Pressure Correction in the Calibration of Heat Dissipation Sensors

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Heat dissipation sensors (HDSs) infer soil matric potential based on the measured rate of temperature rise from a heat source. The process for calibrating these sensors may use a pressure plate apparatus (PPA) to remove water to a certain calibration point that is controlled by pressure. Conventionally, the pressure within the PPA is released before the temperature change calibration points are measured (\(\Delta T_0\)). This conventional HDS calibration approach can take several weeks. We propose that the equilibrated temperature change at pressure (\(\Delta T_p\)) can be corrected empirically to the value at zero pressure. Based on measurements of 14 HDSs between 0.02 and 0.1 MPa, \(\Delta T_p\) was on average 6.2% larger than \(\Delta T_0\). After pressure correction, using an empirical equation, the difference between the corrected \(\Delta T_p\) and \(\Delta T_0\) was only 0.28%. These results demonstrate that this empirical approach provides sufficient accuracy to achieve HDS calibration without performing a PPA pressure release.

Abbreviations: HDS, heat dissipation sensor; PPA, pressure plate apparatus.

Heat dissipation sensors (HDSs) provide an indirect measurement of the matric potential of soil water. They have a cylindrical porous ceramic body designed to have a large variation of pore sizes (Fredlund, 1992; Phene et al., 1992; Scanlon et al., 2002). A heating element, equal in length to the ceramic body, is positioned at the center of the cylinder. A thermocouple is located at mid-length on the ceramic and heating element. The position of the heating element and the thermocouple is maintained by placing them inside a hypodermic needle, which also protects delicate wiring. The volume inside the needle not occupied by wiring is filled with thermally conductive epoxy. These sensors operate by measuring how much a heating element heats the ceramic portion of the sensor. The thermal properties of the ceramic change depending on how much water is retained inside by the capillary forces associated with the various pore sizes within the ceramic. For example, water is more thermally conductive than air. As heat is generated within the ceramic by the imbedded heater, it dissipates more quickly if more water is present within the ceramic. Since changes in water content within the ceramic are associated with changes in matric potential, the temperature change (\(\Delta T\)) associated with heating corresponds to changes in matric potential. The upper measurement range of these sensors is approximately \(-10\) kPa and the lower limit is generally considered to be about \(-1\) MPa (Reece, 1996). Less accurate measurements can be made between \(-1\) and \(-35\) MPa (Scanlon et al., 2002).

One advantage of HDSs is they generally do not need any maintenance during their service life. Heat dissipation sensors have been recently used in numerous studies including, but not limited to, early warning predictions of rainfall-induced landslides (Reder et al., 2018), large-scale drainage estimation (Wyatt et al., 2017), evapotranspiration-induced soil suction (Ni et al., 2017; Ng et al., 2016b; Hazra et al., 2017), environmental monitoring under surface barriers (Zhang et al., 2012; USDOE, 2016; Zhang, 2016; Ng et al., 2016a), and evaluation of desiccation as a remedial technology (Truex et al., 2012, 2015).

As described by Reece (1996) and Flint et al. (2002), HDS calibration can be performed in a pressure-plate apparatus (PPA) where the HDSs are placed on a porous plate with a silt loam or fine silica soil for the porous plate to hydraulically communicate with the HDSs. The bottom of the porous plate is covered with a rubber liner and plumbed to the outside of the PPA so that, as pressure (\(P\)) increases, water will leave the HDSs and
the soil will equilibrate to the pressure of the PPA. Once equilibrium is reached, the soil water matric potential will equal the pressure in the chamber. Usually the soil in the PPA can take hours to weeks to reach equilibrium depending on the pressure applied. It is often difficult to determine when equilibrium has been reached. During calibration, the HDSs can monitor continually. However, the responding HDSs are not a good indicator of soil equilibrium because the porous ceramic of the HDSs respond more quickly to pressure than the soil does during the calibration process. Usually, equilibrium is identified by measuring the amount of water coming out of the pressure plate outflow. If no more water is released, the soil is thought to be at equilibrium. However, at higher pressure steps, the flow is very slow and may be reduced to a few drops a day. Evaporation may potentially keep up with water leaving the pressure plate. Thus, true equilibrium is very difficult to achieve with confidence.

