PROOFS

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Water retention and thermal conductivity of a natural unsaturated loess

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Loess covers large portions of Earth's surface. Loess deposits are typically composed of silt with clay and fine sand particles and usually reach a few meters in thickness. Thermal conductivity of loess varies over a relatively large range from 0·07 to 2 W/(m.K), depending on the particle composition, soil texture and also moisture content. In this study, intact loess was sampled at shallow depth (1 m) in Northern France. Suction, volumetric moisture content and thermal conductivity of soil were measured simultaneously during the application of wetting/drying cycles to the sample. The results show that the volumetric moisture content significantly influences the soil thermal conductivity. As is the case for the water-retention curve, a hysteresis loop can be observed when plotting the thermal conductivity against suction. However, no hysteresis appears when the thermal conductivity is plotted as a function of the degree of saturation.

Q2 **KEYWORDS:** suction

NOTATION

n	porosity of soil
S_r	degree of saturation
s	suction
θ	volumetric moisture content
λ	thermal conductivity
λ_{dry}	thermal conductivity in dry states
λ_o	thermal conductivity of other minerals
λ_s	thermal conductivity of the solids
λ_{sat}	thermal conductivity in saturated states
λ_w	thermal conductivity of water
ρ_d	dry unit mass
ρ_s	unit mass of solids

INTRODUCTION

The main features of natural loess in Northern France are characterised 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, 2012a, 2012b). In addition, its mechanical properties are strengthened by suction, but its open structure collapses on wetting. A number of geotechnical applications require knowledge of the thermal properties of soils, including the thermal conductivity. As summarised by Dong *et al*. (2015), the key governing factors that control the thermal conductivity of unsaturated soils are constituent, soil type, water content
Q3 and particle contact. Dong *et al*. (2015) reviewed the existing models of thermal conductivity of unsaturated soils and found that the pore-scale water distribution has not been reflected in all the existing models. Lu & Dong (2015) established a conceptual model linking soil-water retention regimes to the corresponding thermal conductivity variation behaviour. Moreover, Bidarmaghz *et al*. (2016) mentioned that there was limited literature regarding the thermal characteristics of loess. Most of the existing works focused on the effect of moisture content on the thermal conductivity of loess, while water retention was not investigated simultaneously. In this study, moisture content, suction and thermal conductivity on an intact block of loess from Northern France are simultaneously measured to quantify the effect of moisture content and suction on the soil thermal conductivity.

MATERIAL AND EXPERIMENTAL METHOD

A rectangular prism (~150 mm × 90 mm × 90 mm) is cut from an undisturbed block (obtained from a depth of 1 m in Northern France) by using a handsaw to minimise soil disturbance induced by sample preparation (see Fig. 1(a)). The geotechnical properties of the sampled soil are shown in Table 1. The soil sample is then coated with a thin layer of paraffin on its bottom and lateral surfaces to avoid moisture exchange with the atmosphere. A thin plastic wrap lid is used to cover the top surface. For wetting steps, the wrap lid on the top 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 achieved by waiting for a few hours after each wetting or drying step, by covering the soil surface by the lid to avoid moisture exchange with the atmosphere. The moisture equilibrium is assumed to be reached when suction and moisture content do not change during a 1 h period (< 1 kPa for suction and < 1% for moisture content).

Three sensors are carefully inserted inside the sample (Figs 1(b) and 1(c)) prior to wetting/drying: (*i*) a tensiometer (23 mm in diameter; accuracy equals 1 kPa) to measure the soil suction (Duong *et al*., 2013); (*ii*) a time-domain reflectometry (TDR) probe including three rods (80 mm length, 3 mm in diameter; accuracy equals 1%) to measure the soil volumetric moisture content; (*iii*) and a KD2-Pro probe (60 mm length and 1 mm in diameter; accuracy equals

