Suction and thermal conductivity of unsaturated loess from Northern France

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ABSTRACT: Loess covers large areas around the earth. Loess deposits are typically composed of silt with clay and fine sand particles and it is usually distributed with a few meters thick. Literature review shows that, the thermal conductivity of loess varies in a relatively large range from 0.2 to 2 W/(mK), depending on the particle composition, texture and moisture content of soil. In this study, loess samples were taken at shallow depth from the Northern France. Suction, volumetric moisture content and thermal conductivity of soil were measured simultaneously while wetting/drying cycles were applied to the sample. The results show that, the degree of saturation significantly affects the thermal conductivity of the soil. The relationship between these two parameters is reversible under wetting/drying cycles while hysteresis can be observed while plotting the thermal conductivity versus suction.

1 INTRODUCTION

A geological review of natural loess in Northern France shows that, the thickness of loess deposit ranges between 3 m to 8 m and it is usually composed of less than 10% sand and 10 to 25% clay content (Antoine et al. 2003). The main features are characterized by (*i*) a relative homogeneity, a high porosity and a low plasticity; and (*ii*) a natural unsaturated state even during winter periods (Antoine et al. 2003; Cui et al. 2004; Delage et al. 2005; Yang et al. 2008; Karam et al. 2009; Muñoz-Castelblanco et al. 2011; Muñoz-Castelblanco et al. 2012a, 2012b). Loess is strengthened by suction under partially saturated condition, but its open structure collapses under a high degree of saturation and induces loss of stability of the structure. In addition, Muñoz-Castelblanco et al. (2012) indicated that the hysteresis of the water retention curve of loess is related to the capillary action in the large pores, that exist between the grains, and the water adsorption of clay particles in the small pores.

For thermo-active geo-structures or buried underground cables and pipelines, soil thermal conductivity plays an important role to the heat exchange between the structures and the surrounding soil. In general, loess around the world has thermal conductivity ranging between 0.15 to 2 W/(mK) (Bidarmaghz et al. 2016). This value depends strongly on the soil hydric state, it is higher with a higher water content. The loess in Northern France has a high porosity and therefore the thermal conductivity can be significantly affected by seasonal wetting/drying cycles. In the present work, moisture content, suction and thermal conductivity are simultaneously measured on a single block of loess from Northern France. That allows quantifying the effect of suction and degree of saturation on soil thermal conductivity.

2 MATERIALS AND EXPERIMENTAL METHODS

A block of soil was sampled at 1 m depth in Northern France (Muñoz-Castelblanco et al. 2012a, 2012b). The geotechnical properties of the sampled soil are showed in Table 1.

A rectangular prism (approximately 150 mm x 90 mm x 90 mm) is cut from an undisturbed block by using a hand saw. The weight of the soil sample and its water content are firstly measured. The soil sample is then coated with a thin layer of paraffin on its bottom and vertical surfaces to avoid moisture exchange with the atmosphere. A thin plastic wrap lid is used to cover the upper surface. For wetting steps, the wrap lid on the upper surface is removed and water is sprayed onto the soil surface. For drying steps, the wrap lid is removed, and the sample is dried by allowing water evaporation from the top surface. Moisture equilibrium within the sample is waited for after each wetting or drying step, by covering the soil surface by the lid to avoid moisture exchange with the atmosphere.

Table 1. Geotechnical properties of sampled loess from Northern France.

Natural water content w (%)	14.0
Natural void ratio e	0.84
Dry unit mass ρ_d (Mg/m^3)	1.45
Natural degree of saturation S_r (%)	46
Natural suction (kPa)	40
Clay fraction (%< 2 μm)	16
Quarzt fraction (%)	70
Plastic limit w_p	19
Liquid limit w_l	28
Plasticity index I_p	9

Three sensors are then carefully inserted inside the sample: (*i*) a tensiometer (23 mm in diameter) to measure the soil suction (Duong et al. 2013); (*ii*) a TDR (Time Domain Reflectometry) probe including three rods (80 mm length, 3 mm in diameter) to measure the soil volumetric moisture content; (*iii*) and a KD2-Pro probe (60 mm length and 1 mm in diameter) to measure the soil thermal conductivity. The positions of these sensors are shown in Figure 1. Holes having dimensions similar to those of the sensors are drilled prior to the insertion of the sensors. That allows good contact between the sensors and the soil while minimizing the disturbance of its initial state. The distance between the sensors is large enough to avoid any interference. The tensiometer and the TDR probe are connected to the data logger system for automatic reading; the thermal conductivity is recorded manually.

