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FIELD EVALUATION OF A TENSIOMETER DATA ACQUISITION SYSTEM FOR HYDROLOGIC STUDIES OF WASTE DISPOSAL SITE DESIGN

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ABSTRACT

Commercially available differential pressure transducers, tensiometers and a data acquisition system were combined to study soil water tension changes with time within two trench cap designs used for the shallow land burial of waste materials. Apparent diurnal variations in soil water tension measured with this system are evaluated relative to field variations in temperature, atmospheric pressure and soil water content. On-going research is described which should improve the reliability of future soil water tension data collected in the field.

INTRODUCTION

For years, solid-wall tensiometers have been used as a means of measuring soil water status in the soil profile. Tensiometer data are nominally obtained once or twice a day, but in order to provide the resolution needed to track water movement using tensiometers for detailed hydrologic events in the field, many man-hours are required both in data collection and manipulation. Recent solutions to these problems have resulted in the use of pressure transducers coupled with tensiometers, using single transducer-scanivalve systems or multiple transducer systems with electrical scanning (Lowery et al., 1986). However, unless the transducer-tensiometer system is operated under constant temperature conditions, temperature fluctuations can affect the output of the system (Cassel and Klute, 1986), in part by affecting the electrical characteristics of the transducer. Temperature changes can also cause expansion and contraction of the material of the tensiometer system and of the water in it; these could be translated into an apparent change in system pressure. This paper describes a differential transducer-tensiometer system used in the field in conjunction with a data acquisition system, documents the influence of temperature, atmospheric pressure and soil water content on apparent changes in pressure measured with the system; and makes recommendations on what can be done to avoid these effects in terms of future research needs.

MATERIALS AND METHODS

The pressure transducers used in conjunction with the tensiometers at our facility are the 140 PC series (model no. 141PC[illegible]) solid state sensors manufactured by Micro Switch, a division of Honeywell (Micro Switch, Freeport, Illinois). This model is the differential vacuum gauge type in which pressure is sensed by a diaphram which flexes with reference to ambient pressure and changes the resistance of the unit resulting in a low voltage output which is proportional to pressure. Operating range of the series is -40° to 85°C, with a temperature-compensated range of -18° to 63°C. The 140 PC series sensors normally use an 8-V-DC power supply, but will allow output scaling over a wide range by adjusting the supply voltage. When used at other than an 8-V-DC excitation, however, there is a ratiometricity error that must be used to normalize the retrieved data. When excitation is set precisely at 8-V-DC, the scaling produced is 1.0 V at 0 kPa and 5.9 V at -101 kPa.

In order to facilitate the use of these pressure transducers, an adaptor had to be constructed and fitted to the tensiometers. Swagelok stainless steel fittings (Crawford Fitting Co., Niagara Falls, Ontario, Canada) were used, mainly for ease of use and accessibility. The fittings were installed into the tensiometers (Soilmoisture Model 2725A, Santa Barbara, California) into the socket where the pressure gauge is usually attached. The Micro Switch pressure transducer was then connected to the fittings, was a connection holding a gas chromatograph septum (to be used in conjunction with a second pressure transducer).

A tensimeter (Soil Measurement System, Las Cruces, New Mexico) was used to provide back-up tension data. This unit also uses a differential pressure transducer which has been provided with a digital readout and a luer lock hypodermic needle probe with which to take the readings (Marthaler et al., 1983). The needle is inserted into the gas chromatograph septum and soil water tension readings are obtained immediately.

Data retrieval was accomplished with a Hewlett-Packard (HP) 3054A computer-based automatic data acquisition system (Hewlett Packard, Palo Alto, California). It combines speed, precision, and a variety of control functions with full computational capabilities, and has the flexibility to make a wide variety of measurements including outputs from pressure transducers, thermocouples, strain gauges, flow meters and other types of transducers. The HP 3497A data acquisition/control unit is the instrument that provides the analog multiplexing, digital monitoring, and control functions using various plug-in assemblies. It has digital input/output, relay multiplexing, digital volt meter (DVM), a field-effect transistorized multiplier, and a real time clock. The DVM can resolve a 1-microvolt signal and is ideal for the precise measurement of the outputs of thermocouples, strain gauges, and transducers.