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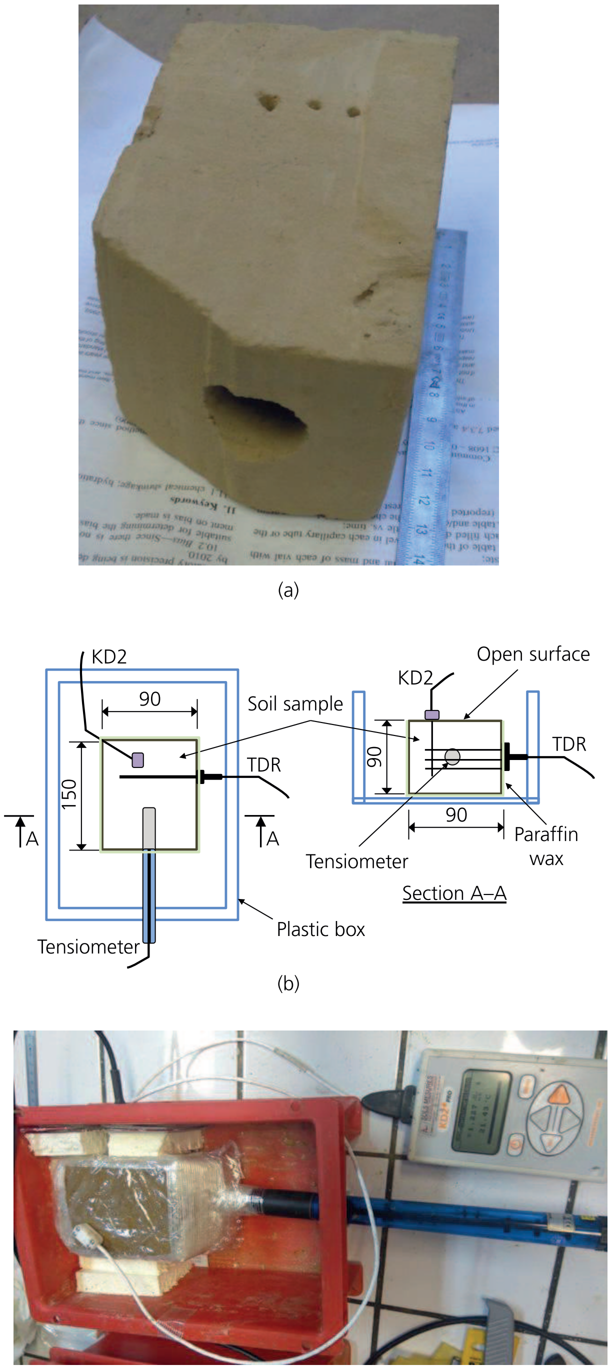

Fig. 1. (a) Photograph of the soil sample, (b) schematic view of the experimental set-up, (c) photograph of the experimental set-up

Table 1. Geotechnical properties of sampled loess from Northern France (Muñoz-Castelblanco *et al.*, 2011)

Natural water content w: %	14·4
Natural void ratio e	0·84
Dry unit mass ρ_d: Mg/m^3	1·45
Soil particle density ρ_s: Mg/m^3	2·67
Natural degree of saturation S_r: %	46
Natural suction: kPa	40
Clay fraction (%< 2 μm)	16
Plastic limit w_p	19
Liquid limit w_l	28
Plasticity index I_p	9
Unified Soil Classification System (ASTM, 2006)	ML

0·1 W/(m.K)) to measure the soil thermal conductivity. 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 minimising the disturbance of its initial state. The tensiometer and the TDR probe are connected to the data-logger system for automatic reading; the thermal conductivity is recorded manually.

RESULTS AND DISCUSSION

Figure 2 shows the results obtained during the first 10 days where the sample was subjected to various wetting steps from