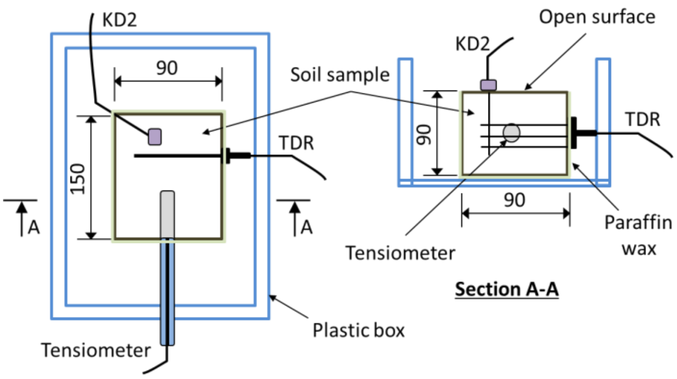

Figure 1. Experimental setup.

3 RESULTS AND DISCUSSION

Figure 2 shows the results obtained during the first ten days where the sample was subjected to various wetting steps from its initial state. From its initial state with s = 40 kPa and θ = 18.7%, adding water increases quickly the moisture content to θ = 23%, but this value decreases progressively and stabilizes at θ = 22% after few hours. At the same time, wetting induces a quick decrease of the suction to 18 kPa, but suction increases progressively afterward to 20 kPa. Such non-monotonous variations of moisture content and suction can also be observed in the subsequent wetting steps. That can be explained by the homogenization process of moisture inside the soil block that takes few hours at high suction but more than one day at low suction (see Figure 2a). From these results, equilibrated points were chosen at the end of each wetting step (see the vertical lines in the Figure 2a). As the thermal conductivity was recorded manually, such evolution during each wetting step could not be observed (see Figure 2b). However, the thermal conductivity corresponding to the end of each wetting step was determined.

Figure 3 shows the results obtained during the subsequent drying path (from 10 to 65 days). When the wrap lid is removed, water evaporation takes place and the moisture content decreases slowly (see Figure 3a). It should be noted that the rate of moisture decreased (by evaporation during drying steps) is much smaller than the rate of moisture increased (by adding liquid water during wetting steps). In addition, the moisture content homogenization is reached quickly when the wrap lid is put back to the top of the soil block. As expected, drying induces suction increase. The time to reach equilibrium is about one day at low suction but may reach several days at high suction. The results obtained during this drying path allow determining nine equilibrated points at the end of the drying steps (vertical lines shown in Figure 3a). The soil thermal conductivity corresponding to these points was then determined from the Figure 3b.

After the drying path, the soil block was rewetted by steps. The results of this rewetting path (from 65 to 90 days) are shown in Figure 4. The rate of suction and moisture content variations versus elapsed time during this path is very similar to that observed during the initial wetting path. Eleven equilibrated points were determined along this path at the end of the wetting steps (Figure 4a). The corresponding thermal conductivity was determined from the Figure 4b.

The values of suction, moisture content and thermal conductivity corresponding to the end of drying or wetting steps (shown in Figures 2, 3 and 4) are plotted in Figure 5. Figure 5a shows the soil suction versus volumetric moisture content and degree of saturation. From the initial state, when the degree of saturation is increased to 0.8, soil suction is decreased to 1 kPa. The subsequent drying path decreases the degree of saturation to 0.3 and increases the soil suction to 70 kPa. The drying curve locates above the wetting curves. Finally, the rewetting curve locates below the drying path and approaches the wetting curve at suctions lower than 10 kPa.

When plotting the thermal conductivity as a function of suction (Figure 5c), a hysteresis loop is observed, quite similarly to the water retention curve. However, when the thermal conductivity versus the water degree of saturation is plotted, an almost linear one-to-one relationship is obtained (Figure 5b). Thermal conductivity increases from 1.0 W/(m.K), at $S_r = 0.3$, to 1.6 W/(m.K) at $S_r = 0.8$.

For further analyses, the model proposed by Johansen (1975) was used to calculate the thermal conductivity of soil from the degree of saturation. According to Farouki (1986), the method developed by Johansen (1975) is applicable for unfrozen fine-grained soils at $S_r > 0.2$. The thermal conductivity (λ) is expressed as: $\lambda = (\lambda_{sat} - \lambda_{dry})(1 + \log_{10} S_r) + \lambda_{dry}$; where λ_{sat} and λ_{dry} are the thermal conductivities in saturated and dry states, respectively.

