Ultrasonic measurements on a porous ceramic to determine soil suction

S.O. Kasap*, D. Lakhanpal*, C. Patzer*, T. Mandziak† and D.G. Fredlund†

*Department of Electrical Engineering, (†Department of Civil Engineering), University of Saskatchewan, Saskatoon, S7N 0W0 Canada

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The attenuation of ultrasonic waves at 117 kHz was investigated as a means of measuring the water content of a highly porous ceramic medium in order to evaluate indirectly the water suction of soils. A porous ceramic disc, with a porosity of about 66%, was prepared whose volumetric water content was related to matric suction. Two PZT transducers were attached to opposite ends of the porous ceramic disc to monitor the attenuation of ultrasonic waves. The output voltage from the receiving transducer was correlated to the water content of the ceramic and hence the matric suction. The present ultrasonic technique was suitable for matric suctions above ~50 kPa. Although the output voltage versus water content relationship was non-linear it could, nevertheless, be represented with reasonable accuracy by a logarithmic–parabolic calibration curve which was independent of the excitation voltage. The main disadvantage of the technique, however, is that the calibration curve depends on the salt content of the water in the ceramic. On the other hand, when the ultrasonic method is used in conjunction with other techniques it provides a further means of characterizing matric suction.

Keywords: water content; porous ceramics; matric suction

The measurement of the matric suction of soils has been of much interest to geotechnical engineers. There are various techniques currently in use for measuring the matric suction, with the most promising being the thermal conductivity and capacitance measurements (e.g. References 1–3). Matric suction is defined as the difference in pressure between the pore–air, u_a, and the pore–water, u_w, pressures in a soil (or ceramic). It forms a stress state variable in geotechnical engineering and is written as u_a-u_w. It is used to describe the mechanical behaviour of soils whenever the pore–water pressure is negative relative to atmospheric conditions.

The importance of matric suction in geotechnical engineering, and hence the need for its measurement, is well recognized (e.g. References 4 and 5). The thermal conductivity method is particularly suitable for *in situ* measurements due to its cost effectiveness. The primary principle is to use a suitable porous ceramic whose thermal conductivity depends upon its water content. When a porous ceramic medium is placed in contact with the soil, the water content of the ceramic depends on the matric suction of the soil. The relationship between the matric suction and the water content of the porous ceramic then provides an indirect means of measuring matric soil suction.

The present study stemmed from a need to investigate whether, with the current availability of inexpensive semiconductor devices, techniques other than thermal conductivity can be used to monitor matric suction. The notion of using ultrasonic waves to evaluate the water content is not new. For example, Mack and Brach[6] in 1966 used low amplitude and very high frequency, VHF (15.9–142 MHz), ultrasonic waves to study ultrasonic wave propagation through soils as a function of the water and salt content. Although, ultrasound has been successfully used in the food industry to monitor the water content of certain manufactured foods[7,8], its application to monitoring the matric suction of soils through the use of a suitable porous ceramic sensor has been limited.

This paper reports the use of low radio-frequency (~100 kHz) ultrasonic measurements to monitor the water content of a highly porous ceramic as an indirect means of evaluating matric suction. The relationship between suction and water content depends on the porosity of the ceramic as well as the pore size distribution[9]. There are various requirements for an ultrasonic-based sensor to compete with current thermal conductivity sensors. The sensor must first be able to provide a measurement which can be correlated to the water content of the porous ceramic and hence indirectly to the suction of the soil. Secondly, it must economically compete with the thermal conductivity method for *in situ* measurements. Generally, VHF- and UHF-based systems require relatively expensive electronic instrumentation that will economically exclude the ultrasonic technique. Moreover, at high frequencies, the

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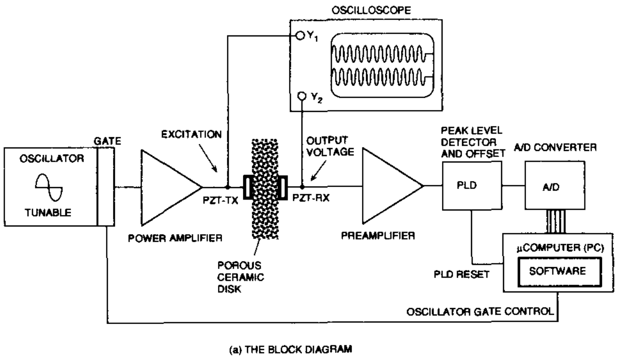
ultrasonic wave propagation in a highly porous medium becomes greatly attenuated. It was therefore decided to investigate the use of an ultrasonic system operating in the low radio-frequency range ($\ll 1$ MHz) where there are commercially available inexpensive semiconductor integrated circuits.

