Engineering Geology 214 (2016) 1–10

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

Influence of environmental factors on the wetting front depth: A case study in the Loess Plateau

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ARTICLE INFO

Article history:
Received 25 February 2016
Received in revised form 15 September 2016
Accepted 19 September 2016
Available online 20 September 2016

Keywords:
Unsaturated loess
Wetting front depth
Water content variation
Environmental factors
Soil temperature
VADOSE/W

ABSTRACT

Reliable information on the wetting front depth and variation of water contents within the zone of wetting is required for addressing geotechnical problems in loess deposits such as estimation of the collapse deformation and assessment of the slope stability. For this reason, a field test was conducted at a site in the Loess Plateau of China to obtain data on soil water contents and temperatures at different depths for a period of one year. The variation of water contents was interpreted from the influence of environmental factors and soil temperature, and used to determine the maximum wetting front depth in the loess soils in the study region. In addition, a commercial software, VADOSE/W, was used to simulate the flow behaviour in unsaturated loess taking account of the influence of environmental factors. A reasonable agreement was found between the results of field investigations and numerical simulations. The study results are useful as they provide valuable information about the wetting front depth and water content variation in unsaturated loess in response to environmental factors. The field investigations and numerical simulations summarized in this paper can serve as a reference for future studies on other soils.

1. Introduction

Loess soils are widely distributed in semi-arid and arid regions around the world; which include countries such as China, Russia, the United States, Argentina, France, Germany and New Zealand (Rogers et al., 1994). These soils are typically in a state of unsaturated condition and are susceptible to collapse (i.e. sudden decrease in soil volume) due to an increase in natural water content under practically unchanged vertical stress (Barden et al., 1973). The prerequisite conditions for collapse include: a soil fabric which is open and potentially meta-stable, an increase in water content that contributes to reduction of soil suction and destruction of bonding agents, and a relatively high level of total vertical stress (Barden et al., 1973). Li et al. (2016) presented a state-of-the-art review on the wetting-induced collapse mechanism with special reference to loess soils. In China, loess soils have deposited since 2.4 million years (i.e., 2.4 Ma) ago, forming the Loess Plateau extending an area of over 440,000 km^2. Loess thicknesses are typically of 50 to 100 m while a thickness up to 300 m was found in Gansu, China (Zhou and Derbyshire, 2008). As per Smalley et al. (2001), Liu and his colleagues were the earliest to conduct large-scale investigations of loess stratigraphy. They divided the loess soils deposited in the Quaternary period (more than 2.4 Ma) into three formations; namely, Wucheng, Lishi and Malan loess corresponding to early, middle and late Quaternary periods, 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, 10–20 m deep below the ground surface) are found collapsible upon wetting (Derbyshire, 2001; Dijkstra et al., 1994). It is difficult to estimate the collapse deformation of loess soils with a reasonable accuracy unless the wetting front depth is determined (Houston et al., 1988).

In addition, rainfall-induced shallow landslides are major geo-hazards in loess regions. The rainfall-induced shallow failure of soil slopes is triggered by a matric suction decrease as a result of wetting (Crosta, 1998; Dai and Lee, 2001). A key issue in assessing this type of slope failure is reliable estimation of the matric suction variation within the zone of wetting (Trandafir et al., 2008). Limited research has focussed on the details of rainfall infiltration and advancement of the wetting front for understanding their effects on the unsaturated soil slope stability (Kim et al., 2004; Yeh et al., 2008; Trandafir et al., 2008; Cho, 2009). For these reasons, there is an urgent need to investigate the wetting front depth and water content variation within the wetted zone in loess soils.

The wetting front depth is defined as the depth to which water contents have either increased due to introduction of water from external sources or decreased due to evaporation (Nelson et al., 2001). External sources include rainfall, irrigation, seepage from water lines, and others. The first conceptual model for estimating the depth of wetting front in

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http://dx.doi.org/10.1016/j.enggeo.2016.09.008
0013-7952/

saturated-unsaturated soil system was introduced by Lumb (1975). In Lumb's study, it was assumed that the soil is saturated near the ground surface and close to saturated down to a certain depth. Sun et al. (1998) extended Lumb's theory and proposed a generalised equation for estimating the wetting front depth. In Sun et al. study, it was suggested that a new infiltration zone forms and gradually progresses downwards when the ground surface moisture flux increases. This equation can estimate the wetting front depth reasonably in one-layered soil profiles (Yeh et al., 2008). Several other methods were proposed based on field and laboratory investigations (El-Ehwany and Houston, 1990; Leconte and Brissette, 2001; Trandafir et al., 2008; Yeh et al., 2008).