- For saturated unfrozen soils: $\lambda_{sat} = \lambda_s^{(1-n)} \lambda_w^{n}$; where n is the porosity and λ_w is the thermal conductivity of water ($\lambda_w = 0.57$ W/(m.K)). The thermal conductivity of the solids λ_s is calculated using the equation: $\lambda_s = \lambda_q^{q} \lambda_0^{1-q}$; where λ_q is the thermal conductivity of quartz ($\lambda_q = 7.7$ W/(m.K)), λ_0 is the thermal conductivity of other minerals ($\lambda_0 = 2.0$ W/(m.K)) and q is the quartz content.
- For dry soils: $\lambda_{dry} = (0.135\rho_d + 64.7)/(\rho_s - 0.947\,\rho_d)$; where the dry unit mass, ρ_d and the unit mass of the solids, ρ_s are expressed in kg/m^3 and λ_{dry} is expressed in W/(m.K).

It can be seen in the Figure 5b that the model can predict correctly the relation between the thermal conductivity and the degree of saturation by using a quartz content of 60%. This value is in the same range as that mentioned previously by Antoine et al. (2003).

The experimental set-up used in this study is quite similar to that used by Smits et al. (2013) to investigate the thermal properties of sand. In the present work, wetting and drying were applied in steps in order to ensure moisture equilibrium at each step. This procedure was necessary because the hydraulic conductivity of loess is much lower than sand. The soil-water-retention curves obtained are similar to those obtained by Muñoz-Castelblanco et al. (2012b) on the same soil (for suction smaller than 100 kPa) but using other techniques (filter paper and high-capacity tensiometer).

In this work, the wetting/drying paths do not correspond to the main wetting/drying paths, which start from a dry state of fully saturated state, respectively. For this reason, analysis on air-entry value or degree of hysteresis (as that performed by Ng et al. 2016) could not be done. Following the conceptual model proposed by Lu and Dong (2015), the soil-water-retention curves obtained in the present work correspond to two regimes: capillary and funicular. The hysteresis observed in the soil-water-retention curve in these regimes can be explained by the combined effects of ink-bottle, contact-angle and entrapped air (Pham et al. 2005; Ng et al. 2016).

Besides, it is well known that the soil thermal conductivity depends on various parameters such as, degree of saturation, microstructure, water distribution, density, etc. (Farouki 1986; Tang et al. 2008; Guan et al. 2009; Dong et al. 2015; Usowicz et al. 2016). In this study, it was assumed that wetting/drying cycles change neither the density nor the microstructure of the loess. At a given degree of saturation, soil suction on a drying path is higher than that on a wetting path. That means the water distributions between the two states are different. However, a unique relationship was found between thermal conductivity and water degree of saturation. These results suggest that, the effect of water distribution on soil thermal conductivity is less significant than those of the other factors.

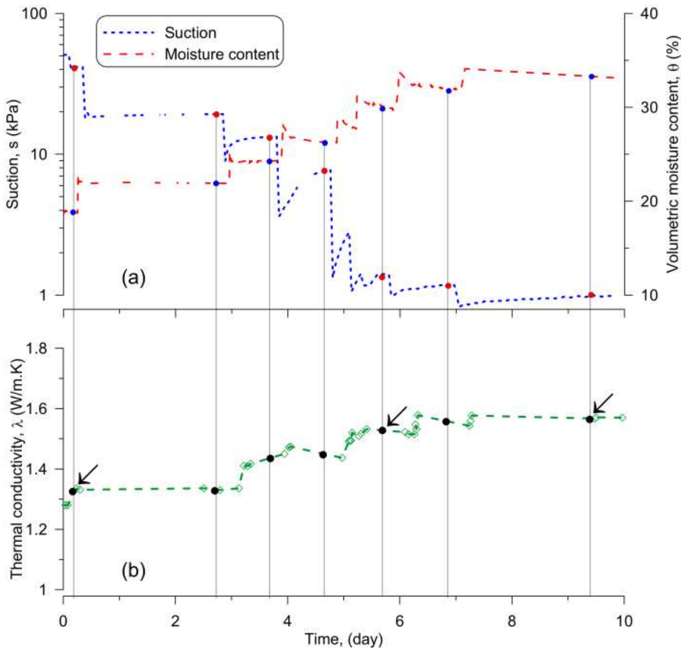

Figure 2. Suction, moisture content and thermal conductivity in the wetting phase. Thermal conductivity is linearly interpolated between two successive manual readings.