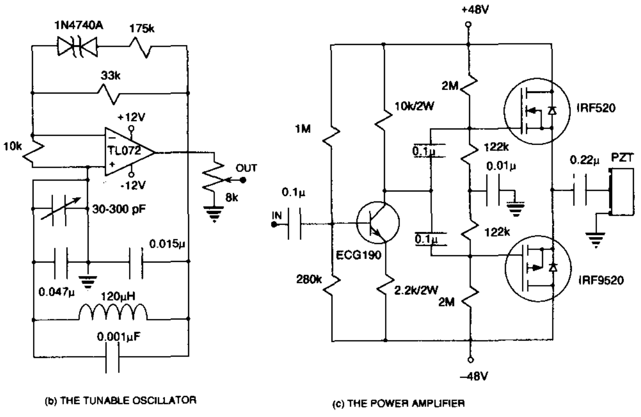
Description of the technique

The principle of the ultrasonic measurement system was based on sending acoustic waves through a porous ceramic, measuring the magnitude of the transmitted wave as an output voltage on the receiving transducer, and correlating the output voltage to a volumetric water content. Therefore, a measurement was made of the attenuation of ultrasonic waves through the porous ceramic medium as a function of its water content. The basic block diagram for the entire system is shown in *Figure 1*.

The ultrasonic measurement technique was based on the sing-around method. A tunable oscillator was the source of the RF signal for the transducer and provided a sinusoidal wave at around the resonant frequency of the transducer up to 20 V_{p-p}. A power-amplifier boosted the signal from the oscillator to a sufficient amplitude to drive the transmitting PZT transducer attached to the porous ceramic disc. A gating circuit between the oscillator and the power amplifier allowed the transmitting PZT to be driven during measurements only. A second and identical PZT transducer attached to the opposite face was used as the receiver. The PZT transducers had coaxial connections and were attached to the opposite faces of the porous ceramic using grease as a coupling medium. The PZT–ceramic–PZT arrangement acted as the 'sensor'. The voltage output from the receiving PZT signal could be directly displayed on the oscilloscope. The apparatus beyond the receiving PZT also contained a preamplifier, a peak level detector (PLD) with an offset facility, an A/D converter and a PC microcomputer to interface the output voltage from the receiving PZT into a computer for data storage and analysis. A menu driven software program enabled the measurements to be user controlled.



(a) THE BLOCK DIAGRAM



(b) THE TUNABLE OSCILLATOR

(c) THE POWER AMPLIFIER

Figure 1 The ultrasonic technique for measuring the water content in the porous ceramic sensors. (a) The entire apparatus. (b) The oscillator. (c) The power amplifier

Example schematic diagrams of the ultrasonic oscillator and driver circuits are also shown in *Figure 1* as an illustration of the particular electronics employed in the present apparatus. The various functions shown in *Figure 1* up to the microcomputer can be readily constructed from various commercial integrated circuits[10]. It is desirable to measure matric suction *in situ* at several separate locations which means that each sensor should have its own ultrasonic driver circuit; thus, cost effectiveness becomes an important factor. It is desirable that a sensor in the field should send a digital signal to a central point where it can be read into a computer and converted to water content and subsequently to matric suction through a suitable calibration curve.

The primary element of the sensor is the porous ceramic whose water content reflects the matric suction in the soil. The porous ceramic in the form of a disc was prepared in the laboratory. The diameter of the disc was 38.3 mm and the thickness was 10.2 mm. The materials for the ceramic disc, flyash (12 wt %), kaolinite (28 wt %), Celite 545 (30 wt %) and Celite 577 (30 wt %), were mixed as dry powder. Some water, about 10% by weight, was added to achieve plasticity and workability. The mixture was then placed in a cylindrical stainless steel mould and pressed into shape. After being moulded into shape the sample was left overnight in an oven at a temperature just above 100 °C to drive out the water. The ceramic was then fired at a temperature of 1000 °C for 495 minutes.