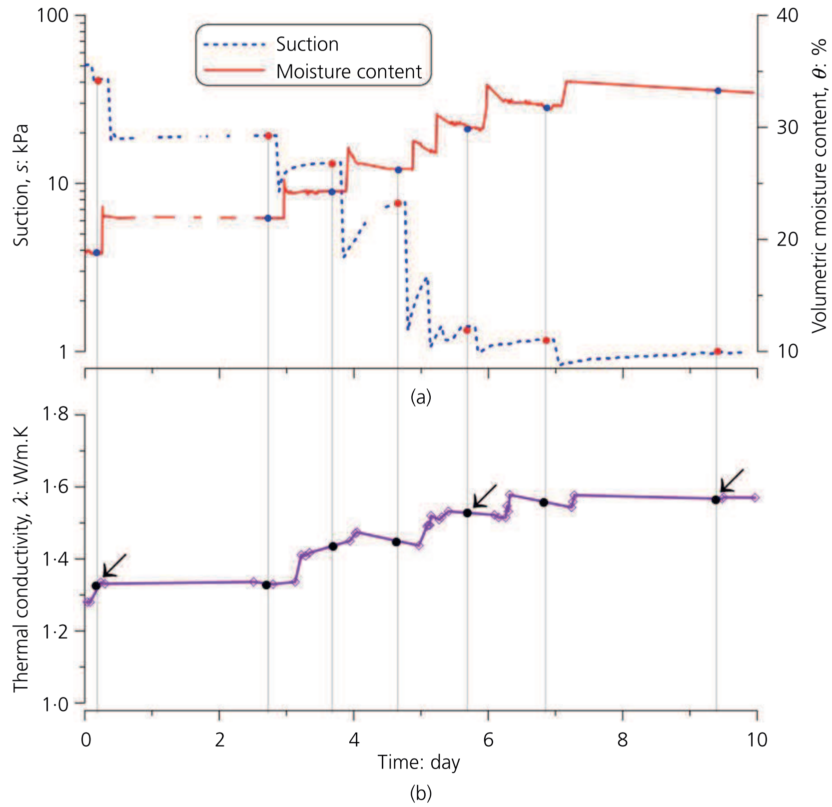

Fig. 2. Suction, moisture content and thermal conductivity in the wetting phase. Thermal conductivity is linearly interpolated between two successive manual readings

its initial state. Actually, from its initial state with $s = 40$ kPa and $\theta = 18{\cdot}7\%$, adding water rapidly increases the moisture content to $\theta = 23\%$, but this value decreases progressively and stabilises at $\theta = 22\%$ after a few hours. At the same time, wetting induces a rapid decrease of the suction to 18 kPa, but suction increases progressively thereafter to 20 kPa. Such non-monotonic variations of moisture content and suction can also be observed in the subsequent wetting steps. That can be explained by the homogenisation process of moisture inside the soil block that takes a few hours at high suction but more than 1 day at low suction (Fig. 2(a)). From these results, equilibrated points were chosen at the end of each wetting step (vertical lines in Fig. 2(a)). As the thermal conductivity was recorded manually, such evolution during each wetting step could not be observed (see Fig. 2(b)). 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 day 10 to 65). When the wrap lid is removed, water evaporation takes place and the moisture content decreases slowly (see Fig. 3(a)). Note that the non-monotonic variations in moisture content and suction are the more obvious during the wetting than during the drying because water was sprayed onto the soil surface at the beginning of the wetting, while the drying took place progressively. As expected, drying induces suction increase. The drying path was stopped when the suction reached close to 85 kPa, which is the limit of the tensiometer. The results obtained during this drying path allow for determining nine equilibrated points at the end of the drying steps (vertical lines shown in Fig. 3(a)). The soil thermal conductivity corresponding to these points was then determined from Fig. 3(b).

After the drying phase, the soil block was rewetted by steps. The result of this rewetting path (from day 65 to 90) is shown in Fig. 4. Eleven equilibrated points were determined along this path at the end of the wetting steps (Fig. 4(a)). The non-monotonic variations in moisture content and suction are the more obvious during the wetting than during the rewetting because the quantity of water added to each step is generally more important in the wetting. The corresponding thermal conductivities were determined from Fig. 4(b).

The values of suction, moisture content and thermal conductivity corresponding to the end of drying or wetting steps (shown in Figs 2–4) are plotted in Fig. 5. The degree of saturation was estimated by assuming that the soil volume change during wetting/drying is negligible in this range of suction (1–100 kPa). Muñoz-Castelblanco *et al.* (2012b) also used this assumption for the same material. Microstructural observations on this loess showed cementation by clay bonding between grains, which would limit the effect of wetting/drying on the soil density and structure. Ng *et al.* (2016) studied the water-retention and volumetric characteristics of intact loess from China, which had higher porosity, and also observed a negligible volume change when suction varied in the range of 1–100 kPa. 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 is located above the wetting curve. Finally, the rewetting curve is located 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 (Fig. 5(c)), a hysteresis loop is observed, quite similar to the water-retention curve. However, when the thermal