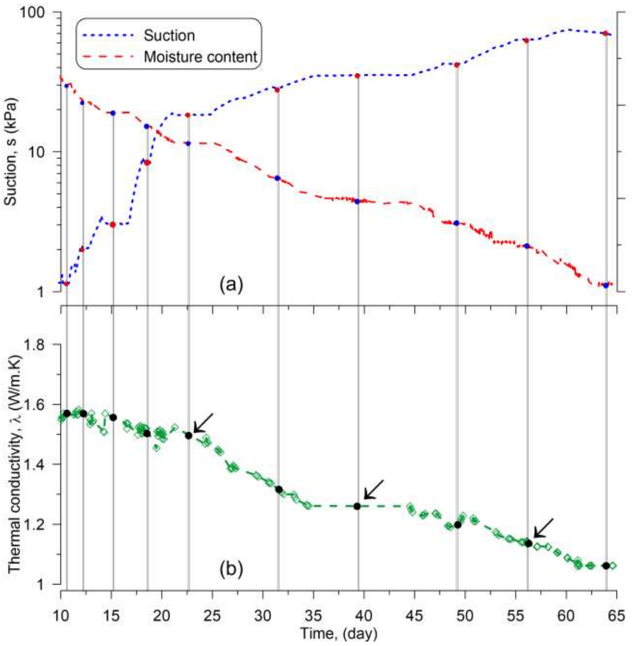

Figure 3. Suction, moisture content and thermal conductivity in the drying phase. Thermal conductivity is linearly interpolated between two successive manual readings.

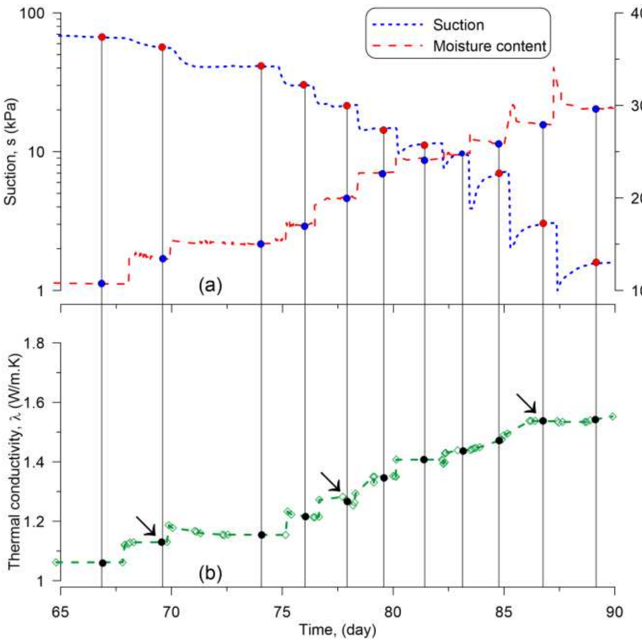

Figure 4. Suction, moisture content and thermal conductivity in the re-wetting phase. Thermal conductivity is linearly interpolated between two successive manual readings.

4 CONCLUSIONS

The relationship between moisture content, suction and thermal conductivity under wetting/drying paths has been investigated on the loess from Northern France. The following conclusions can be drawn:

- Water-retention curve and thermal conductivity of intact loess can be obtained by simultaneous measurement of moisture content, suction and thermal conductivity on a single soil sample.
- The thermal conductivity varies between 1.0 and 1.6 W/ (m.K), when the degree of saturation increases from 0.3 to 0.8. In this range, a one-to-one relationship between these two quantities is observed during the wetting/drying paths.

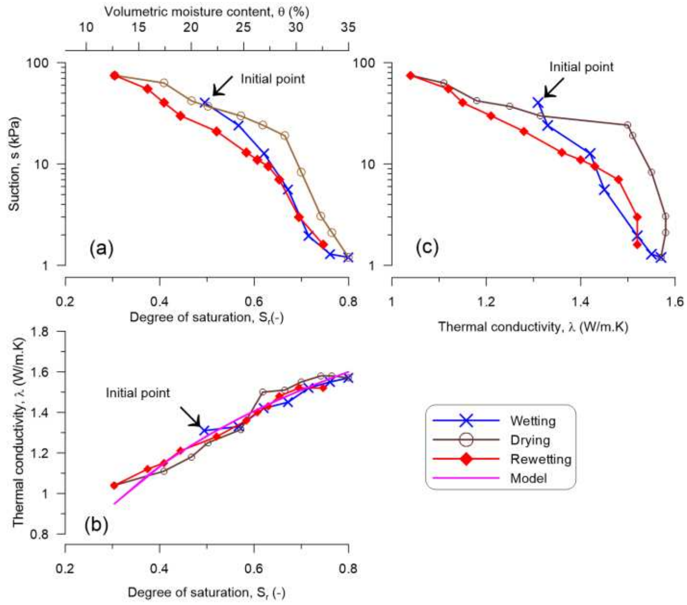

Figure 5. Relationships between thermal conductivity, suction and degree of saturation.

- The relationship between suction and thermal conductivity is characterized by a clear hysteresis loop.
- At a given degree of saturation, soil suction corresponding to a drying path is higher than that of a wetting path. That means the water distribution is different from one path to the other path. As a result, at first order, the thermal conductivity of loess in this study depends on the amount of water but not on its distribution within the soil microstructure in the suction range studied.

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