As the input/output control, the HP 9836A computer was selected because of its speed and versatility. The integrated packages include a 16-bit microprocessor, read/write memory of 2 megabytes, alphanumeric and color graphic cathode ray tube display, multiple language capability, typewriterlike keyboard, a dual disc drive, and a real time clock.

To supply constant excitation voltage to the pressure transducers, two 8-V-DC power supplies (model no. 6050C manufactured by Power Designs, Inc., Westbury, New York) were used in conjunction with the data acquisition system. This type of power supply provides constant (0.005% regulation) voltage and current with automatic crossover, four digit display with an accuracy of 0.1 V, remote sensing or programming, and a short circuit device that prevents instrument failure within 200 msec.

The entire data acquisition system is installed at the Los Alamos Experiment Engineered Test Facility (EETF: see DePoorter, 1981) in an insulated trailer, allowing year-round use of the system and its accessories under optimal temperature conditions. The trailer is located adjacent to field plots containing two different shallow land burial (SLB) trench cap designs as described previously (Abeele et al., 1986). A conventional SLB cap design is being studied in a 3.0 x 10 m plot containing a soil profile consisting of 15 cm of a sandy loam topsoil over 114 cm of a sandy loam crushed tuff backfill; tensiometers are located at depths of 30.5, 76, and 114 cm at six different sampling locations throughout the plot. A modified design is being studied in a 3.7 x 10 m plot consisting of a profile, from the top downward, of 15 cm of a sandy loam topsoil, 1 m of a sandy loam crushed tuff, 25 cm of gravel, 75 cm of cobble, and, at the bottom, 38 cm of sandy loam crushed tuff backfill; the tensiometers are located at depths of 30.5, 61, 66, 76, and 214 cm at nine different sampling locations throughout the plot.

Air temperature and atmospheric pressure measurements were also collected to compare with the tensiometer data collected at the EETF. Temperature measurements were made with a model 070 radiation shield (Met One Inc., Grants Pass, Oregon) which houses a Met One model 060A-2 thermistor. The radiation shield is a fan-aspirated device which claims a radiation error of less than 0.09 °C under maximum solar radiation of 1.6 gm-cal/cm²/minute and has an operating range from -50 °C to +85 °C. The thermistor probe is located 1.2 m above the soil surface, has an operating range from -50 °C to +50 °C, and an accuracy of ±0.1 °C. Barometric pressure was measured using a pressure transducer (model number 270, Setra Systems, Inc., Acton, Massachusetts), which uses a variable ceramic capacitance sensor which deforms proportionally to the applied pressure. This transducer can measure barometric pressure over the range from 60 to 110 kPa with a resolution of 0.01%; barometric pressure readings are determined with an accuracy of ±0.03 kPa over a six-month period.

A field experiment was performed in September through October 1986 at the EETF to determine the influence of three soil water regimes on the diurnal fluctuations of the tensiometer readings collected by the data acquisition system. One 1.5-cm diameter hole was drilled in the bottom of each of six polyethylene containers (41 cm in height with outside diameters ranging from 36 cm at the top to 31 cm at the bottom); a polyethylene connector (inside diameter of 1.5 cm) was glued into this hole and 3 m of plastic tubing (inside diameter of 1.5 cm) was attached to the connector. A 7.5-cm diameter screen was emplaced over the hole in the container, and 3 cm of gravel (1-cm diameter) was then put on top of the screen, followed by 28 cm of crushed tuff (32 kg) which was added in 4 lifts and uniformly compacted. A tensiometer (30 cm long) was then inserted to a depth of 18.5 cm into the crushed tuff with the attached pressure transducer connected to the data acquisition system. Three moisture regime treatments were applied (two experimental units per treatment) by adding water through the bottom of each container: (1) no addition of water, (2) continuous saturation with 1-2 cm of standing water on the soil surface, and (3) treatment (2) applied for about an hour followed by drainage.

