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Does temperature affect the accuracy of vented pressure transducer in fine-scale water level measurement?

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GID
4, 533–561, 2014

Abstract

Submersible pressure transducers have been utilized for collecting water level data since early 1960s. Together with a digital datalogger, it is a convenient way to record water level fluctuations for long-term monitoring. Despite the widely use of pressure transducers for water level monitoring, little has been reported for their accuracy and performance under field conditions. The effect of temperature fluctuations on the output of vented pressure transducers were discussed in this study. The pressure transducer was tested under both laboratory and field conditions. The results of this study indicate that temperature fluctuation has a strong effect on the transducer output. Rapid changes in temperature introduce noise and fluctuations in the water level readings under a constant hydraulic head while the absolute temperature is also related to sensor errors. The former is attributed to venting and the latter is attributed to temperature compensation effect in the strain gauges. Individual pressure transducers responded differently to the thermal fluctuations in the same testing environment. In the field of surface hydrology, especially when monitoring fine-scale water level fluctuations, ignoring or failing to compensate for the temperature effect can introduce considerable error into pressure transducer readings. It is recommended that a performance test for the pressure transducer is conducted before field deployment.

1 Introduction

Submersible gauge pressure transducers are used to monitor water level fluctuation in wells and flow in open channels. Combined with a digital data logger, pressure transducers can be a useful and cost effective tool in the field of hydrology (Rosenberry, 1990; Freeman et al., 2004; McDonald, 2011).

There are two types of submersible pressure transducers. The first is vented to the atmosphere through an integral air tube which allows automatic compensation of barometric pressure change. This type is often referred as gauge pressure transducer.

GID
4, 533–561, 2014

The second type measures the combined atmospheric pressure and the pressure head exerted by the overlying water column. This type is known as absolute pressure transducer. For this type, the barometric pressure needs to be recorded separately to calculate the water level (Post and von Asmuth, 2013).

Despite the wide use of submersible pressure transducers in water level monitoring, little has been discussed about their accuracy and long-term performance. The accuracy of pressure transducers varies among models and manufacturers. Currently there are no industry-wide standard for the calibration of pressure transducers which makes the direct comparison of results extremely difficult (Sorensen and Butcher, 2011). Moreover, the pressure transducers are usually calibrated by manufacturers in their laboratory where the environmental factors are well-controlled, e.g., temperature. However, the performance of the pressure transducer in the laboratory does not equally translate to their field performance, especially when monitoring surface water flow where diurnal fluctuations of temperature and humidity exist.

The accuracy of pressure transducers has been examined in some recent articles. Instrument drift has been found in different branded sensors (Sorensen and Butcher, 2011). The thermal effect on the sensitivity of the pressure transducer was also discussed (Cain et al., 2004; Mclaughlin and Cohen, 2011; Gribovszki et al., 2013). Cain et al. (2004) investigated the noise in pressure transducer readings by measuring a constant water head when the transducer cables are exposed to direct sunlight. They concluded that the noise is caused by the heating and cooling of the air column in the venting tube inside the cable, and the error can be up to 3 cm. The results of Cain et al. (2004) shed some light on our understanding of the accuracy of the pressure transducer for it revealed that there is a relationship between the atmospheric temperature and the transducer reading. Yet it also provoked further thoughts and mathematical analysis presented here.

So far there are only scarce data on the accuracy of fine-scale water level measurement with the vented pressure transducer and no field performance has been evaluated. The authors would like to provide information to fill the gap by testing the

GID
4, 533–561, 2014

performance of the vented pressure transducer in fine-scale water level measurement on both laboratory and field scales.

2 Materials and methods

2.1 Laboratory experiment

Three commercial water level sensors were used in this study (CTD sensor, Decagon Devices, Pullman, WA, USA). All three CTD sensors measure conductivity, temperature, and water level at the same time. The sensor utilizes a vented pressure transducer to measure water level from 0 to 3.5 m. The measurement resolution is 1 mm and it has an accuracy range of ±0.2 % of full scale at 20 °C. All three sensors have a cable length of 10 m. At the end of the cable there is a 3.5 mm stereo plug which connects the sensor to a EM50 data logger (Decagon Devices, Inc.). The venting port is near the stereo plug. An air channel was built inside the sensor cable to remove the effect of the barometric pressure.

One of the three sensors has a unique feature. There is an injection tube connected to the front side of the diaphragm in the pressure transducer. This tube needs to be filled with water to avoid any air bubble before field deployment. In the other two pressure transducers, the diaphragm directly contacted with the water.

The three sensors were placed in a water bucket at a fixed depth. The total water depth inside the bucket was kept constant. The opening of the bucket was covered to reduce evaporation however a venting hole was left to make sure the air above the water surface is vented to the atmosphere. Then the bucket was placed on a concrete surface where all the sensor cables were fully exposed to the sunlight. Later the whole setup was moved into a well vented room with a relative constant temperature and humidity.

