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TECHNICAL NOTE

Calibration of a thermal conductivity sensor for field measurement of matric suction

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This paper examines the calibration of a thermal conductivity sensor used for in situ matric suction measurement. A new calibration method is introduced. Performance of the thermal conductivity sensor in terms of salinity of pore water, heating power, hysteresis, response time and matric suction measurement range is also examined.

KEYWORDS: compaction; field instrumentation; laboratory tests; residual soils

La présente communication examine le calibrage d'un détecteur de la sensibilité thermique utilisé pour la mesure de l'aspiration matric in situ. Une nouvelle méthode de calibrage est présentée. Les performances du détecteur de conductivité thermique sur le plan de la salinité de l'eau interstitielle, du pouvoir calorifique, de l'hystérésis, du temps de réponse et de la plage de mesure de l'aspiration matric sont également examinées.

INTRODUCTION

Conventional tensiometers are widely used for field measurement of matric suction. However, suction measurement using conventional tensiometers is limited to 85 kPa (Stannard, 1992). Therefore it is necessary to use a complementary instrument for field measurement of matric suction above 85 kPa. One such instrument is the thermal conductivity sensor (TCS). The objective of this paper is to examine the calibration and performance of the more widely used CS229 TCS (Campbell Scientific Inc., USA).

WORKING PRINCIPLES OF TCS

The TCS consists of a heater, a temperature-sensing unit, a ceramic tip encasing a probe consisting of a heater and temperature sensor, and cables (Fig. 1). When the heater is turned on, the generated heat will result in a temperature rise ΔT , which is recorded by the temperature sensor. The accuracy of temperature measurement is $\pm 0.1^\circ\text{C}$. The TCS relies on the difference in thermal conductivities of air ($= 0.026 \text{ W/(m K)}$) and water ($\approx 0.60 \text{ W/(m K)}$) present in the pores of the ceramic tip. The dry ceramic tip of the TCS has a thermal conductivity of 0.35 W/(m K) (Reece, 1996). Thus, for a dry ceramic tip, negligible heat is dissipated by air in the pores. If water is present in the pores, more heat is dissipated. Therefore, the thermal conductivity of the ceramic tip will increase with water content.

MATERIALS AND CALIBRATION PROCEDURES

Differences in thermal transfer properties between the heater and ceramic tip make it necessary to calibrate each TCS individually (Fredlund & Wong, 1989; Reece, 1996; Flint *et al.*, 2002). Conventionally, the TCS is calibrated in a pressure plate apparatus by embedding it in a soil mixture with applied matric suction (e.g. Fredlund & Wong, 1989; Reece, 1996; Feng & Fredlund, 1999; Fredlund *et al.*, 2000;

Fig. 1. Schematic diagram of CSI 229 TCS

Flint *et al.*, 2002). Flint *et al.* (2002) released the air pressure before making measurements to preclude the effects of pressure on the TCS calibration. It is believed that heat transfer in the ceramic tip is highly pressure dependent, as it is due to latent heat transfer (personal communication from Campbell, G. S., 2006). Gee *et al.* (2002) and Cresswell *et al.* (2008) found that the equilibrated matric suction of the soil in the pressure plate is lower than the applied matric suction. The response time of the TCS cannot be evaluated in the above calibration procedures, as both the soil mixture and the TCS are equilibrating at the same time with the applied air pressure in the pressure plate apparatus. In this paper, a new calibration method is suggested for the CS229 TCS using soil samples prepared by the standard Proctor test. The matric suctions of the compacted samples were measured using a null pressure plate apparatus (Leong *et al.*, 2009).

Materials

As the TCSs were to be used to measure matric suctions in residual soil slopes, residual soil was used to calibrate the TCSs. The residual soil consists of 25% sand, 39% silt and 36% clay, and has a specific gravity of 2.73, a plastic limit of 25%, and a liquid limit of 57% (Unified Soil Classification System: MH).

Soil samples were prepared using the standard Proctor test (ASTM, 1997). Air-dried soil was kneaded with water and cured in sealed containers for 7 days to ensure uniform moisture distribution throughout the soil. The soil was again

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kneaded before compaction. The matric suction of the compacted soil samples (100 mm in diameter by 100 mm high) was measured using the null pressure plate apparatus. The relationship between matric suction ($u_a - u_w$) (kPa) and water content w (%) for the compacted soils is given by the equation

$$(u_a - u_w) = -1446.8 \ln w + 4709.3 \quad (1)$$

Calibration procedures

The calibration set-up consists of a sealed foam box, a constant current power supply, and a data acquisition system. The foam box was used to minimise temperature fluctuation and moisture loss of the soil samples. The TCSs were preconditioned by immersing them in distilled/de-aired water for a week to saturate, followed by air-drying for a few days, after which they were re-saturated. After re-saturation, the TCSs were again air-dried. The preconditioning is needed to check the TCS ceramic tips. Poor-quality ceramic tips crack during preconditioning. The ceramic tips of two of the 34 TCSs cracked during preconditioning.