RESULTS AND DISCUSSION

Both the tensiometer-transducer units and the tensimeter were calibrated by applying known hydraulic heads to the tensiometers and measuring the resulting tension according to previously-described methods (Cassel and Klute, 1986). After installation of 40 tensiometer-transducer units in our field plots, the pressure transducer data was then compared with the tensimeter data collected for these units in both field plots (Fig. 1). These two distinctly different means of collecting the tensiometer data more than met our expectations ($r^2 = 0.994$).

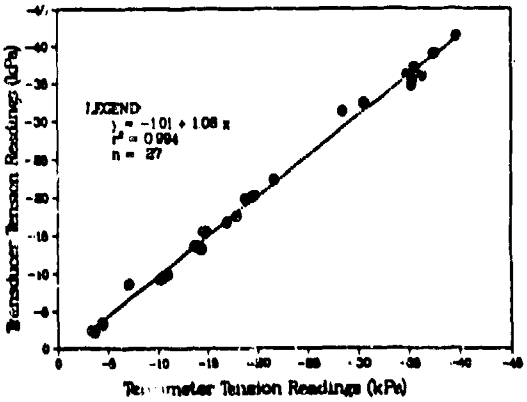

Figure 1. Comparison of tension readings collected in our field plots with the tensiometer and with the pressure transducer.

The second step in evaluating the tensiometer-transducer units was to have a way of measuring a known tension with time as the system collected hourly data in the field. To accomplish this, two reference tensiometers were selected and equipped identically to those in the field installation. One was placed in a bucket of water inside the trailer which housed the data acquisition system. The second was placed outside the trailer in the experimental area and inside an aluminum tube already inserted into the ground. The hydraulic heads on both reference tensiometers were kept the same. This provided a reference of the effects caused by the environment inside the equipment trailer and the effects of the environment in our experimental area, less those caused by the soil itself.

The results from these two tensiometers show (Fig. 2) that changes of less than 0.1 kPa occurred inside of the temperature-controlled environment in the trailer, while outside diurnal changes in tension were observed to range from 0.1 to 0.3 kPa during a typical period in September 1986. Since the differential pressure transducers used to detect tension changes were designed to compensate for changes in temperature and pressure, it was unclear to us at first what was causing the variations in pressure in the reference tensiometer located in the field. This unexpected diurnal variation in tension always coincided with the occurrence of sunrise and sunset: the negative pressure readings generally decreased (notice that the convention used in expressing soil water tension is the one where a soil which has just received water exhibits a decrease in negative pressure or tension, and vice versa) from sunrise to the middle of the solar day, and then the negative pressure readings generally increased from the middle of the solar day to the next sunrise (Fig. 2). Obviously, the daily variations in solar radiation were causing diurnal temperature changes, which in turn are known to be the primary cause of daily variations in atmospheric pressure (Taylor, 1954).

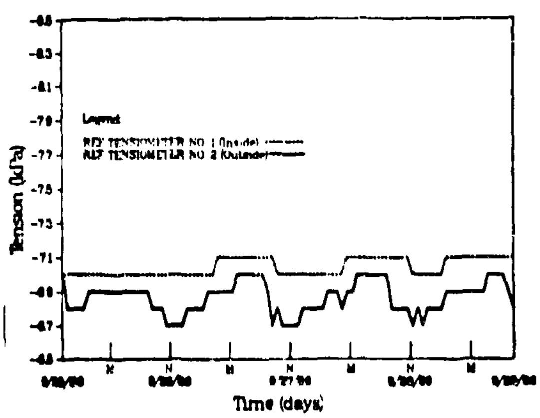

Figure 2. Comparison of hourly tension data collected in September, 1986 from two reference tensiometers with known, constant hydraulic heads. N and M indicate noon and midnight, respectively.