GID
4, 533–561, 2014

2.2 Field experiment

CTD sensors are installed within a roadside filter strip in Oregon; one near Alsea, and one near Stayton (on Santiam Highway). Here, the CTD sensors were used to collect highway surface stormwater runoff data. The sensor was positioned inside a v-notch flow container to monitor water level change which was later converted into runoff flow rate through a rating curve.

Figure 1 shows the field installation of the sensor inside the flow container at Alsea site, the installation at Santiam site is similar. About 30 cm of the container was buried into the ground so that the soil can protect the water inside the container from freezing during cold days in winter. The water level is at the bottom of the weir and the sensor is fixed below the water level. During rainfall events, runoff water is routed through the device via a set of collection pipes. Water level inside the container will rise and then flow out of the bucket through the weir. The water level will fall back to the baseline (at the weir bottom) after the rainfall event stops. A full description of this device is provided in Stewart et al. (2014). During dry days, the water level will drop due to evaporation. The sensor cable was laid on the ground and partially covered by soil and vegetation. An EM50 datalogger was used to collect time series data. The measurement interval for both laboratory and field conditions is one minute.

3 Results and discussions

3.1 Laboratory results

Figure 2 shows the water level readings for all three pressure transducers and the water temperature in the bucket during a 24 h period. Some evaporation from the container is inevitable but was controlled to a minimum extent so that it would minimally affect the water level readings. The figure clearly shows that temperature has an effect on the pressure transducer. As the temperature increased at the beginning of the test,

GID
4, 533–561, 2014

the transducer readings has more noise and when the temperature dropped during the night time, the transducer readings became smoother. Then when the temperature rose from 7.8 to 28.0 °C, more noise can be observed in the readings.

Temperature fluctuation also tends to shift the baseline in the transducer readings. The extent of the effect differs within each pressure transducer. This effect is especially strong in pressure transducer 2. Interestingly, the three pressure transducers did not show a consistent fluctuation pattern with respect to the change in temperature. The high readings in water level corresponded with peaks in temperature for pressure transducer 1 and 2. However, pressure transducer 3 showed an inverse relationship between the water level and temperature readings.

Figure 3 shows the relationships between the temperature and the water level readings. Linear regression was applied for all three sensors. Pressure transducer 2 showed a strong positive correlation between the temperature and the water level with a R^2 equals to 0.9725. Pressure transducer 3 showed a clear negative relationship with contrast to pressure transducer 2. There is also a positive correlation between temperature and water level reading in pressure transducer 1, although the R^2 equals to 0.439.

Cain et al. (2004) found a similar pattern as shown in pressure transducer 3 when they tested a vented pressure transducer (Cain et al., 2004). They concluded that the fluctuation in the pressure head readings was caused by the expanding and contracting of air column inside the venting tube. When the temperature is high, the sensor cable heated and the air column expanded, thus applied a positive pressure on the backside of the diaphragm. As a result of that, the output pressure head readings are smaller which eventually presented an inverse relationship between temperature and pressure head. However, if this was the mechanism responsible for the relationships in Fig. 2, then all pressure transducers in current study should exhibit similar behavior which they did not. In Cain's study, cable color and length were all considered to contribute to the noise since darker color can absorb more solar radiation and longer cable can create more resistance for air flow in the venting tube. Admittedly, the cable they used was much longer (123 and 23 m) than the one used in this study (10 m). A simple mathematical analysis of the venting system provides some clues.

The pressure difference caused by the thermal expansion/extraction between the sensor diaphragm and the venting end can be derived by considering the movement of a small air column inside the cable. Figure 4 shows a schematic of the derivation.

For an air column with a length of x to expand to a length of $x+\mathrm{d}x$, the force exerted along the cable wall can be give as:

$$F = \tau \cdot \mathrm{d}x \cdot 2\pi R \tag{1}$$

where F is the tangential force, ML/T^2; τ is the shear stress, M/LT^2; $\mathrm{d}x$ is the expanded length, L; R is the radius of the cable, L.

Integrate the force exerted from $\mathrm{d}x$ to the whole cable length:

$$\int_0^L \tau \cdot \mathrm{d}x \cdot 2\pi R = \Delta P \cdot A \tag{2}$$

$$A = \pi \cdot R^2 \tag{3}$$

where L is the total length of the venting cable, L; A is the cross section of the venting cable, L^2; ΔP is the total pressure difference between the venting end and the sensor end, M/LT^2.

Equation (2) can be re-written into the following format:

$$\Delta P = \frac{2}{R}\int_0^L \tau \cdot \mathrm{d}x \tag{4}$$

For an air column to expand from a length x to a length $x+\mathrm{d}x$, the change of the volume can be expressed as:

$$\Delta V = \alpha \cdot \Delta T \cdot V \tag{5}$$

GID
4, 533–561, 2014

where ΔV is the volume change of the air, L^3; ΔT is the change of the temperature, K; α is a thermal expansion coefficient, K^{-1}.