For installation of the TCS into the soil sample, a 45 mm deep hole was pre-drilled using a portable drill and subsequently enlarged using a steel pipe such that there was a snug fit of the TCS in the hole. Once the TCS was installed in the soil sample, the sample was wrapped with cling film and sealed in the foam box. The TCS was monitored every 60 min for the first 12 h, and subsequently every 4 h until equilibrium. Once equilibrium was reached, the TCS was removed from the soil sample, and the water content of the soil sample was re-measured. There was negligible change in the water content of the soil sample.

The above procedure was repeated with soil samples of various matric suctions from 25 kPa to 700 kPa, and then the TCS was air-dried, thus completing the first drying calibration curve. Next, the TCS was first subjected to wetting calibration using soil samples of various matric suctions from 500 kPa to 10 kPa, and then finally resaturated by immersing it in distilled/de-aired water. The procedure was repeated with a second drying and wetting calibration. It took about 14 days to obtain a single drying and wetting calibration curve. Despite the careful installation procedures, the ceramic tips of ten TCSs cracked during the calibration process, and only 22 TCSs were successfully calibrated.

PERFORMANCE OF TCS

Effect of pore water salinity

If water with salinity corresponding to seawater (34.7 g/kg) does not influence the TCS readings, it can be concluded that pore water salinity has no influence on the TCS. Two TCSs were first saturated in distilled water under vacuum of 75 kPa. During saturation, the ΔT values of the TCSs were monitored. After a constant ΔT was obtained, the TCSs were air-dried and their ΔT values were monitored again. Once a constant ΔT was obtained, the saturation and air-drying processes were repeated, but with the TCSs saturated in sodium chloride solution with a salinity of 34.7 g/kg.

Figure 2 shows a typical plot of the difference in ΔT between the TCS saturated in sodium chloride solution and then in pure water: this was less than 0.1°C, indicating that pore water with salinity up to 34.7 g/kg has negligible influence on the saturated TCS. However, ΔT obtained from the air-dried TCS pre-saturated in pure water was about 0.2°C higher than that obtained from the air-dried TCS pre-saturated in sodium chloride solution. This is due to the residual sodium chloride in the pores of the ceramic tip when the TCS pre-saturated with sodium chloride solution was air-dried. The

Fig. 2. Effect of pore water salinity on TCS-PS-01

higher ΔT is due to the higher thermal conductivity of sodium chloride compared with that of air. As the salinity of the pore water is expected to be much lower than that of seawater, it is expected to have a negligible influence on the TCS.

Heating power

To the best of the authors' knowledge, to date there is no experimental study to determine the appropriate heating power of the CS229 TCS. To determine the appropriate heating power, the heating time for the TCS was increased from 24 s to 70 s. Fig. 3 shows a typical plot of ΔT against elapsed time under different matric suctions for the TCS. The rate of increase in ΔT is initially rapid, and then gradually decreases. Once the heater is turned off, there is a sharp decrease in ΔT . To determine when heat reaches the surface of the ceramic tip, a TCS probe (without ceramic tip) was attached with insulation tape to the surface of a TCS ceramic tip in dry and saturated states. Fig. 4(a) shows that ΔT on the surface of the dry TCS starts to increase after about 30 s of heating, and Fig. 4(b) shows that ΔT on the surface of the saturated TCS starts to increase after about 24 s of heating. Therefore, using a heating time of 24 s for the CS229 TCS is reasonable to avoid heat being dissipated out of the ceramic tip and thus influencing the TCS reading. To improve the reliability of ΔT , it is suggested that it be taken as the average of the last three readings in 24 s heating time, ΔT_A .

Response time

Response time is defined as the time taken for a TCS to achieve matric suction equilibrium with the soil: that is, when ΔT_A is constant. Fig. 5 indicates that the response time of the CS229 TCSs under both wetting and drying processes varies from an hour to several tens of hours. Fig. 6 summarises the response times of the 22 TCSs at various

Fig. 3. Temperature rises at different matric suctions

Fig. 4. Temperature rise against elapsed time on surface of TCS ceramic tip: (a) dry TCS; (b) saturated TCS

matric suctions. The wide range in response time is attributed to the contact condition between the TCS and the soil, which affects the rate of capillary flow between TCS and soil. In the field, the response time of the TCS is expected to be shorter, as it follows the changes in matric suction of the soil as affected by climatic conditions.

Hysteresis

All porous materials exhibit hysteresis during drying and wetting. However, only Feng & Fredlund (1999) and Fredlund *et al.* (2000) considered hysteresis in the calibration of TCSs. To study the effect of hysteresis, the ceramic–water characteristic curves of two ceramic tips (obtained from damaged TCSs) were determined using a pressure plate apparatus with hysteresis attachments (Fredlund & Rahardjo, 1993). Fig. 7 shows two cycles of drying and wetting ceramic–water characteristic curves of the ceramic tips. The difference is due to the different saturation conditions. For the first drying curve, the ceramic tips were saturated under vacuum (75 kPa) for 10 days to ensure full saturation. However, for the second drying curve, the ceramic tips were saturated in water for 5 days at atmospheric condition: hence it was impossible to saturate the ceramic tip completely. As a result, the water content of the ceramic tip at the beginning of the first drying curve was higher than that of the second drying curve. It is recommended that the CS229 TCSs should only be saturated at atmospheric condition instead of under vacuum during calibration, as this is the operating field condition of the TCS.