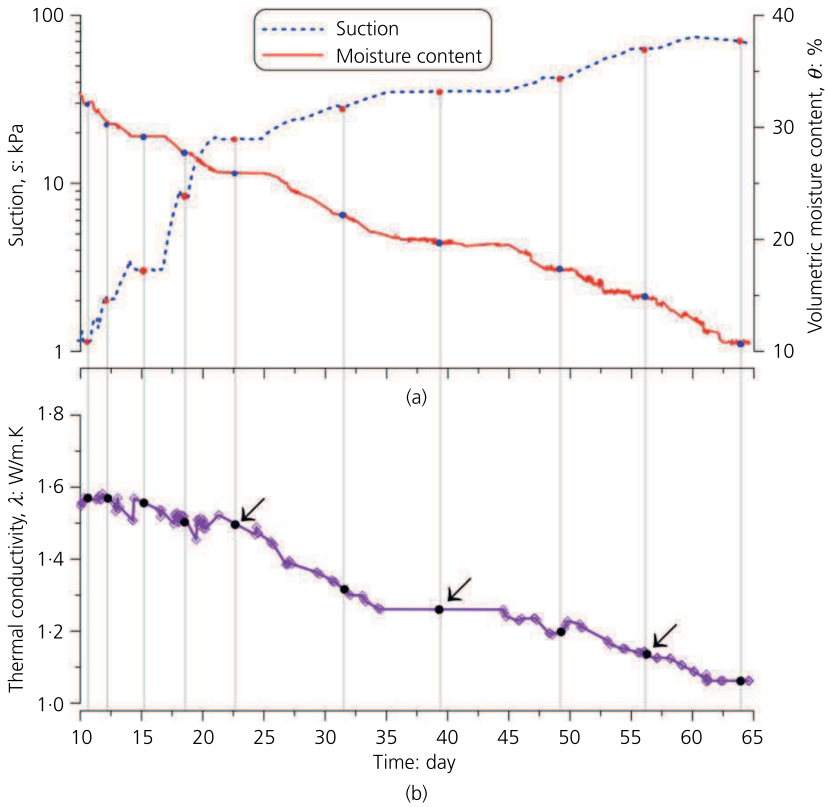

Fig. 3. Suction, moisture content and thermal conductivity in the drying phase. Thermal conductivity is linearly interpolated between two successive manual readings

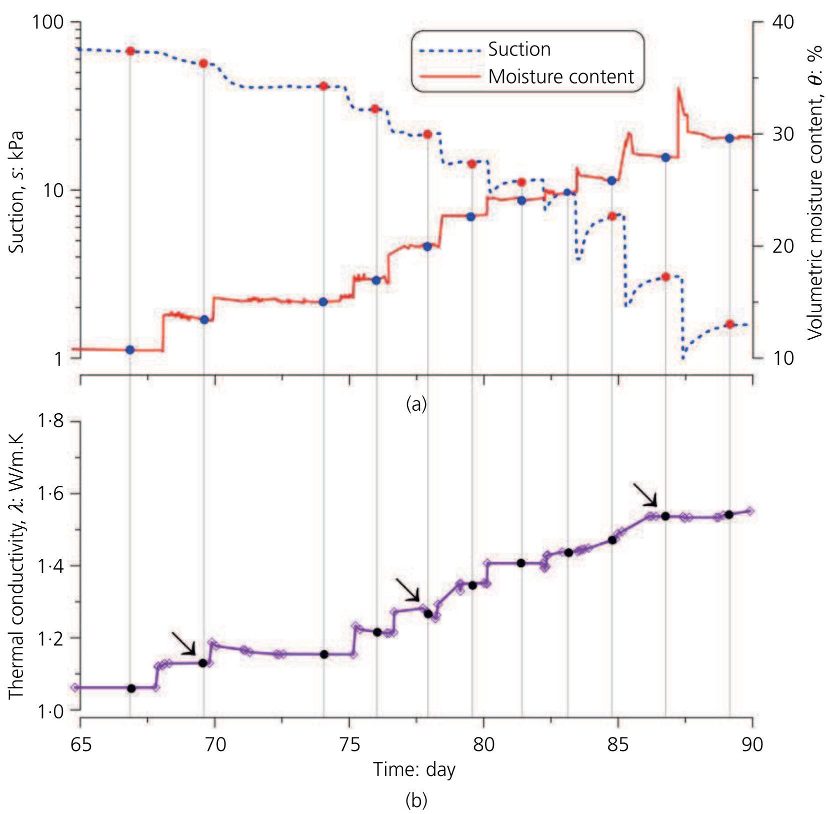

Fig. 4. Suction, moisture content and thermal conductivity in the re-wetting phase. Thermal conductivity is linearly interpolated between two successive manual readings

