

A Case Study: Characteristics of Unsaturated Loess (Q₃) Sampling on Loess Plateau, NW China

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Abstract

The late Pleistocene loess (Q₃) widely distributes in the northwest area of China. As for loess landslides, it has great importance to research the physical and mechanical characteristics of unsaturated loess (Q₃). Therefore, to determine the Soil Water Retention Curve (SWRC), Hydraulic Conductivity Function (HCF) and Suction-Stress Characteristic Curve (SSCC) play a key role in analyzing the mechanical behavior of unsaturated loess. In this paper, the SWRC, HCF and SSCC of loess (Q₃) sampling on Chinese loess plateaus have been measured by the TRIM apparatus. The results show that the parameters have obvious difference under drying and wetting state, and the difference reflects the hysteresis characteristics of SWRC, HCF and SSCC. In fact, "the hysteresis effect" will control the rainfall-induced loess landslides. Finally, the research indicated that the suction stress is more able to reflect the unsaturated hydraulic properties of loess than the matric suction.

Keywords: Unsaturated loess, Suction stress, TRIM test, Loess landslide

1. Introduction

According to unsaturated soil theory, the shear strength, stress-strain relationship, consolidation and groundwater seepage are closely related to the matric suction. Moreover, the soil water characteristic curve (SWCC) reveals the relationship between matric suction (u_a-u_w) of unsaturated soil and humidity (e.g., volumetric water content, water content or saturation) (Fredlund and Rahardjo, 1993; Miller et al., 2002; Mbonimap et al., 2006). So far, the soil water characteristic curve (SWCC) has been widely used in unsaturated soil theory (Gardner, 1958; Li, 2005; Pham et al., 2005; Nuth and Laloui, 2008; Mualem and Beriozkin, 2009; Min and Huy., 2010; Vanapalli et al., 1999; Romero et al., 2001; Imbert et al., 2005). In fact, the water-soil coupling effect of unsaturated soil is one of the research hotspots. In recent years, the concept of suction stress has been proposed by Lu et al. (2004, 2006a, 2006b, 2010), and the suction stress characteristic curve (SSCC) has become an alternative method to study the hydraulic property of unsaturated soil.

Generally speaking, to measure unsaturated hydraulic properties includes different experimental tests, such as tensiometer, psychrometer and chilled mirror hygrometer. However, these methods have some disadvantages of complexity, time-consuming

and limited measuring range (Hilf, 1956; Spanner, 1951; Gee et al., 1992; Houston et al., 1994; Likos and Lu, 2003). In the research, the Transient Release and Imbibition Methods (TRIM) has been used to measure the Soil-Water Retention Curve (SWRC), Hydraulic Conductivity Function (HCF) and Suction Stress Characteristic Curve (SSCC) of loess within a range of suction (0-10⁶ kPa) under both drying and wetting conditions. The research can be used to establish the irrigation or rainfall warning criteria of loess landslide hazards.

2. Study Area

The Heifangtai terrace is located 42 km west of Lanzhou city, Gansu Province, NW China. The study area is on the fourth terrace of the Yellow River, and is about 100 - 133 m higher than the water table. The terrace has been cut by the Yellow River, Huangshui River and other small valleys, and formed deep valleys and slopes with severe water and soil losses. The outcropped layers are the Upper Pleistocene wind-blown loess underlying sandy gravel layer. The bottom of layers is the Cretaceous mudstone and sandstone, presently forming steep, high cliffs along the river corridor. The upper layer of loess is composed of silty particles, and is loose with big voids and vertical joints.

In the past decades, agricultural irrigation in the study area has greatly changed the groundwater through infiltration of irrigation water. Irrigation penetration increased the recharge of the groundwater and manually broke the balance of the groundwater condition. In recent years, the average yearly irrigation volume is about $590.91 \times 10^4 \text{ m}^3/\text{a}$ and the groundwater recharge has gone up to $362.57 \times 10^4 \text{ m}^3/\text{a}$. As a result, the water table has risen several meters, and the unsaturated zone of loess has increased gradually, resulting in many loess landslides. According to statistics, there are 14 loess landslides in the 2.8 km distance of Jiaojiaya slopes. Therefore, the research on hydro-mechanical properties of loess in the study is very important.