The diurnal variation in tension observed in the reference tensiometer located in the field was also observed in all of the tensiometer-transducer units installed in the soil of the two field plots, but differed from the reference tensiometer data in having a much larger amplitude. Hourly soil water tension measurements collected for three soil depths in the modified field plot are shown for four days in September 1986, along with observed variations in air temperature and atmospheric pressure (Fig. 3). Sinusoidal-type soil water tension fluctuations were again observed for all soil depths and seemed to follow the variations in air temperature more than atmospheric pressure changes. During this time period, as the air temperature ranged from a minimum of 2.2°C to a maximum of 17.8°C, atmospheric pressure only varied in amplitude by 0.57 kPa (Fig. 3). The corresponding average diurnal variations in soil water tension for this time period generally decreased with soil depth: 5.3, 3.4, and 2.9 kPa, for tensiometer data collected at depths of 30, 60, and 220 cm, respectively. This daily pattern of change in the amplitude of the apparent soil water tension diurnal variations with depth is directly correlated with the known daily pattern of change in amplitude of soil temperature with depth (Kohnke, 1968), with daily fluctuations in soil temperature normally being great only in surface soils.

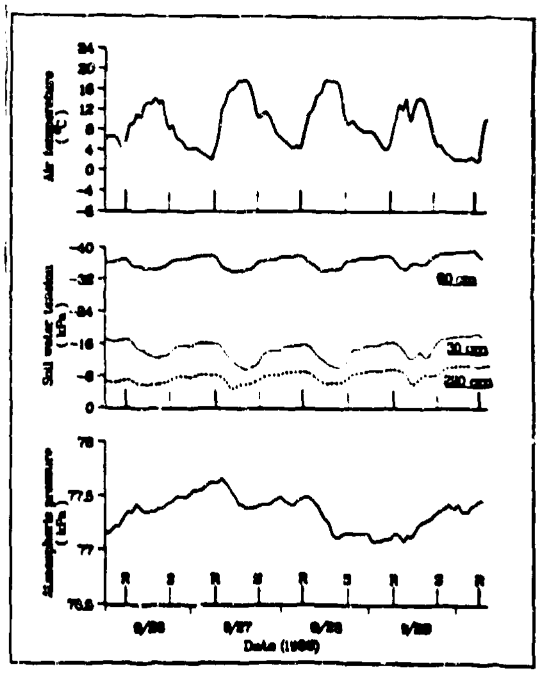

Figure 3. Air temperature, atmospheric pressure, and hourly transducer-tensiometer data collected in September, 1966 for three soil depths in the field plot containing the modified SLB design. R and S indicate sunrise and sunset, respectively.

The amplitude of the diurnal variations in soil water tension decreased with time as data was collected on the modified plot from mid-September through early November, 1986 (Fig. 4). The average amplitude of the diurnal soil water tension variation for 9 locations at the 30 cm soil depth on the modified plot decreased from about 4.5 kPa on September 18 to 2 kPa on October 15 to only about 0.5 kPa on November 2. Less dramatic fluctuations were observed on the control plot (Fig. 4), which normally exhibited wetter soil conditions than the modified plot. The maximum/minimum daily temperatures for these three dates showed a progressive cooling trend: 23.4/7.0°C (September 18), 16.3/-1.0°C (October 15), and 10.1/1.4°C (November 3). Atmospheric pressure variations for this entire time period only ranged from 76.8 to 78.5 kPa, again showing a minimal influence on the tensiometer-transducer data compared with that of temperature.

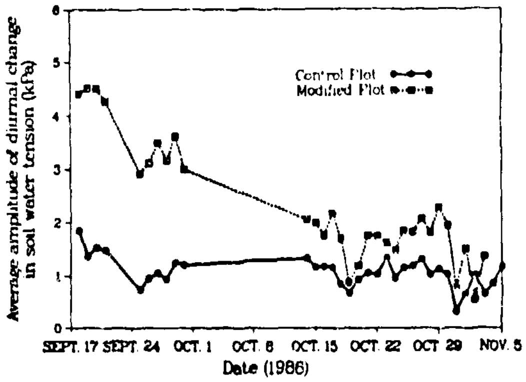

Figure 4. Amplitude of the diurnal fluctuation in hourly soil water tension data collected at the 30 cm soil depth in both field plots as a function of time.