The wetting front depth was commonly determined from artificial rainfall tests in the field or wetting column tests in the laboratory for various soil types (Zhang et al., 2000; Li et al., 2005; Singh et al., 2006; Tu et al., 2009). This is because the simplified conceptual models do not take account of many other factors which influence the wetting front depth (for example, Lumb, 1975 and Sun et al., 1998). Various factors, including soil properties, topographic features, rainfall intensity and duration, other climate factors (such as evaporation and atmospheric temperature) and land-use type (i.e. vegetation factors or cover type), influence the wetting front depth in loess soils. Several studies were performed to investigate the response of loess soils to varying rainfall intensity and duration, slope height and gradient, soil properties, type of land-use, respectively (De Roo and Riezebos, 1992; Gvirtzman et al., 2008; Zhao et al., 2012). For example, Zhao et al. (2012) conducted large-scale laboratory column tests and found that the influence of precipitation is typically within 1.6 m for loess soils from Changwu, China. Most of these studies focused on the influence of precipitation and land use, while few studies considered the comprehensive influence of environmental factors.

In order to investigate the influence of environmental factors on the water contents in loess soils, a field test was undertaken at a site in the Loess Plateau of China. At the site, water contents and temperatures of the soils at different depths were measured for a period of one year. The variation of water contents was interpreted and used to determine the maximum wetting front depth in response to environmental factor. In addition, the flow behaviour in unsaturated loess was successfully simulated using a commercial software, VADOSE/W, in order to provide a reliable and more economical method for estimating the wetting front depth and water content variation under environmental factors. This study highlights the field investigation of soil water contents and temperatures over a long period of time, as well as the numerical modelling of the flow behaviour in unsaturated loess soils under environmental factors.

2. Site description

Two key factors were considered for selecting a test site to undertake the field test. First, the site should be free of vandalism so that the instrumentation system would not be disturbed during the testing period. Second, the soil at the site has to be a typical loess soil that is representative of the Loess Plateau. Considering these two factors, a site was selected at an abandoned school yard, in Zhengning County, Gansu, China (geographical location of the site in the map of China is shown in Fig. 1). As the study region is located in the central Loess Plateau, the soil at the site is representative of the Loess Plateau.

The annual precipitation is less than 500 mm, while the annual evaporation can reach up to 1500 mm in the study region. This region has four distinct seasons and the atmospheric temperature typically varies from −20 to 35 °C.

2.1. Soil properties

A well of 1 m in diameter and 10 m in depth was excavated at the site for installation of instruments. Along the depth, the soil of pale yellow color extending from the ground surface to about 8.5 m deep was classified as Malan loess. One layer of paleosol sandwiched between loess layers was identified from 8.5 to 10 m deep. Paleosol soil deposited during wet and warm periods has typically red-brown color and denser structure than loess soil which deposited during dry and cold periods.

To characterize the soils at the site, soil samples were collected at integer depths (i.e. 1, 2, …, 10 m) during the excavation of the well for laboratory test program. In addition, one more sample was taken at a depth of 0.5 m. The physical properties determined from laboratory test program include: (i) bulk density, (ii) natural water content, (iii) Atterberg limits, and (iv) particle size distribution. The test results are shown in Fig. 2. From these results, it can be observed that the content of silt- and clay-size particles increases with the depth; the dry density varies between 1.3 and 1.4 Mg/m^3; the natural water content varies from 13 to 18%; both the plastic and liquid limits show small variations along the depth.

3. Instrumentation system

The moisture probes and thermometers were used to measure the soil water contents and temperatures at specified depths, respectively. Before their installation, all the instruments were checked for proper functioning in the laboratory.

3.1. Moisture probe

YT-DY-0101 moisture probes were used to measure soil water contents. The moisture probe has a high-frequency moisture detector that uses the principle of standing-wave to indicate the ratio of three or more substances (i.e. typically, soil particle, water and air) forming a mass of material. Each substance has a specific dielectric constant. The water content can be estimated from the change in dielectric constant value. The output of the moisture probe is volumetric water content calculated using the calibration coefficient provided by the manufacturer. However, the moisture probe needs to be recalibrated before using

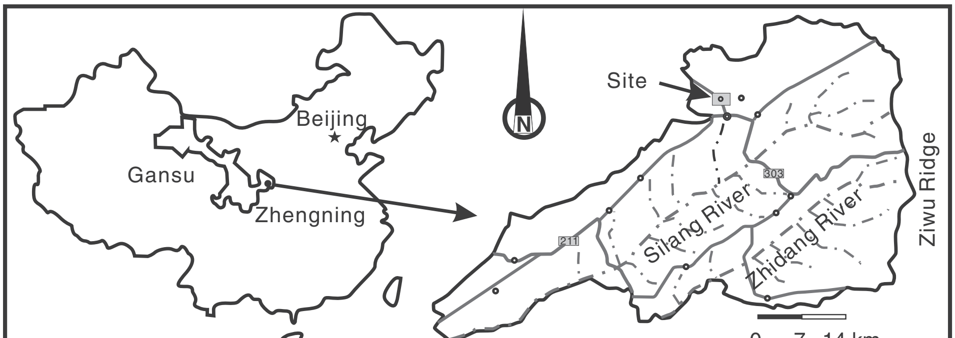

Fig. 1. Geographical location of the test site.