3. Experimental method

3.1 Apparatus and method

The apparatus of TRIM tests introduced from Colorado School of Mines in America showed in Figure 1. The TRIM System is a simple-to-use laboratory device for measuring SWRC and HCF of unsaturated soils. The SWRC and HCF may be measured along either wetting or drying paths in as little as 5-7 days using either disturbed or undisturbed samples. The system may be operated in either steady-state mode or transient mode and is applicable for all major soil types, including sand, silts, and clays. Some features of the TRIM System as follows.

- Precision flow cell with integrated high-air-entry base (300 kPa);
- Capability to extrapolate suction range to several thousand kPa;
- Control panel for dual-range air-pressure (< or > 15 kPa) control;
- Undisturbed or remolded specimen for dimensions of 5-14 cm (diameter) x 5-10 cm (height);
- Completion of both wetting and drying SWCC and HCF shown above in one week.

3.2 Sampling and parameters

In the study, the undisturbed loess samples were collected from the Heifangtai platform in Gansu Province of Northwest China. The size of these samples is $H2.54 \text{ cm} \times \Phi 6.18 \text{ cm}$. The basic physical parameters of the test completed in the Key Laboratory of Geo-hazards in Loess area, Xi'an Center of Geological Survey. All the parameters were shown in Table 1.

In particular, the loess and the ceramic stone must be saturated before the TRIM test; otherwise the experimental data cannot be used as the objective function of inversion. After several tests and improvements, we used the saturated method of continuous pumping air. The detailed operation includes the following steps of: (1) Put the loess and the ceramic stone into the vacuum apparatus for two hours, and then open the valve to make the pneumatic water into the vacuum apparatus; (2) Close the valve when the water rises to half height of the loess and the ceramic stone, and then closes the valve; (3) Pump continuously for more than an hour, and then open the valve when the water completely submerged the loess and the ceramic stone; (4) Close the valve, and then pump more than an hour; (5) Finally, make the loess and the ceramic stone immerse in the water for twenty-four hours. Usually, according to the improved method, the degree of saturation can reach 100%.

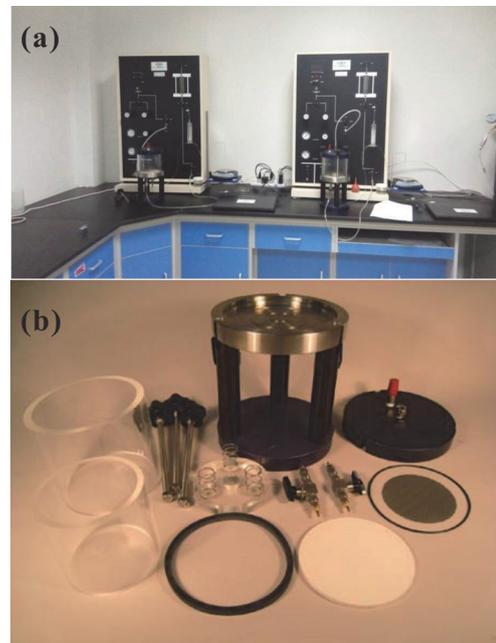


Fig. 1 (a) TRIM system; (b) The components of the flow cell

4. Results and Discussion

4.1 SWRC and HCF

Based on the theory of unsaturated soil, the soil-water retention curve (SWRC) and hydraulic conductivity function (HCF) can be used to predict

Table 1 Physical parameters of undisturbed loess

Sampling area	Density (g/cm^3)	Water content (%)	Dry density (g/cm^3)	Porosity Ratio	Specific Gravity (kN/m^3)	Liquid Limits (%)	Plastic Limits (%)	Saturated Infiltration Coefficient
Heifangtai	1.452	7.7	1.348	1.01	2.71	26.55	15.92	$5.07\text{E}-4$

the effective stress and the change rules of the shear strength. By means of Hydrus-1D code, the SWRC and HCF of the loess samples were obtained under both drying and wetting conditions, and suction of 0-10⁶ kPa. The results and the model parameters as shown in Figure 2.

For a given water content, the value of matric suction under wetting conditions is lower than the value of matric suction under drying condition. Moreover, the energy of pore water along the wetting path is higher than the drying path. The results reflect the soil's hysteresis, which generally results from tortuous soil pore structure and /or difference in affinity between soil grains and water under different wetting histories. Loess landslides usually occur due to heavy rainfall, so the wetting path is generally more relevant in describing the failure processes than the drying path. Specifically, although both the drying curve and the wetting curve can be used to build rainfall warning criteria for rainfall-induced landslide, the wetting curves of SWCC are the most significant hysteresis model for unsaturated soil slope seepage.