Given

$$\Delta V = \mathrm{d}x \cdot A$$

and

$$V = x \cdot A$$

Equation (5) can be transformed into:

$$\mathrm{d}x \cdot A = \alpha \cdot \Delta T \cdot x \cdot A \tag{6}$$

Cancel A and divided both side of the equation by $\mathrm{d}t$ we have:

$$v = \frac{\mathrm{d}x}{\mathrm{d}t} = \alpha \cdot \frac{\mathrm{d}T}{\mathrm{d}t} \cdot x \tag{7}$$

where v is the average velocity of the moving air column, L/T.

The shear stress is related to the viscosity of air and the velocity profile by:

$$\tau = \mu \cdot \frac{\mathrm{d}v}{\mathrm{d}r} \tag{8}$$

where μ is the viscosity of the air, M/LT; $\frac{\mathrm{d}v}{\mathrm{d}r}$ is the velocity gradient along the cable radius, T^{-1}.

Assuming the flow inside the cable is Poiseuille flow so the velocity profile can be given by:

$$V(r) = V_0 \cdot \left(1 - \left(\frac{r}{R}\right)^2\right) \tag{9}$$

GID
4, 533–561, 2014

where V_0 is the maximum velocity at the centerline of the flow; r is the radical position measured from the centerline.

Insert Eq. (9) into Eq. (8) yields:

$$\tau = \mu \cdot \frac{-2V_0 r}{R^2} \tag{10}$$

In Poiseuille flow, the maximum velocity V_0 equals twice the mean velocity v. With this relationship, combine Eqs. (7) and (10) we have:

$$\tau(r) = \frac{\mu \cdot -2 \cdot 2 \cdot \alpha \cdot \frac{dT}{dt} \cdot x \cdot r}{R^2} \tag{11}$$

Consider the shear force exerted at the boundary of the air column and the cable wall where $r = R$, Eq. (11) can be written into:

$$\tau(R) = \frac{-4 \cdot \mu \cdot \alpha \cdot \frac{dT}{dt} \cdot x}{R} \tag{12}$$

Insert Eq. (12) into Eq. (4) we have:

$$\Delta P = \frac{2}{R} \int_0^L \frac{-4 \cdot \mu \cdot \alpha \cdot \frac{dT}{dt} \cdot x}{R} \cdot dx \tag{13}$$

Solve the integration with respect to x we can express ΔP in the following form:

$$\Delta P = \frac{-4\mu\alpha^2}{R^2} \cdot \frac{dT}{dt} \tag{14}$$

According to Eq. (14), we expect the errors associated with venting to be proportional to the thermal gradient. Indeed, in Fig. 5a this is shown explicitly. Note that in this plot

GID
4, 533–561, 2014

we use the temperature of water in lieu of an air temperature measurement. The errors associated with absolute temperature is shown in Fig. 5b. From the strong correlation we believe that differential thermal expansion of the stain gauge on the pressure transducer diaphragm can better explain the temperature effect seen in Fig. 2. The sensitivity of the strain gauge can be expressed as (Watson, 2008):

$$F = \frac{\Delta R/R}{\varepsilon} \tag{15}$$

$$\varepsilon = \Delta L/L \tag{16}$$

$$R = \rho \cdot \frac{L}{A} \tag{17}$$

where F is the strain sensitivity, also called the gauge factor; R is the conductor resistance; ε is the strain; L is the conductor length; ρ is the resistivity; A is the conductor area.

The changing of the ambient temperature causes resistance changes in the metal conductors from which the strain gauge is built. The variables in Eq. (17) are functions of temperature themselves. The transducer diaphragm where the strain gauge is bonded can also contract or elongate with temperature changes (Cappa et al., 1992; Richards, 1996; Vishay Micro-Measurement, 2007). This thermal output error is more prominent than that was produced from the extraction or expansion of air column inside the venting tube in this experiment.

The derivation of Eq. (14) is under the assumptions that the air flow inside the tube can be considered as laminar Poiseuille flow and the velocity profile is fully developed inside the cable. Although these assumptions sometimes are difficult to meet in reality, the calculation provides a theoretical base for investigating the error source in pressure transducer measurements.

Figure 6 shows the long-term monitoring data of the water levels and the temperature in the bucket. After the bucket was exposed to the sunlight on the roof for few days, it was moved indoor in the laboratory. The temperature in the laboratory is relatively

GID
4, 533–561, 2014

stable compare with the outdoor conditions. Although the room temperature is not directly measured with a thermometer, the water temperature inside the bucket should be a good surrogate to reflect the changes. It is clearly shown in Fig. 6 that there is less fluctuations in temperature after the bucket was indoor and the fluctuations resumed after the bucket was moved to the outdoor condition again. Accordingly, the water level readings from the pressure transducers became more stable when they are in the controlled environment. The large peaks at the transition points were caused by moving the bucket. The small wiggles in the signal is expected as the resolution of the sensors is 1 mm.