The ceramic used in the ultrasonic apparatus was one of several ceramics produced in the laboratory for the purpose of studying the relationship between matric suction, water content, and pore size distribution. The ceramic selected for the ultrasonic measurements had a porosity of 66% as determined from Mercury Intrusion Porosimetry and had a distribution of pore sizes (i.e. mean diameters) ranging from ~ 0.2 to $\sim 5\,\mu m$; the majority of the pores were $\sim 3\,\mu m$ in diameter. The relationship between the water content of the ceramic disc and matric suction was obtained by using the Pressure Plate Apparatus[9]. The results from the ultrasonic measurements could then be correlated to matric suction.

A highly porous ceramic medium, as in the present example of 66% porosity, is highly attenuating to ultrasonic waves due to the scattering of waves at the pores. It is therefore necessary to use an ultrasonic transducer that has good electrical-to-mechanical energy conversion efficency such as the PZT transducer. Further, due to the highly attenuating nature of the medium, reflections of ultrasonic waves between the faces of the ceramic disc and the resulting interference will not be significant which means that one can simply excite the transmitter continuously and monitor the received signal; a relatively simple and desirable measurement procedure.

Initially, an ultrasonic RF tone-burst system, based on the combined pulse–echo and sing-around techniques described in References 11 and 12, operating at around

~4 MHz, was used. Owing to the large attenuation at ~4 MHz, the received signal was below the noise floor of the receiver and therefore could not be used to monitor the water content. A further reason for using a ~100 kHz system was to reduce the scattering of ultrasonic waves in the porous ceramic to obtain a detectable output from the receiving transducer.

Experimental results

All ultrasonic measurements were performed with the transmitting transducer excited at 117 kHz at its resonant frequency. Readings were initially taken on a water saturated ceramic. Saturation was achieved by immersing the ceramic in water. The ceramic was then dried in an oven for approximately five minutes, and the output voltage was measured again. This process was repeated until all the water was driven out from the ceramic. At each stage, the ceramic was weighed and from the change in weight of the ceramic disc, the volumetric water content was calculated.

The results from the ultrasonic testing of the porous ceramic, as output voltage versus volumetric content, are shown in *Figure 2* for two different excitation voltages of the transmitting PZT transducer. As the input voltage (peak-to-peak at 117 kHz) is doubled from 30 V (peak-to-peak) to 60 V, the output voltage at the receiving transducer also approximately doubled. The amplitude of the received signal was directly proportional to the amplitude of the excitation signals as illustrated in *Figure 3* for three water contents. It is clear in *Figure 2* that the relationship between the output voltage and the water content is highly non-linear, which means that the relationship must be represented by a polynomial for calibration purposes (a form that is used in many calibration procedures, such as the thermocouple emf-temperature calibration). The solid curves in *Figure 2* represent fourth-order polynomial best-fits to the data. A cubic polynomial best-fit was almost indistinguishable from the fourth-order fit. *Figure 2* also shows the relationship between the matric suction and the water content for this particular ceramic measured on the pressure plate apparatus. When the output voltage and matric suction versus water content data are compared, it is apparent that the ultrasonic technique is suitable for matric suctions above ~50 kPa.

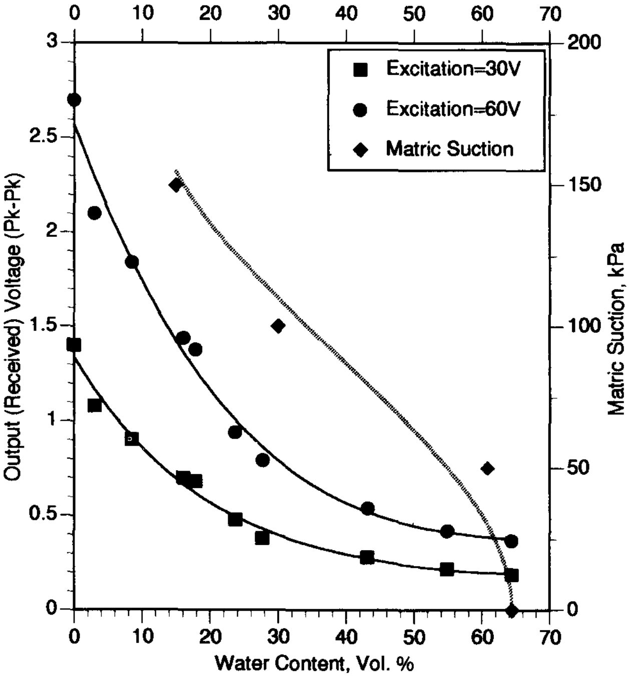


Figure 2 Output voltage (peak-to-peak) from the receiving PZT transducer at two excitation voltages (peak-to-peak) of the transmitting PZT. The solid curves are the best fourth-order polynomial fits. The relationship between matric suction and water content in the porous ceramic. The solid curve is a guide to the eye for the general behaviour