At soil water equilibrium, it is recommended that the PPA be depressurized prior to measuring the temperature change because of the effect of pressure on heat transfer in the gas phase within the sensor (Flint et al., 2002; Phene et al., 1992; Scanlon et al., 2002). However, the reset of pressure in the PPA to zero may lead to water flow back from the soil and ceramic pressure plate to the HDS ceramic if the soil water is not in true equilibrium.

The objective of this study was to quantify the pressure effect on HDS measurements during calibration and develop a method to correct this effect by eliminating the depressurization step when calibrating HDSs with a PPA. Potential causes for this effect are discussed below.

Methods and Materials

Three sets of experiments were performed, one to calibrate a batch of HDSs with the conventional procedure using a PPA, one to quantify the pressure effect under constant soil wetness (without using a ceramic plate), and one to confirm that the cause of this pressure effect is not caused by water soil interaction under pressure. All experiments used the same datalogger, PPA, and pressure controller within an environmental chamber with a controlled temperature of 20.0 ± 0.5°C. The PPA and environmental chamber used for these experiments were designed for HDS wiring to pass through ports that seal around the wiring.

Sensor Calibration

The calibration procedures using the PPA (Soil Moisture Equipment Corp.) are summarized for context. Fourteen HDSs (Campbell Scientific) were placed in de-aired water under a −0.07 MPa vacuum and allowed to equilibrate for a minimum of 24 h to achieve saturation. A thin (approximately 0.5 cm) layer of saturated Warden silt loam (a coarse-silty, mixed, superactive, mesic Xeric Haplocambid) was placed on a pre-saturated 0.1-MPa ceramic plate. The saturated HDSs were then laid horizontally in the soil on the ceramic plate and the sensors were pushed down into the saturated soil. Wires from the sensors were routed through pressure fittings to the datalogger. The top of the PPA was then sealed and a pressure controller (Alicat Scientific) was attached. The pressure was set to the target matric potential, and water flowed out of the PPA outlet until equilibrium was observed as no change of water volume for a 24-h period within a 10-mL graduated cylinder used to catch PPA effluent. A datalogger was used to record measurements of temperature change (ΔT) for HDSs with a 30-s heating period; these measurements were taken every 15 min. Subsequently, soil-water equilibrium was observed by measuring the outflow of water from the porous plate. When no change in water volume was observed for a 24-h period, the system was considered to reach equilibrium and the ΔT was treated as the value under the corresponding pressure (ΔT₀). Note that the 24-h period of no water change was a minimum time period—for most cases, this period was much longer, especially for higher pressure steps. The water outflow was then closed so that no water or air could flow back into the PPA outlet, and the pressure in the PPA was dropped to zero. Data collection at zero pressure (ΔT₀) continued through at least seven temperature change measurements of the HDSs before the next pressure was applied. This process continued until data for all six pressures, i.e., 0.02, 0.03, 0.04, 0.05, 0.07, and 0.1 MPa were measured.

Constant Wetness Experiment

Unlike the calibration process, in these experiments water flow in response to pressure gradients was prevented to isolate the effect of pressure on HDS temperature change. Eight HDSs were packed in a 5.08-cm-deep, 15.24-cm-diameter pan with approximately 1.5 kg of premixed Warden silt loam soil that had a matric potential of approximately −0.046 MPa (measured using a UMS T5 tensiometer). The pan containing the packed soil and HDSs was placed in the PPA for at least 24 h, and then the PPA was pressurized to a specified pressure and held constant for at least 24 h. Afterward, the PPA was set to zero pressure again for 24 h before another pressure was applied and held constant for at least 24 h. Four pressures, i.e., 0.03, 0.05, 0.07, and 0.09 MPa, were applied. Before the end of the experiment, the pressure was dropped to zero and this pressure was maintained for at least another 24 h. Also, to verify that changes in ΔT associated with pressure were not caused by ceramic–soil water exchange, the constant-wetness experiment was repeated with the HDSs suspended in the PPA instead of installed in the soil. It was also determined from the initial constant-wetness experiment with HDSs installed in soil that the ΔT responses were almost instantaneous, thus pressure was only held to at least 4 h instead of 24 h.