Pressure transducers 1 and 3 showed that they did not experience baseline shift problem when the daily temperature change is not sharp under indoor condition. However, the baseline reading in pressure transducer 2 increased during the indoor monitoring period. The expanding and contracting of air column inside the venting tube did not cause the baseline shift in pressure transducer 2 since the cables were not exposed to solar radiation and the room temperature change is not sharp during the monitoring.

After about 11 days, the bucket was moved outdoor where the daily temperature again has a pattern of sharp and rapid change as the solar radiation varied with the position of the sun. Almost immediately, the water level readings begin to show more noises as the water temperature increased during the day. The noise pattern in all three pressure transducers are repeatable and similar with the previous observation. The fluctuations of the water level readings still showed either positive or negative relationships with the water temperature. The noises in the signal were larger when the temperature climbed up during the daytime and obviously smaller as the temperature dropped down. Interestingly, although the water temperature data showed that the climbing and dropping parts of the curve were equally sharp, noises were most prominent when the temperature was increasing.

For submersible pressure transducers, the key component is a pressure sensitive diaphragm on the back of which are attached with a series of strain gauges. The

GID
4, 533–561, 2014

water head above the transducer causes a flexing across the diaphragm which is measured to an electrical signal and then converted to the water depth. Poor or nonexistent temperature compensation will generate thermal effects in pressure transducers as the water density is normally affected by the temperature (Freeman et al., 2004; Sorensen and Butcher, 2011). In the current study, the manufacture likely used one compensation algorithm for the same model, and individual sensors vary in characteristics and calibration. So applying the same temperature compensation algorithm to these sensors would reduce some noises and errors, but the extent will vary in different sensors. For instance, pressure transducer 1 and 2 are the same design and they showed similar patterns of thermal effect on their output, however, the temperature compensation in pressure transducer 1 is better than pressure transducer 2 as it showed smaller peaks in fluctuation and provided a stable baseline during the indoor test. Pressure transducer 3 seems to have a reversed compensation algorithm. Nonetheless, the changes in sensor output under the thermal effect in the laboratory test is mainly caused by the temperature change on the transducer element or circuit board components.

3.2 Field test results

Under the field conditions, natural events like precipitation (rainfall and snowfall), frosting, and evaporation will affect the pressure transducer output. Also the pressure transducer is exposed to more severe and extreme weathers, especially during winter time in cold regions. Because the function of the pressure transducer in this field test is to monitor stormwater runoff, the inflow water from the collection pipes is another factor that will change the water level readings.

A long-term field monitoring data was shown in Fig. 7. The pressure transducer used in field tests are the same model with pressure transducer 3 in the above laboratory test. The specification of this model states that the pressure transducer can not be operated below freezing point, other wise ice crystals will form and permanently damaged the transducer (Freeman et al., 2004). To avoid this situation which is likely to

GID
4, 533–561, 2014

occur since the site in located in the remote mountain area, the sensor was submerged into the water in the flow bucket and the bottom part of the bucket where the sensor is sitting in was buried into the ground to a depth of 40 cm. The soil functions like an insulation layer to protect the water inside the bucket from freezing. The temperature readings in Fig. 7 showed that even during the cold days in the winter, the water did not freeze in the bucket thus the sensor was safe.

The large peaks in the water level readings are produced by the inflowing runoff water. Most of the runoff peaks corresponded with precipitation peaks recored from a rain gauge on site. Note that not all the precipitation peaks will translate into a runoff peak since it was affected by the antecedent soil moisture content. When intensive rainfall occurred during the wet winter days (12 to 21 February 2014), the water content in the soil on highway shoulder is also high, sometime reached saturation. The low ambient temperature during these days hardened the surface soil which also contributed to the low infiltration rate. Under such situations, consecutive rainfall events will generate more surface runoff as shown in the upper plots in Fig. 7. During the days where there is no or limited precipitation, as the period shown from 22 to 28 February 2014, the soil moisture content decreased as evaporation and drainage depleted the water from the soil which resurrected the ability for the highway shoulder strip to store storm runoff water. So when it rained for few days from 1 to 3 March 2014, no significant runoff was observed. And when the dry period is short from 3 to 4 March 2014, the following rainfall produced more runoff peaks as show in the figure. Similar observations can also be seen in the lower plot in Fig. 7.

The baseline water level during this long-term field monitoring is fairly stable. A drop in the scale of millimeters in the baseline reading was expected as the evaporation under the field condition is inevitable. The intermittent precipitation replenished the water level in the bucket. Interestingly, during the days when there were no precipitation, we still observed a noise pattern in the transducer output which showed a periodic correlation with the temperature signal. The magnitude of the noise is more prominent when the temperature change is sharper. When temperature is relative constant or has less fluctuations, the noise is smaller.