Figure 8 shows two cycles of drying and wetting calibra-

Fig. 5. Temperature rise ΔT_A against time t for TCS-PS-07: (a) first drying process; (b) first wetting process; (c) second drying process; (d) second wetting process

tion curves obtained for TCS-PS-07. The two cycles of calibration curves are identical. Thus one cycle of drying and wetting calibration curves is sufficient. The effect of hysteresis on matric suction measurement is significant, and needs to be considered.

Fig. 6. Response times for 22 TCSs under drying and wetting processes

Range of matrix suction measurement

The calibration curve for the CS229 TCS can be expressed in the form

$$\ln(u_a - u_w) = a\Delta T_A + b \quad (2)$$

where a is the rate of change in $\ln(u_a - u_w)$ with ΔT_A , and b is the value of $\ln(u_a - u_w)$ when ΔT_A equals zero

Figure 9 shows typical drying and wetting calibration curves expressed using equation (2), and Table 1 summarises the calibration results of 22 TCSs pre-saturated at atmospheric condition. The slopes of the drying calibration curves are smaller than those of the corresponding wetting calibration curves. The manufacturer's recommended equation for CS229 TCS calibration curve is

$$\ln(u_a - u_w) = 2.661\Delta T_A - 2.571 \quad (3)$$

Comparing equation (3) with the values in Table 1, it is evident that equation (3) corresponds to the drying calibration curve.

Figure 9 also shows the drying and wetting calibration curves converging at point A, and asymptotic to the dashed

Fig. 7. Hysteresis of TCS ceramic tips: (a) TCS ceramic tip no. 1; (b) TCS ceramic tip no. 2

line indicating the maximum possible ΔT_A given by a dry TCS. The mean maximum possible ΔT_A of the 22 TCSs is 4.7°C. The matrix suction at point A is about 1200 kPa, which can be taken as the maximum matrix suction measurement limit for the CS229 TCS, similar to the observation of Reece (1996).

Table 1. Calibration results of 22 TCSs

TCS no.	Drying calibration equation			Wetting calibration equation		
	$\ln(u_a - u_w) = a\Delta T_A + b$			$\ln(u_a - u_w) = a\Delta T_A + b$		
	a	b	R^2	a	b	R^2
TCS-PS-07	1.6081	-0.4516	0.995	2.6802	-5.2641	0.996
TCS-PS-08	1.9749	-1.0373	0.984	2.8910	-4.6857	0.996
TCS10	1.6878	-0.3213	0.999	2.6737	-4.3755	0.997
TCS11	3.4017	-6.7790	0.992	5.2433	-13.9740	0.999
TCS12	2.3550	-2.6771	0.958	3.3153	-7.3117	0.991
TCS13	1.7704	-0.9513	0.997	2.6288	-5.2175	0.995
TCS14	1.8965	-0.9107	0.989	2.7417	-4.6116	0.989
TCS15	2.7940	-3.5860	0.988	3.6652	-7.9404	0.999
TCS16	2.0057	-1.6706	0.988	2.8287	-5.6802	0.992
TCS17	2.5430	-3.5001	0.989	3.5401	-8.0721	0.980
TCS19	2.6216	-2.7608	0.997	4.0059	-7.5627	0.995
TCS20	1.9103	-1.3411	0.986	2.9846	-5.7162	0.991
TCS21	2.3331	-1.3286	0.974	2.7258	-3.2496	0.974
TCS22	2.7742	-4.6140	0.999	4.0059	-9.5656	0.995
TCS23	3.2260	-4.2905	0.992	4.1344	-7.8512	0.992
TCS24	1.9103	-1.3411	0.986	2.7400	-4.7979	0.998
TCS25	3.7961	-6.7532	0.995	5.4801	-13.0180	0.998
TCS26	1.5931	-0.6044	0.995	2.5352	-4.6617	0.988
TCS27	1.7686	-1.0402	0.983	2.7258	-5.3403	0.974
TCS28	1.7782	-1.0699	0.994	2.7356	-5.1247	0.991
TCS29	1.9090	-1.435	0.995	2.8721	-5.9235	0.994
TCC30	1.9155	-1.503	0.999	3.3521	-8.5493	0.986
Average	2.2533	-2.2712	0.990	3.2957	-6.7497	0.991

Fig. 8. Matric suction against temperature rise ΔT_A for TCS-PS-07

Fig. 9. Calibration curves for TCS-PS-07

CONCLUSIONS

A new calibration method for CS229 TCS using standard Proctor compacted soil samples whose matric suctions were measured using the null pressure plate apparatus was described. The performance of the CS229 TCS was examined in terms of salinity of pore water, heating power, hysteresis, response time and matric suction measurement range, and it was found to be a useful complement to the conventional tensiometer for field measurement of matric suction measurement above 85 kPa.

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