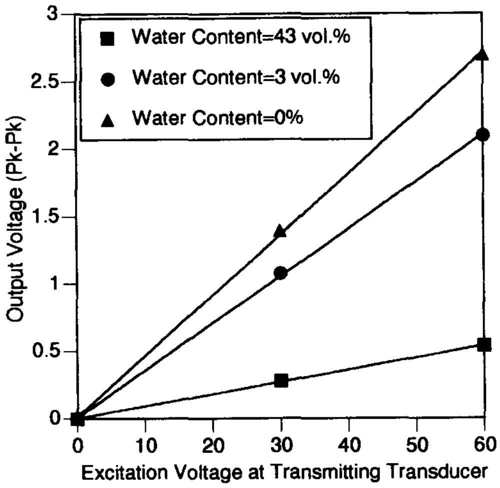


Figure 3 Output voltage (peak-to-peak) versus excitation voltage (peak-to-peak) for three different water contents in the porous ceramic

A calibration curve can be established for this sensor independent of the excitation voltage from physical arguments. If V_{out} is the output signal from the receiving PZT transducer and V_{in} is the input signal that excites the transmitting PZT transducer then

$$V_{\mathrm{out}} = KV_{\mathrm{in}} \exp(-\alpha L) \exp(-\alpha_C L_C) \tag{1}$$

where K is a constant that incorporates electrical to mechanical to electrical conversion factors, α is the attenuation coefficient for ultrasonic waves through the porous ceramic medium, L is the effective thickness of the ceramic disc, α_C is the attenuation coefficient of the coupling medium and L_C is the effective thickness of the coupling medium where $L_C \ll L$. The attenuation coefficient α is expected to depend on the frequency, or wavelength λ, and the water content, w, thus $\alpha = \alpha(\lambda, w)$. For a given frequency of excitation, $\alpha = \alpha(w)$. Rearranging Equation (1)

$$\ln\left(\frac{V_{\mathrm{out}}}{V_{\mathrm{in}}}\right) = -K_1\alpha + K_2 \tag{2}$$

where K_1 and K_2 are constants for a given sensor (fixed L, α_C and L_C). For small amounts of water, the attenuation coefficient will change linearly with the water content. As the water content increases further, the linear relationship will not hold. In many applications the non-linearity can be accounted for by adding a w^2 term to the linear dependence (i.e. representing the variation parabolically as in regular solution theory)

$$\alpha = \alpha(w) = a_0 + a_1 w + a_3 w^2$$

where a_0, a_1 and a_3 are constants. Equation (2) then becomes

$$\ln(V_{\mathrm{out}}/V_{\mathrm{in}}) = A + Bw + Cw^2 \tag{3}$$

where the coefficients A, B and C for a given sensor are constants.

Figure 4 depicts a plot of $\ln(V_{out}/V_{in})$ versus volumetric water content for the two excitations. The solid curves are the best parabolic fits (best A, B and C in Equation (3)). It is apparent that Equation (3) is a reasonable representation of the data and that a single calibration curve of the form in Equation (3) for the particular ceramic is sufficient to measure the water content for any excitation.

Figure 5 shows a semilogarithmic plot of the normalized output voltage, V_{out}/V_{in}, against the matric suction for this particular ceramic medium. The solid curve is the best parabolic fit to the data. V_{out}/V_{in} for a given matric suction was obtained by noting the corresponding water content (experimental points in *Figure 2*) and using Equation (3). The solid curve in *Figure 5* is the best parabolic fit to the data, given only four experimental matric suction points are known. Nevertheless, it is apparent that a logarithmic–parabolic calibration curve is a reasonable representation.