Figure 8 presented a zoomed-in time series from 20 to 24 March 2014 when no precipitation occurred. The baseline gradually decrease at 1 mm step due to the evaporation from the flow bucket. The diurnal temperature pattern corresponded with the noises in the water level readings. For a temperature ranges from 6.3 to 10.1 °C, the noise can be as large as 7 mm (accuracy of this sensor is ±7 mm) and as small as 1 mm. when temperature varied rapidly in a wider range as shown in Fig. 6, the noise is much larger, sometimes exceeded the accuracy level of this sensor. A similar pattern can also be seen in the pressure transducer installed at Santiam site on Oregon Highway 22 (Fig. 9). Without considering the temperature effect, the peaks in the water level reading could be mistaken as inflow runoff water.

In ground-water or deep well monitoring, the water temperature is relatively stable and often times the researcher looked at water level fluctuation on a much larger scale from few centimeters to few meters (Schaefer and Hemond, 1986; Novakowski and Gillham, 1988; Rasmussen and Crawford, 1997). In those cases, submersible pressure transducers are well suited for data collection. However, in surface water monitoring where fine-scale data are needed (Gribovszki et al., 2013), the variable water temperature could be a problem because inadequate temperature compensation will affect the performance of submersible pressure transducer. As the water level data often will be converted into flow rate in stream or runoff, then small errors or noise will be amplified through the calibration curve, which eventually will lead to misinterpretation of the results.

During the monitoring at Santiam site, two snowstorm events were recorded. The pressure transducer is very vulnerable under a severe weather condition, especially when the ambient temperature decreased rapidly and sometimes below freezing point. Extra attention needs to be paid to the performance of the transducer as well as the its safety.

GID
4, 533–561, 2014

Figure 10 showed the effect of the snowfall event on the performance of the pressure transducer during one of the two recorded snowfall events. The ambient temperature fell below the freezing point. According to the water temperature, the bottom part of the bucket and the water inside it were not frozen during the snowfall even when the air temperature is below zero. This is corroborated by the soil temperature sensor installed nearby. However, an ice lens was believed to form at the water surface. The pressure transducer can still register the pressure fluctuations because it was submerged in the relatively deep water. But the reliability of the data is lowered since the ice lens can introduce errors.

The large peaks highlighted with the dash line box showed how the transducer performed during and after snow events. The readings reached up to 4000 mm in those large peak whereas the upper measurement limit is 3500 mm in this pressure transducer.

Here the error was created by the developing of the ice layer within the container and frosting or the frozen of thin water film around the venting port. The venting tube is normally very small in diameter and contact directly with the transducer component. It may not be a problem in dry and warm environment, however, under cold and wet climate, the moisture is like to accumulate and block the thin venting tube which could be another error source (Katsuta and Tshihara, 1986). The pressure transducer at Santiam site was not damaged by the snowfall event and cold temperature because it was protected by the in-ground installation.

Without cold-protection and desiccation system, using vented submersible pressure transducer for surface water monitoring like in the current study is under the risk of losing data or pressure transducer damage.

4 Conclusions

The results of the laboratory and field tests indicate that temperature has a clear effect on the performance of vented submersible pressure transducers. The noises or errors in the sensor output caused by thermal effect bring in uncertainties in the experiments results, especially in fine-scale surface water monitoring where the water head change can be very small (in millimeter scale). Small errors in water level measurements may lead to large uncertainties in the calculated flow velocity either in a stream or a V-notch weir equipment, sometimes the uncertainty can be up to 100 % (Sweet et al., 1990; Grant and Dawson, 2001).

The rapid increase of temperature produces more noises in the transducer output and the magnitude of the fluctuations in the water level reading sometimes can exceed the accuracy specification of the sensor. When the pressure transducers was operated in an environment where temperature is relatively stable, the output contains much less noises. The fluctuation of the signal is within the measurement resolution. Individual sensors have different responses to the temperature fluctuation due to various thermal compensation algorithms. Both positive and negative relationships were observed between the temperature and sensor output. Under extreme climate condition where ambient temperature can dropped below freezing point, the pressure transducer can generate erroneous outputs due to the failure of communication to the atmosphere through the venting cable.

From the discussion presented above, it is notable that the measurement of water level or hydraulic head, especially at a fine-scale, is not simple. Errors can still be generated from environment factors even other operation procedures are carefully followed. Influencing factors such as temperature are not negligible under field conditions. Several recommendations for using vented pressure transducer in the field are provided here based on the preceding experience:

1. If not integrated inside the sensor with the pressure transducer, a temperature probe is recommended to be installed in the water where the pressure transducer

GID
4, 533–561, 2014

is located. Because the noise and error brought by temperature effect normally have a pattern and predictable, they can be corrected if the water temperature is recorded simultaneously.

2. It is important to keep moisture from entering the venting tube for pressure transducer , especially for installations in wet and cold climate. A desiccation system for the venting ports on the sensor cable can provide reliable data output for long-term monitoring. Frequently checking and replacing the desiccants after intensive precipitation.