In order to see if the apparent changes in soil water tension observed in our field plots were reasonable, they were compared with previous tensiometer data collected with tensiometers similar to those used in our studies, but situated at the EETF under conditions where temperature variations were much smaller in an enclosed caisson (Abeele, 1984). This experiment consisted of measuring the matric potential and volumetric water content of saturated crushed tuff with time as the column of tuff drained so that unsaturated conductivity could be calculated as a function of the water status of the tuff. The results of this experiment demonstrated that the rates of change of matric potential of the tuff ranged from approximately 1.0 kPa/day within the first four days of drainage (the matric potential dropped from 3.1 to 5.5 kPa in three days) to 0.10 kPa/day after 100 days of drainage (the matric potential dropped from 18.9 to 20.7 kPa between 80 days and 100 days after drainage was started). Comparing this data with the apparent daily fluctuations in tension measured in our field plots (Fig. 4), it can easily be observed that the tensiometer data collected in the caisson was at a much more constant temperature than our field data, and, thus, showed smaller variations in tension readings.

Since there was some evidence from the tensiometer data that the diurnal changes in tension seemed to decrease in amplitude after small rainstorms in late summer and early fall, a small scale field experiment was performed to determine the influence of three soil water regimes on the diurnal fluctions in hourly tensiometer data. The results of first treatment (Fig. 5) consisting of no water addition to the crushed tuff, exhibit the commonly-observed diurnal variations in soil water tension with an average daily amplitude of 5.6 kPa over the 10 days of this experiment. The last two treatments in this experiment both involved saturating the crushed tuff, since none of the precipitation events had saturated the soils in our experimental plots to a depth of 30 cm. Soil tension data was collected for a couple of days (the results are comparable to the soil treatment described above), and then the soil in both treatments was saturated on September 24 (Fig. 5). The tension observed immediately approached values of about 2 kPa due to the fact that excess water collected on the soil surface. Although the soil water was allowed to drain out of the container in our treatment (Fig. 5), the greatly enhanced soil water status of these two treatments dramatically reduced the magnitude of the diurnal fluctuations in tension.

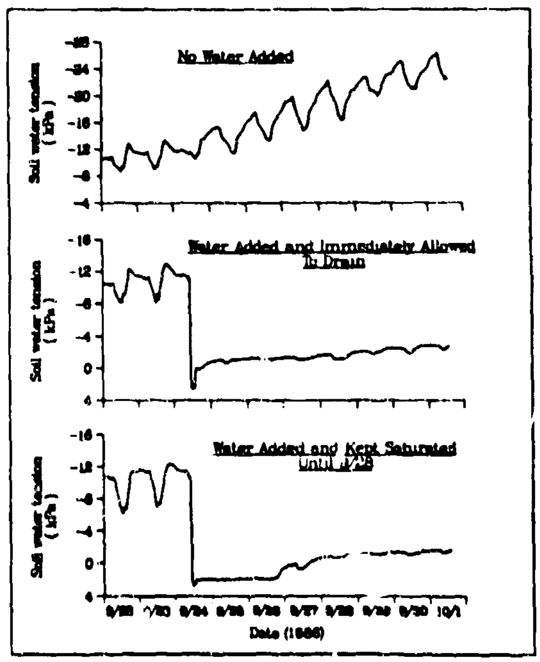

Figure 5. Soil water tension data collected on an hourly basis for crushed tuff receiving three different soil water treatments in a small-scale field experiment.

The explanation behind the reduction in the diurnal tension fluctuations with enhanced soil water status is related to thermal effects on the soil, on the water inside of the tensiometer, and on the air space inside of the top of the tensiometer. The diurnal cycle of solar radiation causes daily fluctuations in soil temperature, an effect which is further influenced by soil water content. The thermal conductivity of most soils lies around 0.005 mcal/sec-cm-^{o}C; that of air is about 100 times smaller, while that of water is about one-fifth that of soils (Kohnke, 1968). Thus, the resulting temperature gradient in the wet soil is dampened as well as its effect on the water inside of the tensiometer, which is trying to come to equilibrium with the temperature gradient along the entire length of the tensiometer. Finally, the temperature of the liquid water in the tensiometer changes and the vapor pressure of water in the enclosed air space at the top of the tensiometer is then dramatically influenced. When this occurs, the vacuum pressure measured with the pressure transducer in this enclosed air space is inversely proportional to temperature changes. However, temperature is exponentially related to the vapor pressure of water in the enclosed air space in the tensiometer, making an interpretation of tensiometer-transducer field data more complex as the average soil temperature varies. Nonetheless, this explanation does suoport the daily decreases in tension observed in tensiometer-transducer readings starting at sunrise and proceeding to mid-day as the temperature gradually increases (Figs. 2, 3). The rest of our field data also shows a general decrease in the amplitude of the observed diurnal fluctuation in soil water tension from the warm late summer period through the cooler mid-fall period (Fig. 4).