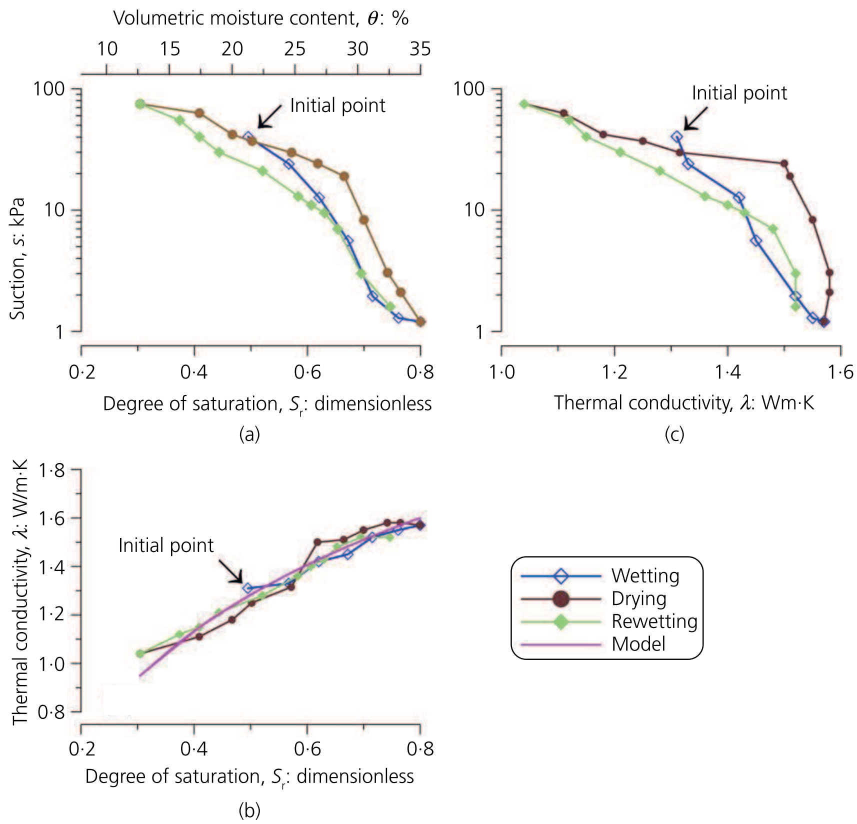

Fig. 5. Relationships between thermal conductivity, suction and degree of saturation

conductivity is plotted against the degree of saturation, a one-to-one relationship is obtained (Fig. 5(b)).

For further analyses, the model proposed by Johansen (1975) was used to calculate the thermal conductivity of soil. 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, $\lambda_w = 0{\cdot}57$ 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 ($\lambda_q = 7{\cdot}7$ W/(m.K)), λ_0 is the thermal conductivity of other minerals ($\lambda_0 = 2{\cdot}0$ W/(m.K)) and q is the quartz content.
- For dry soils: $\lambda_{dry} = (0{\cdot}135\rho_d + 64{\cdot}7)/(\rho_s - 0{\cdot}947\rho_d)$, 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 Fig. 5(b) 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 or 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 & 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 and so on (see 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 at a drying path is higher than that at 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.

CONCLUSIONS

The relationship between moisture content, suction and thermal conductivity under wetting/drying paths has been investigated for 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 unique relationship between these two quantities is observed during the wetting/drying paths.
- The relationship between the suction and the thermal conductivity is characterised 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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REFERENCES

Antoine, P., Catt, J., Lautridou, J. P. & Sommé, J. (2003). The loess and coversands of northern France and southern England. *Journal of Quaternary Science* **18**, No. 3–4, 309–318.

ASTM (2006). ASTM 2587-06: Standard practice for classification of soils for engineering purposes (unified soil classification system). Q4

Bidarmaghz, A., Makasis, N., Narsilio, G. A., Francisca, F. M. & Carro Pérez, M. E. (2016). Geothermal energy in loess. *Environmental Geotechnics* **3**, No. 4, 225–236, http://dx.doi.org/10.1680/jenge.15.00025.