3. Ensure if the pressure transducer is protected from temperature below freezing points. When installing pressure transducers to measure water levels in surface flow devices such as weirs and flumes, try to position the pressure transducer deep into the ground. The soil layers are good insulation. Together with the desiccation system, the results should be reliable for scientific analysis and report. The ice lens formation on water surface sometimes is inevitable, extra examination is needed for the data collected during cold days.

4. Even for the same model, individual pressure transducer can have its own characters in response to the temperature fluctuation. Customized calibration in the laboratory and field is recommended before the final installation for each sensor for noise level and baseline drift.

5. Test the pressure transducers for at least a few days to examine the output fluctuation over the temperature range expected in the field installation. This way the behavior and performance can be estimated for a wide range and data can be calibrated and corrected correspondingly.

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GID
4, 533–561, 2014

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GID
4, 533–561, 2014

Temperature effect on vented pressure transducer accuracy

Z. Liu and C. W. Higgins

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GID
4, 533–561, 2014

Temperature effect on vented pressure transducer accuracy

Z. Liu and C. W. Higgins

Title Page
Abstract | Introduction
Conclusions | References
Tables | Figures
◀| |▶
◀ ▶
Back | Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

Figure 1. Field installation of water level sensor inside a flow container.

GID
4, 533–561, 2014

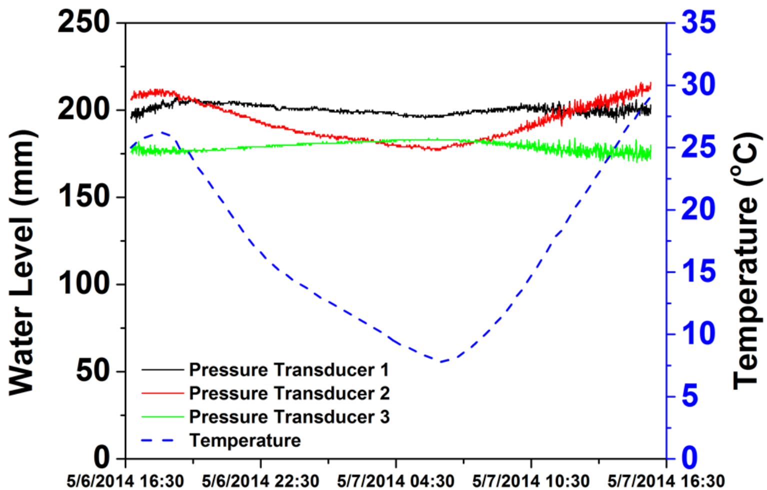

Figure 2. Water levels from three pressure transducers during a 24 h period when the cables were exposed to sunlight. Left y-axis shows the water level measurement and right y-axis shows the water temperature inside the bucket.

GID
4, 533–561, 2014

Temperature effect on vented pressure transducer accuracy

Z. Liu and C. W. Higgins

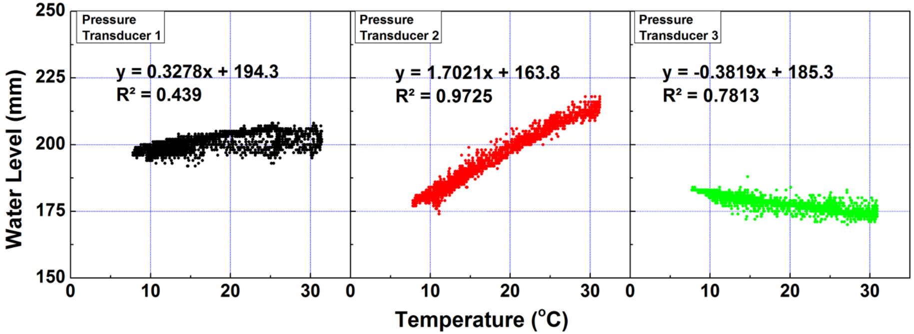

Figure 3. Relationships between temperature and water level readings.

GID
4, 533–561, 2014

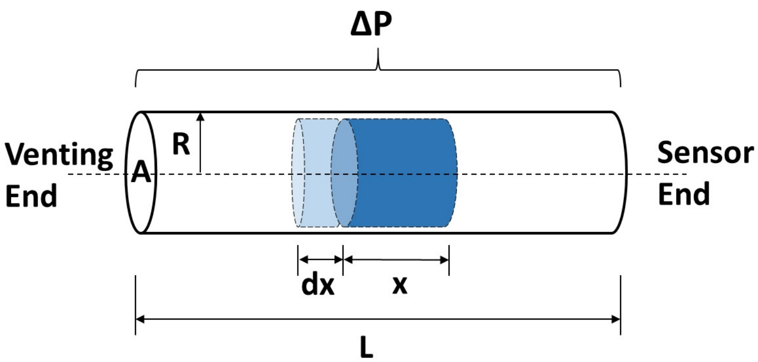

Figure 4. Schematic plot of the air movement inside the venting cable by thermal expansion.

