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Prediction of the wetting-induced collapse behaviour using the soil-water characteristic curve

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ABSTRACT

Collapsible soils go through three distinct phases in response to matric suction decrease during wetting: pre-collapse phase, collapse phase and post-collapse phase. It is reasonable and conservative to consider a strain path that includes a pre-collapse phase in which constant volume is maintained and a collapse phase that extends to the final matric suction to be experienced by collapsible soils during wetting. Upon this assumption, a method is proposed for predicting the collapse behaviour due to wetting. To use the proposed method, two parameters, critical suction and collapse rate, are required. The former is the suction value below which significant collapse deformations take place in response to matric suction decease, and the later is the rate at which void ratio reduces with matric suction in the collapse phase. The value of critical suction can be estimated from the water-entry value taking account of both the microstructure characteristics and collapse mechanism of fine-grained collapsible soils; the wetting soil-water characteristic curve thus can be used as a tool. Five sets of data of wetting tests on both compacted and natural collapsible soils reported in the literature were used to validate the proposed method. The critical suction values were estimated from the water-entry value with parameter a that is suggested to vary between 0.10 and 0.25 for compacted soils and to be lower for natural collapsible soils. The results of a field permeation test in collapsible loess soils were also used to validate the proposed method. The relatively good agreement between the measured and estimated collapse deformations suggests that the proposed method can provide reasonable prediction of the collapse behaviour due to wetting.

1. Introduction

Loess soils are widely distributed and constitute about 10% of the total land area of the world. Several countries including China, Russia, the United States, France, Germany, New Zealand and Argentina have a large area of loess soils (Derbyshire and Mellors, 1988; Rogers et al., 1994). In China, soil materials from Gobi Desert were brought by wind to the Loess Plateau where the basin-shaped geomorphology is favorable for deposition of aeolian materials (Fig. 1). For this reason, loess soil particles are observed to be finer and have better sphericity from the northwest to southeast of the Loess Plateau. These soils are typically partly saturated with high matric suction or water-sensitive cementations at the particle contacts, which imparts loess soils an open and metastable fabric that is susceptible to collapse upon wetting (Barden et al., 1973; Lawton et al., 1992). In the Loess Plateau of China, loess soils deposited in the Pleistocene (more than 2.4 Ma) were divided into three sets; namely, Wucheng, Lishi and Malan corresponding to early, middle and late Pleistocene, respectively. The initially loose-structured wind-blown loess soils become stable with time and depth due to the increasing consolidation pressure. However, recently-deposited loess soils are susceptible to collapse upon wetting. The upper Lishi and Malan loess (typically, within 10–20 m depth below the ground surface) are typically collapsible upon wetting (Derbyshire, 2001; Dijkstra et al., 1994). In addition to naturally deposited soils, fine-grained soils compacted at dry of optimum condition with a flocculated structure also collapse upon wetting (Tadepalli et al., 1992; Fredlund and Gan, 1995; Kato and Kawai, 2000; Pereira and Fredlund, 2000; Sun et al., 2004, 2007). Not only collapse itself but also collapse-induced problems such as slope failure and cracking have brought series damages to the infrastructures constructed either on or in collapsible soils, including loss of human lives in certain scenarios (Sun et al., 2013). As urbanization advances in these regions, loess soils have more access to various types of water intrusions, such as leakage from broken pipelines, sewer lines, as well as water from runoff or irrigations. Therefore, it is of great importance to predict the collapse behaviour due to wetting, which will provide evidence for prevention of geohazards and treatment of foundations in loess soil regions.

Many attempts have been made to predict the collapse behaviour

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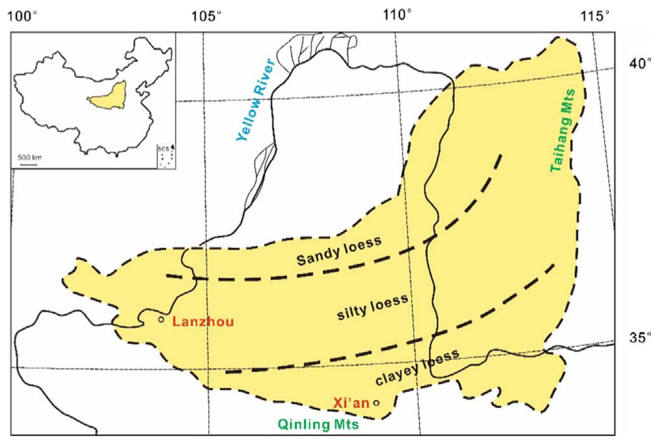

Fig. 1. Loess Plateau of China.

