko et al., 2008; Gaaver, 2012). These soils are typically formed with a loose honeycomb-type meta-stable structure and are susceptible to a sudden decrease in total volume or collapse upon wetting (Feda, 1988; Houston et al., 1988; Lommler and Bandini, 2015). Different types of natural soils may develop a collapsible fabric provided there is an open, potentially meta-stable, partly saturated structure, and a high enough applied stress (Barden et al., 1973; Lawton et al., 1989). In addition, any type of soil compacted at dry of optimum condition is collapsible in nature (Fredlund and Gan, 1995; Kato and Kawai, 2000; Pereira and Fredlund, 2000). Collapse and other collapse associated problems, such as differential settlement, earth cracks, landslides and falls, have contributed to serious damages to the infrastructures that are constructed on loess soils, including loss of human lives in certain scenarios (Derbyshire, 2001; Houston et al., 2001; Peng et al., 2006). During the period of 1974–1975, in China, it was reported that a total of 1505 buildings were damaged and 80 km-long underground pipeline ruptured due to collapse of loess soils (Sun et al., 2013). Fu (2005) reported that typically a quarter of time is required with respect to the entire construction period to treat the collapsible soils prior to placing foundation. Also, the cost associated with collapsible ground preparation is typically about one third of the total cost of the infrastructure. With urban development on the rise in various regions of the world with collapsible soil deposits, there will be more access to water for these soils. As a result, there will be more wetting associated collapse problems. For

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this reason, it is important to understand the collapse mechanism of these soils.

During the last six decades, many researchers have focused on studying the collapse mechanism of various collapsible soils upon wetting. The discussions on this topic are summarized under three categories, i.e. traditional approaches, microstructure approach, and soil mechanics-based approaches. Among the traditional approaches, collapsibility was always interpreted considering one sole factor. For example, collapse was attributed to loss of capillary tension or solution of soluble salts (Guo, 1958; Dudley, 1970). In addition, many researchers studied the influence of soil properties, such as the density, clay content, Atterberg limits and grain size distribution, on the collapsibility of loess soils (Sun, 1957; Liu, 1994; Zhao and Chen, 1994; Zhang, 2002; Fan and Guo, 2003; Song and Wang, 2004; Chen et al., 2006; Yuan, 2009), and a large number of empirical equations have been proposed in the literature relating the collapsibility to conventional soil properties (Clevenger, 1958; Feda, 1964, 1966, 1995; Handy, 1973; Basma and Tuncer, 1992; Fan and Guo, 2003; Song and Wang, 2004; Ayadat and Hanna, 2007; Zorlu and Kasapoglu, 2009; Noor et al., 2013). However, most of these empirical equations can be extended only for local soils for which they have been developed. In other words, the proposed empirical equations are not universally valid for use in conventional geotechnical engineering practice (Sun, 1957; Gao, 1979, 1990; Yang, 1988). This is due to soils exhibiting different forms of microstructure and hence presenting different mechanical behaviors in spite of having similar physical properties. For example, a loess soil with few large pores may have the same void ratio or density as another loess soil with many small pores; however, their collapse behaviors will be significantly different.

The collapse nature of loess and other soils is interpreted using the information of soil microstructure as a tool (Derbyshire and Mellors, 1988; Delage et al., 1996; Romero and Simms, 2008). Loess soil microstructure can be analyzed in terms of four key factors based on the comprehensive studies on microstructure of loess soils, i.e. particle pattern, contact relation, pore form, and bonding material. These four factors are dependent on each other; however, the pore form and bonding material are suggested as the two dominant factors that have more influence on the collapse behavior (Gao, 1980a, b; Lei, 1983, 1987; Yang, 1988; Zhao and Chen, 1994). Many researchers have been involved in classifying soil pores and distinguishing the water stability of various possible bonding materials, as well as exploring their respective influence on the collapsibility of loess (Lei, 1983, 1987; Derbyshire and Mellors, 1988; Yang, 1988; Zhao and Chen, 1994; Osipov and Sokolov, 1995; Assallay et al., 1997; Smalley et al., 2001; Jiang et al., 2014a, b; Lommler and Bandini, 2015). It is widely accepted that microstructure plays a key role in controlling the collapse behavior; however, it lacks a simple quantitative descriptor for estimating collapse deformations (Alonso et al., 1993). This limitation has been addressed and alleviated to a great extent in recent years by extending image processing techniques which facilitate the quantitative analysis of soil microstructure (e.g. Chen and Sha, 2009a, b; Gu et al., 2011; Fang et al., 2013a, b). These image processing programs are mostly based on the principle of binary grey segmentation to provide reasonably satisfactory results, particularly, for coarse soils. However, their application to fine-grained silts and clays has not been well validated. Gu et al. (2011) indicated that it is difficult to clearly distinguish the grains and pore sizes from digital images using the presently available programs.