Results and Discussion

Pressure Effects during Sensor Calibration

Fourteen HDSs were calibrated between 0.02 and 0.1 MPa. For all the HDSs, the ΔT₀ values were always larger than ΔT₀, and their difference increased as the applied pressure increased. As an example, Fig. 1 shows the time course of ΔT for these HDSs.
under the 0.07-MPa pressure and after the pressure was reduced to zero. Although the \( \Delta T \) values for individual HDSs were slightly different, all HDSs had similar behavior when the pressure in the PPA was dropped to zero. The response to the measurements was nearly instantaneous, indicating that pressure change was probably the primary factor contributing to the change in \( \Delta T \).

Figure 2 shows the average \( \Delta T \) with one standard deviation (\( \sigma \)) for the 14 HDSs measured at positive and at zero pressure. The difference (\( d\Delta T \)) between \( \Delta T_p \) and \( \Delta T_0 \) generally increased with pressure and ranged between 0.0346°C at 0.02 MPa and 0.1261°C at 0.1 MPa (Table 1). On average, \( \Delta T_p \) was larger than \( \Delta T_0 \) by 6.2%, which can lead to an error of about −12 to −30% in the matric potential. The error increases at larger matric potentials because of the exponential relationship between \( \Delta T \) and the matric potential. Error was determined by developing an exponential calibration curve fit to the \( \Delta T_p \) data and by inputting \( \Delta T_0 \) values into the derived function.

The \( \Delta T \) variation under different pressures from the constant-wetness experiment is shown in Fig. 3. When the pressure was reduced to 0 MPa between pressure steps, the \( \Delta T_0 \) values returned to nearly the same value as the original \( \Delta T_0 \) (no more than 1.4% difference), indicating consistency of the measurements. The average values of \( d\Delta T \) and the standard deviation across the eight HDSs packed in soil and suspended within the PPA are summarized in Table 2. The \( d\Delta T \) values for both the HDSs in soil and suspended within the PPA increased consistently with applied pressure, which is in agreement with the HDS calibration results.

The measured positive \( d\Delta T \) values were not anticipated. It was expected that \( \Delta T_p \) would be less than \( \Delta T_0 \) and consequently \( d\Delta T \) would be negative because the air within the HDS becomes denser under pressure, increasing the thermal conductivity of the HDS ceramic cups. A larger thermal conductivity of the HDS would lead to a smaller \( \Delta T_p \) than \( \Delta T_0 \). The observed positive \( d\Delta T \) values indicate that other factors besides the increased air density affected the \( \Delta T_p \) values. Some researchers (e.g., Massoudi and King, 1974; Masterton et al., 1963; Slowinski et al., 1957) found that water surface tension decreases with pressure. Although the change in pressure is not expected to lead to a change in water content in the HDS ceramics, it might change the curvature of water menisci, the thickness of some water film on the ceramic matrix, and/or the continuity of pore water. It may be possible that, under pressure, the pore water in the HDS ceramic is less continuous, hence decreasing the thermal conductivity, which may result in a larger \( \Delta T_p \).

![Fig. 1. Time course of the temperature change for 14 heat dissipation sensors (HDSs) with 0.7-bar pressure or zero pressure. The vertical dashed line indicates the time that pressure was reduced to zero.](image1)

![Fig. 2. The average temperature change values at pressure on a pressure plate apparatus (PPA) and at zero pressure from the calibration of 14 heat dissipation sensors.](image2)

![Fig. 3. Temperature change values of eight heat dissipation sensors (HDSs) measured during a constant-wetness experiment.](image3)

<table>
<thead>
<tr>
<th>Pressure (MPa)</th>
<th>( d\Delta T ) Avg. (°C)</th>
<th>( d\Delta T ) SD (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
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<tr>
<td>0.03</td>
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</tr>
<tr>
<td>0.1</td>
<td>0.1261</td>
<td>0.0097</td>
</tr>
</tbody>
</table>