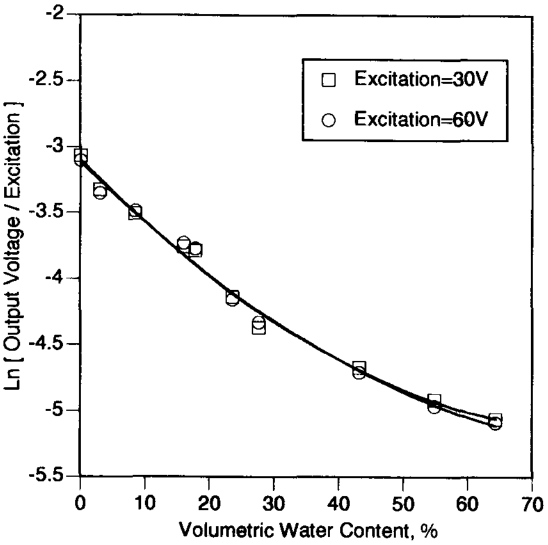


Figure 4 Semilogarithmic plot of the output voltage/excitation versus volumetric water content for two different excitation voltages. Natural logarithms are used. The solid curves are the best parabolic fits along Equation (3)

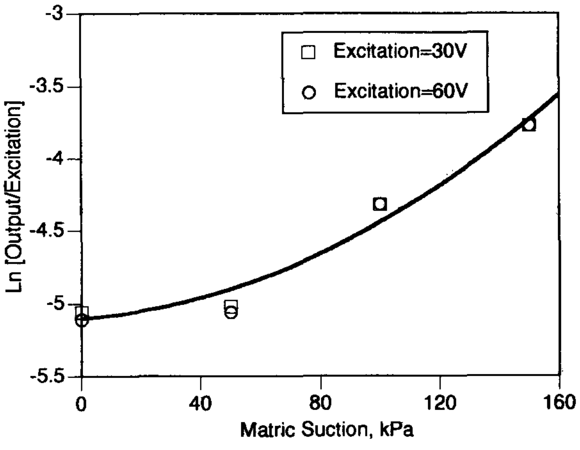


Figure 5 Semilogarithmic plot of the output voltage/excitation versus matric suction for two different excitation voltages. Natural logarithms are used. The solid curve is the best parabolic fit

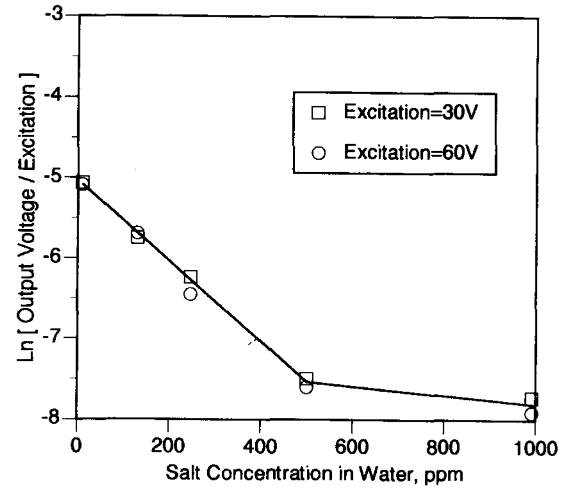


Figure 6 Semilogarithmic plot of the output voltage/excitation versus salt content (ppm) for two different excitation voltages. Natural logarithms are used and the voltages are peak-to-peak

The effect of NaCl concentrations on the output voltage readings was also studied. The porous ceramic was saturated in solutions with 125, 250, 500 and 1000 parts per million NaCl concentrations. As the NaCl concentration increased, the output volage dropped dramatically. *Figure 5* shows a semilogarithmic plot of the normalized output voltage against the salt content of the water, where it is clear that, up to ~500 ppm salt content, the normalized output signal drops almost exponentially with the salt content. From Equation (1) it can be inferred that the attenuation coefficient is increasing linearly with the salt content up to ~500 ppm. The amplitude of the output signal was proportional to the excitation voltage, regardless of the salt content which is indicated in *Figure 6*. It is apparent that the strong dependence of the output signal on the salt content is a major drawback for using this technique as a sole means of evaluating the water content in the porous ceramic.

Conclusions

The attenuation of ultrasonic waves propagating through a porous ceramic disc was investigated as a means to measure the volumetric water content of the ceramic. This measurement, in turn, can be used to determine the matric suction of the soil. The study was successful in that it developed a relationship, of the form of Equation (3), between the output voltage of the receiving transducer and the volumetric water content of the porous ceramic (and hence matric suction) which was independent of excitation. The main drawback of using ultrasound for monitoring the water content is the dependence of the volumetric water content measurement upon the salt concentration of the water. However, when the ultrasonic technique is used in conjunction with another method it can serve as a further means of characterizing matric suction.

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