GID
4, 533–561, 2014

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Z. Liu and C. W. Higgins

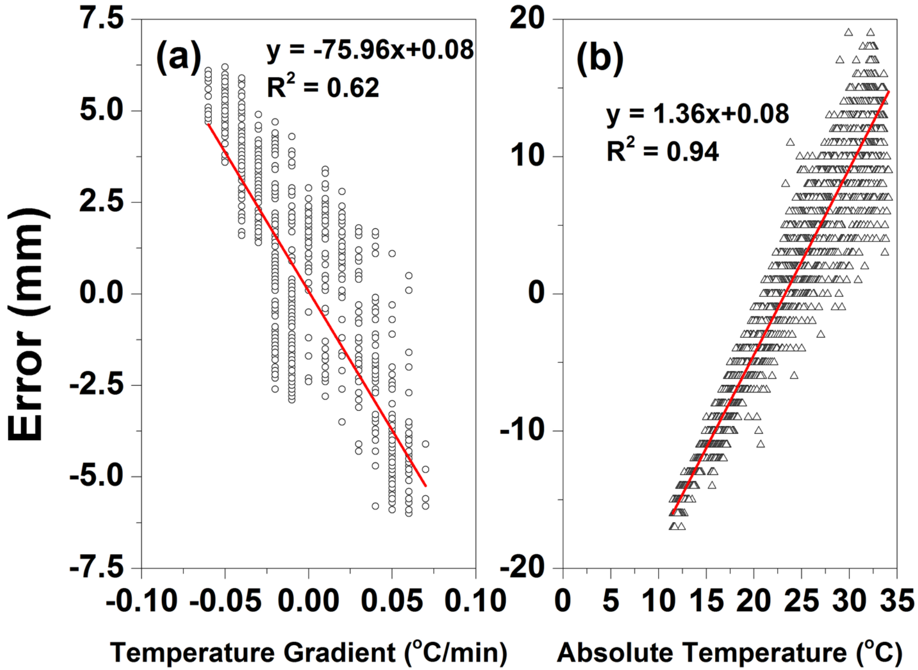

Figure 5. Errors in water level measurement associated with temperature gradient and absolute temperature.

GID
4, 533–561, 2014

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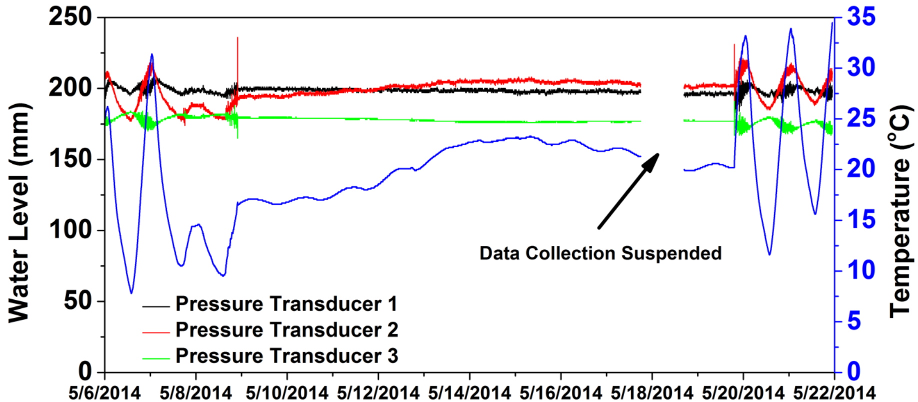

Figure 6. Time series of water level readings and water temperature in the bucket. The gap in the curves indicates the suspension of data collection.

GID
4, 533–561, 2014

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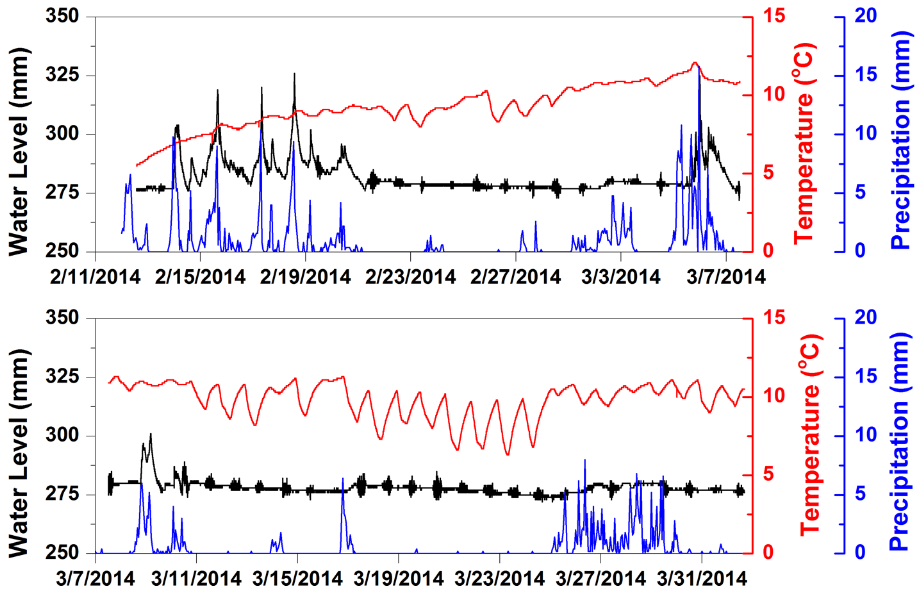

Figure 7. Long-term field monitoring data from the pressure transducer installed at Alsea site on Oregon Highway 34. The black, red, and blue lines represent water level, temperature, and hourly precipitation, respectively. The continuous monitoring was divided into two plots to show more details.