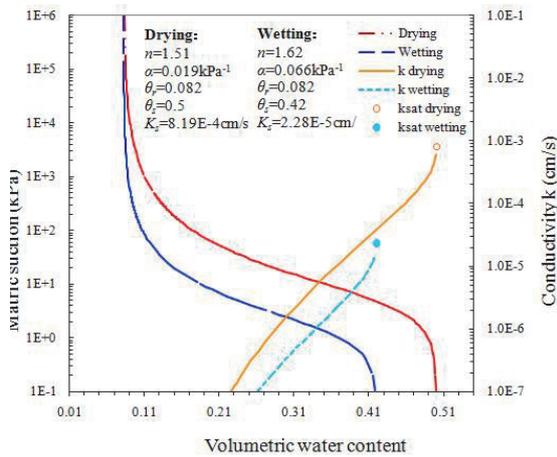


Fig. 2 SWRC and HCF of undisturbed loess under wetting and drying conditions

4.2 SSCC

The suction stress characteristic curve (SSCC) can be quantified from SWRC. The Figure 3 and 4 show the SWRC and SSCC for Q₃ loess under both wetting and drying conditions. The maximum suction stress under the drying conditions is -684 kPa corresponding to a water content of 9.08%. However, the maximum suction stress under the wetting conditions is -177 kPa corresponding to a water content of 8.38%. Meanwhile, the air-entry pressure (1/α) under the drying path is 52.63 kPa, and the air-entry pressure (1/α) under the wetting path is 15.15 kPa. The difference of suction stress due to hysteresis for the loess sample can be up to 37 kPa. This difference of suction (effective stress) is enough

to trigger loess landslides in the study area.

Usually, the suction stress can supply tensile forces between the soil particles. Therefore, it can increase the effective stress of soils. As we all known, the effective stress may be very low (0-20 kPa) in the layer of shallow soil, so the variation of suction stress is very sensitive. This is why the loess hill slopes slide frequently under irrigation and rainfall conditions.

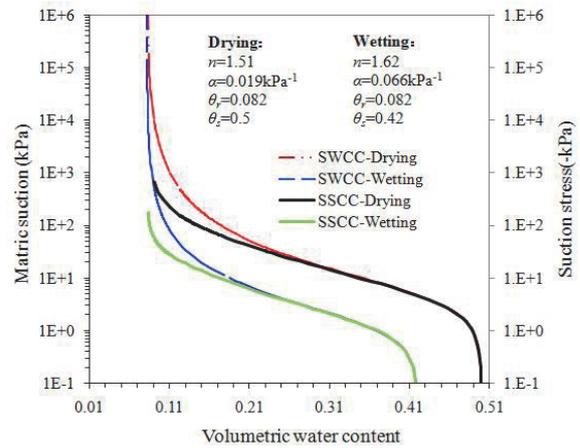


Fig. 3 SWRC and SSCC of undisturbed loess under wetting and drying conditions

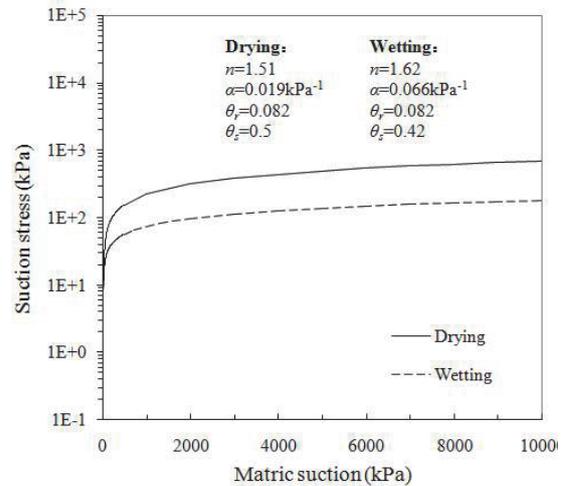


Fig. 4 SSCC, as a function of matric suction under wetting and drying conditions

5. Conclusions

Firstly, the hysteresis behaviors for the SWRC, HCF and SSCC of the loess are quite different under the wetting and drying conditions. Secondly, loess landslides usually occur due to heavy rainfall or irrigation, so the wetting path is generally more relevant in describing the failure processes than the drying path. Thirdly, the difference of suction stress due to hysteresis for the loess sample can be up to 37 kPa, and the difference of suction (effective stress) is

enough to trigger loess landslides in the study area. Finally, suction stress is more able to reflect the unsaturated hydraulic properties of loess than the matric suction.

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