Table 1. The difference (\( d\Delta T \)) between HDS temperature changes measured with (\( \Delta T_p \)) and without (\( \Delta T_0 \)) pressure of 14 heat dissipation sensors (HDSs).
The results of testing suggest that the change in $\Delta T$ due to pressure change is probably not caused by water flow back to the HDS ceramics from the soil after pressure is released. However, if the soil has not reached equilibrium with the pressure in the PPA (with outflow) and this pressure is released, water may flow back to the HDSs. The $\Delta T$ time series shows that HDSs respond quickly to pressure changes during calibration in a PPA and plateau within 3 to 6 h, indicating that they have reached equilibrium with the pressure, but the soil will take 6 h to 2 wk to reach equilibrium as observed by measuring outflow with a graduated cylinder. During this time, the $\Delta T$ of the HDSs remains the same. Based on the potential error, difficulty determining if equilibrium is reached, and the extended period of time for soil to reach equilibrium, we propose using $\Delta T_P$ for calibration and use the pressure–$d\Delta T$ relationship to correct to $\Delta T_0$.

**Pressure Correction**

An empirical relationship between $d\Delta T$ ($°C$) and $P$ (MPa) was established, based on the data from the constant-wetness experiment (Table 2), as

$$d\Delta T = 0.0580\ln(P) + 0.270; \quad R^2 = 0.850$$

As a verification, Eq. [1] was used to correct the $\Delta T_P$ values by removing the pressure effect for all the measurements of the 14 HDSs that were calibrated between pressures ranging from 0.02 to 0.1 MPa. The corrected $\Delta T_P$ values were then compared with the measured $\Delta T_0$ values. Figure 4 compares $\Delta T_P$ before and after pressure correction for all measurements of the 14 HDSs with the measured $\Delta T_0$. The corrected $\Delta T_P$ values were nearly the same as the measured $\Delta T_0$. The corrected $\Delta T_P$ is only 0.28% less than $\Delta T_0$. The results indicate that the HDSs may be calibrated using a PPA without the need for the pressure release. The measurement under pressure can be corrected to corresponding values at zero pressure.

The use of Eq. [1] or repeating the constant-wetness experiment for a more HDS-specific correction could potentially improve future calibration by (i) reducing the potential for error caused by uncertainty associated with soil-water equilibrium during the current PPA calibration procedure, and (ii) reducing the time needed for calibration by eliminating the need to reach equilibrium in the soil.

**Conclusions**

The change in temperature ($\Delta T$) of the HDSs associated with increasing pressure is positive. This change in temperature was originally expected to be negative because it was thought to be caused by a change in air density associated with increasing pressure.

The difference ($d\Delta T$) between the temperature change in HDSs at calibration pressure ($\Delta T_P$) and the temperature change in HDSs once calibration pressure is reduced to zero ($\Delta T_0$) are consistent and predictable, allowing this effect to be removed. The advantages of using $\Delta T_P$ for calibration and subtracting out $d\Delta T$ is that it also removes uncertainty associated with the matric potential equilibrium of the soil and reduces the time needed for the calibration process by eliminating the need for the soil to reach full equilibrium. The HDSs reach equilibrium within 3 to 6 h, as indicated by the $\Delta T$ time series. Soil equilibrium in a PPA can take from 6 h to 2 wk depending on the pressure step and the soil properties. This study identified that an empirical relationship between $d\Delta T$ and $P$ was established based on the data of the constant-wetness experiment. After pressure correction using an empirical equation, the difference between the corrected $\Delta T_P$ and $\Delta T_0$ was only 0.28%.

**Data Availability**

The data from this study are available through the Dryad Data Repository (Thomle et al., 2019).

**References**


Fredlund, D.G. 1992. Background, theory, and research related to the use of thermal conductivity sensors for matric suction measurement. In: G.C. Topp et al., editors, Advances in measurement of soil physical...