Cui, Y. J., Terpereau, J. M., Marcial, D., Delage, P., Antoine, P., Marchadier, G. & Ye, W. M. (2004). A geological and geotechnical characterisation of the loess of Northern France. In *Advances in geotechnical engineering: the Skempton conference*, pp. 417–428. Q5

Delage, P., Cui, Y. J. & Antoine, P. (2005). Geotechnical problems related with loess deposits in Northern France. In *Proceedings of international conference on problematic soils*, pp. 517–540. Q6

Dong, Y., McCartney, J. S. & Lu, N. (2015). Critical review of thermal conductivity models for unsaturated soils. *Geotechnical and Geological Engineering* **33**, No. 2, 207–221.

Duong, T. V., Trinh, V. N., Cui, Y. J., Tang, A. M. & Calon, N. (2013). Development of a large-scale infiltration column for studying the hydraulic conductivity of unsaturated fouled ballast. *Geotechnical Testing Journal* **36**, No. 1, 54–63.

Farouki, O. T. (1986). *Thermal properties of soils*. Trans Tech Publications. Q7

Guan, X., Huang, J., Guo, N., Bi, J. & Wang, G. (2009). Variability of soil moisture and its relationship with surface albedo and soil thermal parameters over the Loess Plateau. *Advances in Atmospheric Sciences* **26**, No. 4, 692–700.

Johansen, O. (1975). *Thermal conductivity of soils*. PhD thesis, Trondheim, Norway. (CRREL Draft Translation 637, 1977). ADA 044002. Q8

Karam, J. P., Cui, Y. J., Tang, A. M., Terpereau, J. M. & Marchadier, G. (2009). Experimental study on the cyclic resistance of a natural loess from Northern France. *Soils and Foundations* **49**, No. 3, 421–429.

Lu, N. & Dong, Y. (2015). Closed-form equation for thermal conductivity of unsaturated soils at room temperature. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* **141**, No. 6, 04015016.

Muñoz-Castelblanco, J. A., Pereira, J. M., Delage, P. & Cui, Y. J. (2011). Some aspects of the compression and collapse behaviour of an unsaturated natural loess. *Géotechnique Letters* **1**, No. 2, 17–22, http://dx.doi.org/10.1680/geolett.11.00003.

Muñoz-Castelblanco, J. A., Delage, P., Pereira, J. M. & Cui, Y. J. (2012a). On-sample water content measurement for a complete local monitoring in triaxial testing of unsaturated soils. *Géotechnique* **62**, No. 7, 595–604, http://dx.doi.org/10.1680/geot.10.P.129.

Muñoz-Castelblanco, J., Pereira, J. M., Delage, P. & Cui, Y. J. (2012b). The water retention properties of a natural unsaturated loess from northern France. *Géotechnique* **62**, No. 2, 95–106, http://dx.doi.org/10.1680/geot.9.P.084.

Ng, C. W. W., Sadeghi, H., Hossen, S. B., Chiu, C. F., Alonso, E. E. & Baghbanrezvan, S. (2016). Water retention and volumetric characteristics of intact and re-compacted loess. *Canadian Geotechnical Journal* **53**, No. 8, 1258–1269.

Pham, H. Q., Fredlund, D. G. & Barbour, S. L. (2005). A study of hysteresis models for soil-water characteristic curves. *Canadian Geotechnical Journal* **42**, No. 6, 1548–1568.

Smits, K. M., Sakaki, T., Howington, S. E., Peters, J. F. & Illangasekare, T. H. (2013). Temperature dependence of thermal properties of sands across a wide range of temperatures (30-70°C). *Vadose Zone Journal* **12**, No. 1. Q9

Tang, A. M., Cui, Y. J. & Le, T. T. (2008). A study on the thermal conductivity of compacted bentonites. *Applied Clay Science* **41**, No. 3–4, 181–189.

Usowicz, B., Lipiec, J., Lukowski, M., Marczewski, W. & Usowicz, J. (2016). The effect of biochar application on thermal properties and albedo of loess soil under grassland and fallow. *Soil and Tillage Research* **164**, 45–51. Q10

Yang, C., Cui, Y. J., Pereira, J. M. & Huang, M. S. (2008). A constitutive model for unsaturated cemented soils under cyclic loading. *Computers and Geotechnics* **35**, No. 6, 853–859.

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