The third category approaches use the concepts of soil mechanics for explaining the collapse behavior. Collapsible soils are typically unsaturated and significant collapse generally occurs prior to reaching fully saturated condition (El-Ehwany and Houston, 1989). For this reason, the concepts of mechanics for unsaturated soils are more rational for interpreting the collapse behavior (Tadepalli and Fredlund, 1991; Fredlund and Rahardjo, 1993; Fredlund and Gan, 1995; Habibagahi and Mokhberi, 1998; Chen, 1999; Pereira and Fredlund, 2000). The two stress state variables approach proposed by Fredlund and Morgenstern (1977) for describing the mechanical behavior of unsaturated soils has been extended to studies of volume change behavior due to loading and wetting of collapsible soils. Collapse is attributed to the loss of strength associated with suction decrease as a result of wetting (Fredlund and Gan, 1995). For this reason, collapse behavior has been widely investigated using suction-controlled wetting tests (e.g. Chen, 1999; Chen et al., 1999; Sun et al., 2004, 2007a, b; Jotisankasa, 2005), based on which, various models have been proposed for modeling the collapse behavior with respect to varying stress state variable (i.e. matric suction) (Tadepalli et al., 1992; Fredlund and Gan, 1995; Pereira and Fredlund, 1997, 2000). During the last quarter century, a number of elastoplastic models have been developed for modeling the behavior of unsaturated soils (Alonso et al., 1990; Josa et al., 1992; Gens and Alonso, 1992; Wheeler and Sivakumar, 1995; Cui and Delage, 1996; Wheeler, 1996; Wheeler et al., 2003). These models have been extended or modified to interpret the volume change behavior of collapsible soils (e.g. Chen et al., 1999; Kato and Kawai, 2000; Sun et al., 2004, 2007a, b). In these models, collapse is explained as a part of deformation when the stress path crosses the elastic region or yield surfaces. For quantitative analysis, elastoplastic models provide a more precise way to estimate the collapse deformations with respect to varying stress state variables. However, they are too complex as a large number of parameters are required to be determined from cumbersome suction-controlled tests. On the other hand, for addressing some scenarios of collapse, only a few model parameters are required. However, the parameters will be different for the same soils when their initial conditions, such as the initial water content, and the stress state, are different. In other words, when using these models, for each soil sample with a different initial condition, one suction-controlled test should be conducted, from which the model parameters can be determined. In addition, most of these models were proposed based on the experimental results of compacted soils, which may show different collapse behavior from the natural loess soils. For this reason, soil mechanics-based approaches proposed especially for natural loess soils are reviewed in this paper. Loss of structural strength is considered to be a key factor for natural loess soil collapse. The structural strength is mainly influenced by the factors associated with loess soil deposition and initial water content (Hu et al., 2000, 2004). Two models based on the concepts of breakage mechanics proposed by Shen and his group (Shen, 1993, 2003; Shen and Deng, 2003; Shen and Hu, 2003) for modeling the collapse behavior of natural loess soils due to loading and wetting were reviewed. These models have the same limitation as the models described earlier; they are complex, and cumbersome tests are required for determining the parameters, which restricts the application of these models in conventional geotechnical engineering practice. For these reasons, relatively simple models with less parameters or parameters that are easy-to-determine from conventional tests are suggested for advancing research related to collapse behavior of natural loess soils.

The comprehensive summary provided in this paper can be useful for addressing problems associated with collapsible soils and for proposing more efficient approaches in the future.