from empirical equations using easy-to-obtain physical properties, such as dry density and water content. However, these equations were not found to be suitable for loess from any region (Basma and Tuncer, 1992; Song and Wang, 2004; Ayadat and Hanna, 2007; Zorlu and Kasapoglu, 2009). That is because the grain-size distribution varies not only with location, as shown in Fig. 1, but also with depth and this variation represents the changing geological environment in the past, resulting in the differing soil microstructure in terms of pore-size distribution and cementation, et al. As unsaturated soils, modified oedometer or triaxial test apparatus for unsaturated soils in which matric suction can be controlled or applied independently has been increasingly used for investigation of the collapse behaviour of loess soils, loess collapsing is suggested to be triggered by loss of shear strength due to matric suction decrease as a result of wetting (Fredlund and Gan, 1995; Chen et al., 1999; Zhang et al., 2016). Elastic constitutive equations which relate deformation state variables, such as void ratio and volumetric strain, to matric suction with stiffness terms have been used to model or predict the collapse behaviour (Tadepalli et al., 1992; Fredlund and Gan, 1995; Pereira and Fredlund, 2000). During the last 25 years, the collapse behaviour of unsaturated soils has been modelled using elasto-plastic models (Alonso et al., 1990; Balmaceda et al., 1992; Cui and Delage, 1996; Wheeler et al., 2003; Sun et al., 2004; Thu et al., 2007). Under isotropic loading conditions, for example, the LC yield curve on (p, s) plane (where, p represents net mean stress and s represents matric suction) and stiffness parameters for changes in matric suction, both for elastic region and virgin states of the soil, are required for using an elasto-plastic model. Li et al. (2016) provided a comprehensive summary of various approaches for interpreting and modelling the collapse behaviour, with a special reference to loess soils.

In the present study, the results of wetting tests with suction control on both natural collapsible soils and compacted soils reported in the literature are reviewed, and the wetting-induced collapse behaviour is interpreted. Since either many or hard-to-obtain parameters are involved in most of the current elasto-plastic models, a method which takes full consideration of the experimental evidence and microstructure characteristics of collapsible soils is proposed for predicting the wetting-induced collapse behaviour. The proposed method is validated using both laboratory and field test results.

2. The proposed method

Collapsible soils go through three distinct phases in response to matric suction decrease during wetting under constant applied stress; namely, pre-collapse phase, collapse phase and post-collapse phase (Pereira and Fredlund, 2000; Kato and Kawai, 2000; Sun et al., 2004; Garakani et al., 2015; Zhang et al., 2016). The first phase (pre-collapse phase) occurs when the soil is subjected to high matric suction values.

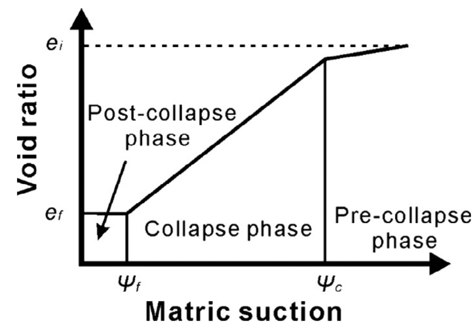

Fig. 2. Volume change in various collapse phases during wetting (modified after Pereira and Fredlund, 2000).

In this phase, small volumetric deformations that are elastic-dominated take place in response to matric suction decrease, while the soil structure remains intact. The second phase (collapse phase) occurs as the soil experiences medium matric suction values. In this phase, the soil undergoes a significant volumetric compression in response to matric suction decrease. The soil structure alters due to bonding breakage. The third phase (post-collapse phase) occurs as the soil approaches close to saturated condition. In this phase, no further volume reduction occurs in response to matric suction decrease. The wetting-induced collapse behaviour in terms of three phases can be observed in a number of experimental studies, such as Kato and Kawai (2000), Sun et al. (2007), Garakani et al. (2015) and Zhang et al. (2016). The idealized relationship between void ratio and matric suction during wetting is shown in Fig. 2, where, e_i = initial void ratio; e_f = final void ratio; ψ_c = suction value below which significant deformations take place; ψ_f = suction value below which nonsignificant volumetric changes are measured. Collapsible soils especially compacted soils may expand or maintain constant volume in the pre-collapse phase besides of slightly collapsing, and may collapse as significant as that in the collapse phase or slow down collapsing in the post-collapse phase besides of stopping collapsing (see Fig. 3, where, p_{atm} = atmospheric pressure; s_f = final suction, being always considered as 0; $s_0(p)$ = critical suction; $\lambda_s(p)$ = collapse rate). The above discussion suggests that there are nine possible strain path scenarios to completely characterize the volume change behaviour of collapsible soils during wetting (i.e. No. I, II, …, IX, see the inset table in Fig. 3).

The volume change behaviour in the pre-collapse phase depends on soil physical properties (e.g. void ratio and water content) and applied stress. In Fig. 3, path ① indicates that the soil expands in response to matric suction decrease as matric suction is larger than a critical value (i.e. critical suction). Collapsible soils wetted under a lower stress or having a higher initial density are more likely to go through this path in the pre-collapse phase. Path ③ indicates that the soil collapses slightly as it is subjected to a matric suction greater than the critical suction value, collapsible soils wetted under a higher stress or having a lower initial density are more likely to fall into this category (Sun et al., 2007). Similarly, whether the soil slows down collapsing or stops

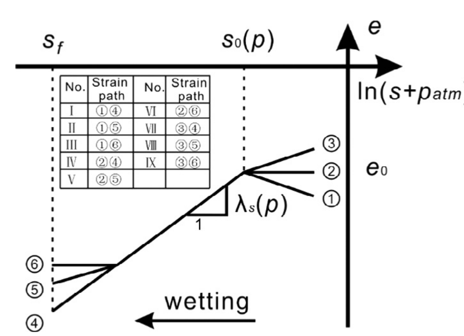

Fig. 3. Collapse behaviour in terms of three collapse phases during wetting.