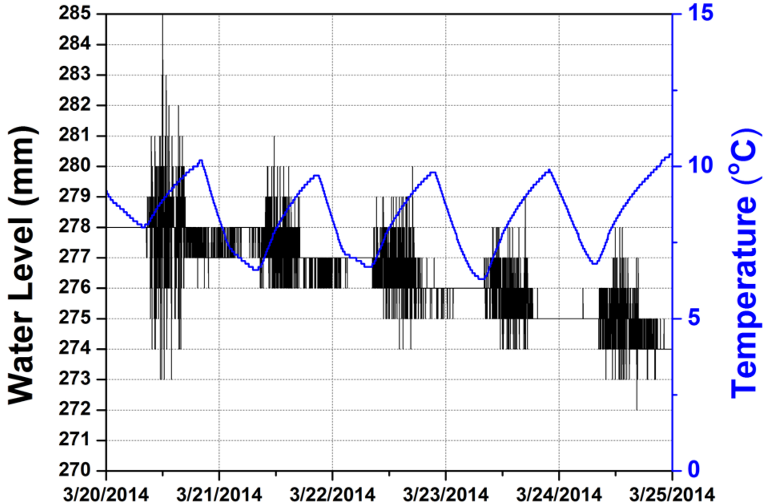

Figure 8. Water level and temperature readings during a five-day period at Alsea site on Oregon Highway 34.

GID
4, 533–561, 2014

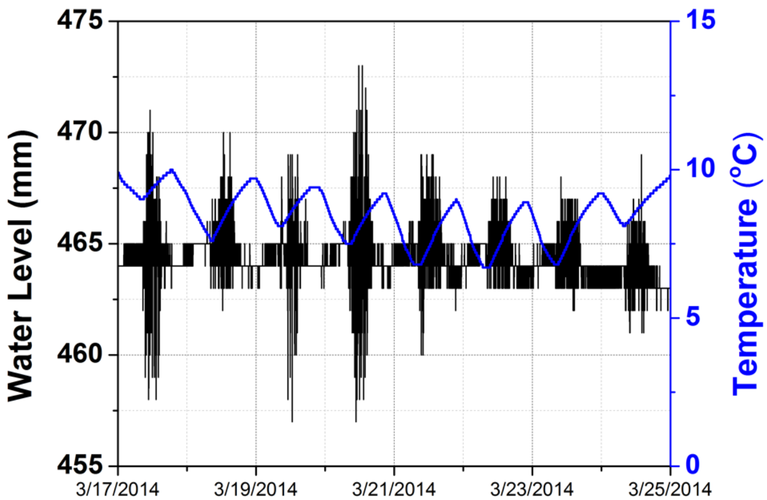

Figure 9. Water level and temperature readings during a seven-day period at Santiam site on Oregon Highway 22.

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4, 533–561, 2014

Temperature effect on vented pressure transducer accuracy

Z. Liu and C. W. Higgins

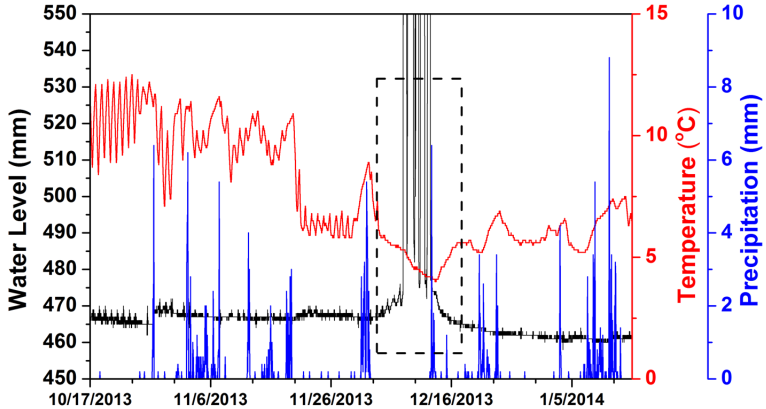

Figure 10. Effect of snowfall event and low temperature on the performance of pressure transducer at Santiam site on Oregon Highway 22. The black line is the water level inside the bucket, the red line is the water temperature, and the blue line is the precipitation. The large peaks were topped off to show other details in the black curve. The dash line box showed the period where the sensor is affected by the snow event.

GID
4, 533–561, 2014