The data presented in Fig. 5 also demonstrates that it is soil temperature that seems to control the apparent daily diurnal fluctuations in tension, and not air temperature effects on the aboveground portions of the transducer-tensiometer system. The tops of all three tensiometers were exposed to diurnal air temperature variations, yet the tensiometers in the two relatively wet treatments exhibited greatly reduced diurnal fluctuations in tension (Fig. 5).

SUMMARY AND CONCLUSIONS

In order to measure the relative reduction in potential of water as a result of the attraction of the soil matrix, the procedure and instrumentation must have certain exacting characteristics. Theoretically, it must be possible to hold all the variables constant except the matric attraction, which in turn must be capable of measurement. Thus, the water in the tensiometer system should be in thermodynamic equilibrium with the soil water; however, in reality, tensiometers commonly do not achieve equilibrium immediately, i.e. - they exhibit non-zero response times (Cassell and Klute, 1986; Klute and Gardner, 1962; Towner, 1980). Theoretically, the measurement of matric attraction of soil requires constant temperature, such as can be achieved in a constant temperature laboratory or chamber. However, the common practice when working with tensiometers in the field is to ignore temperature effects - a practice that our field experiments document to be a major error, especially when dealing with soils containing small amounts of soil water!

Using a differential pressure transducer either attached to a tensiometer with a known hydraulic head of water (reference tensiometer), or to a tensiometer in contact with soil in a field plot, apparent diurnal changes in tension were observed and correlated with diurnal temperature variations. Reference tensiometers exhibited sinusoidal-type tension fluctuations with a daily amplitude of 0.1 to 0.3 kPa, while the corresponding values for tensiometers in one of our field plots ranged from about 4 to 6 kPa in the warm portions of early September to less than 1 kPa in the much cooler portions of November. Daily fluctuations in soil water tension were shown to decrease with soil depth just as would be expected to occur with the pattern of daily soil temperature fluctuations with depth. Atmospheric pressure variations, both on a daily basis and on a 1 1/2-month basis, were found to have a minimal effect on observed changes recorded by the tensiometer-transducer system compared with the effect of temperature. The temperature-influenced apparent rates of change of soil water tension measured using the tensiometer-transducer units were also found to be considerably larger than data collected from a similar experiment conducted at the EETF where temperature effects were minimized.

Enhancing the soil water status of the crushed tuff in a small-scale field experiment caused a dramatic decrease in the apparent diurnal fluctuations in soil water tension measured wh the tensiometer-transducer units. These observations were explained relative to thermal effects on the moisture in the soil, and on the water and air inside of the tensiometers. Air temperature effects on the above-ground portions of the transducer-tensiometer units were found to be minimal.

The tensiometer data collected in the field studies reported on in this paper and in one other study (Lowery et al., 1986) demonstrate the influence of a diurnal temperature-induced effect on data collected in the field. Our current research involves developing a method to correct field tensiometer data for diurnal thermal fluctuations not compensated for by differential pressure transducers, i.e. fluctuations related to expansion and contraction of the material of the tensiometer system and of the water in it. This correction factor will have to take into account temperature gradients in the soil adjacent to the below-ground portion of the tensiometer and will have to be dependent on the moisture status of the soil. The only way this might be done to account for all of these effects seems to be through the use of a tensiometer-transducer unit which measures only the thermally-induced effects, and not matric potential. This "background tensiometer" would probably be identical in length, construction, and water-air content to that of a nonbackground tensiometer, except that the porous cup at the bottom of the tensiometer would be sealed to eliminate measured changes in soil matric potential. Thus, rather than ignoring temperature -induced effects on tensiometer data collected in the field, temperature effects could be quantitatively taken into account in the future.

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