A new matric suction sensor based on volume change

Adedeji Dunmola[1], Paul Simms[1] and Manuel Padilla[2]
[1]*Department of Civil and Environmental Engineering, Carleton University, Ottawa, ON Canada*
[2]*GCTS Testing Systems, Tempe, AZ USA*

ABSTRACT
This paper describes the design and preliminary results from testing a prototype matric suction sensor made from a Poroelastic material with an air entry value of 8000kPa. The proposed sensor operates on poroelasticity theory: volume change of porous material resulting from a change in matric suction. Matric suction values of drying silt and gold tailings measured using the Poroelastic sensor were well correlated with corresponding values obtained using a T5 Tensiometer and psychrometer, and with matric suctions established using axis-translation. The range of the sensor appears to be at least 5500 kPa.

RÉSUMÉ
Cet article décrit la conception et les résultats préliminaires de l'essai d'un prototype de capteur de succion matricielle faite d'un matériau Poroélastique issue d'une valeur d'entrée d'air de 8,000kPa. Ce capteur fonctionne sur le principe de la théorie de Poroélasticité: changement de volume d'un matériau poreux résultant d'un changement dans la succion matricielle. Les valeurs de succion matricielle de limons séchant et de résidus de pâte d'or, mesurées à l'aide du capteur Poroélastique, sont bien corrélées avec les valeurs correspondantes obtenues en utilisant un tensiomètre T5 et un psychromètre. Elles sont également bien corrélées avec la succion matricielle déterminée par translation d'axe. La gamme du capteur semble atteindre au moins 5,500 kPa.

1 INTRODUCTION

Matric suction data are important for many geotechnical applications. The prediction of water coefficient of permeability and shear strength of unsaturated soil require matric suction data input (Huang et al. 1998; Vanapalli et al. 1996). Matric suction data is also required for long-term slope stability analysis (Feuerharmel et al. 2006), prediction of long-term performance of soil covers for waste disposal site (Weeks and Wilson, 2005). In addition, matric suction the design and operations of mine waste disposal facilities require matric suction data (Newson and Fahey, 2003; Simms et al. 2007). The accurate, fast and convenient determination of matric suction under field or laboratory conditions is therefore important for practitioners.

None of the current devices and techniques used for determination of soil suction is capable of measuring the wide range of suction (0 to 1GPa) that can be encountered in unsaturated soils (Rahardjo and Leong, 2006). Improving the capacity of geotechnical practitioners to measure this wide range of suction in soil is desirable. Also, there are several benefits afforded by devices and techniques currently used for measuring soil suction, but there are limitations to each method. A detailed review of features, advantages and limitations of currently available devices and techniques is provided in Rahardjo and Leong (2006). This paper proposes a new method for measuring matric suctions of up to several MPa in unsaturated soils that potentially avoids the problems of cavitation and hysteresis. The new method is based upon volume change of a porous material with a high air entry value (AEV), such that neither hysteresis nor cavitation will influence readings below this AEV. A prototype sensor is described and its performance is compared with simultaneous measurements using a tensiometer, a psychrometer, and against matric suctions established in test soil using axis-translation. The sensor was tested in artificial silt and gold tailings.

2 POROELASTICITY THEORY

The proposed sensor is made from a porous material of high AEV sufficiently "soft" to undergo measurable volume change due to change in pore-water pressure, but stiff enough to be used as a robust sensor in soil. The volume change of porous material is correlated to change in positive or negative pore-water pressure by poroelasticity theory. According to Mackenzie (1950), the change in negative or positive pore-pressure of a linearly-elastic porous material with an interconnected solid phase that is partially saturated can be related to volume changes using the following equation:

$$\varepsilon = \frac{SP}{3}\left[\frac{1}{K} - \frac{1}{K_S}\right] \qquad [1]$$

Where ε is the linear strain, S is the degree of saturation, P is the capillary pressure (kPa) in the pore fluid of porous material, K is the Bulk modulus of porous solid and K_s is the Bulk modulus of material that makes up the solid frame of porous material. Equation (1) is known to hold very well when the degree of saturation is 80% or more, but its accuracy decreases with decreasing degree of saturation (Mackenzie 1950). Therefore, it is anticipated that this equation should be accurate for matric suctions less than the AEV of porous material of proposed sensor.

The other values in Equation 1 may be determined from basic poroelasticity theory: K_s can be determined by:

$$K_s = 1 - \frac{E_s}{3\,(1-2\mu)} \qquad [2]$$

Where E_s and μ are the Young Modulus (kPa) and Poisson ratio of solid backbone of porous material from which sensor was made, respectively, with known values for the sensor material. The Bulk Modulus of porous material of Poroelastic sensor, K may be determined using:

$$K = K_s\left(1 - \frac{(3K_s+4G_s)c}{4G_s}\right) \qquad [3]$$

Where c is the porosity of the material and G_s is the Shear Modulus of material given by:

$$G_s = \frac{E_s}{2(1+\mu)} \qquad [4]$$

3 MATERIALS AND METHODS

3.1 Assembly of Poroelastic Sensor

The candidate porous material for design of sensor (name withheld for proprietary considerations) has good absorption properties, high mechanical strength, is chemically non-reactive and does not flake. The material has an internal surface area of $250m^2g^{-1}$, an approximate dry specific gravity of 1.5, porosity of 45.8, average pore diameter of 4 millimicrons and is opalescent in appearance. Also, the AEV of material was estimated from its average pore-size to be about 8000kPa using the Young-Laplace equation. The Elastic Modulus and Poisson ratio of the bulk constituent from which the porous material is made are 65GPa and 0.24, respectively.

An electrical resistivity strain gage was mounted on a thin cylinder of the porous material (Figure 1) after its surface had been prepared and conditioned to ensure proper bonding of strain gage. The strain gage was bonded onto porous material using adhesive and catalyst combination compatible with the strain gage and left to cure for about 1 hour before attachment of lead wires.

Two thin enamel-coated tin wires were soldered onto terminals of bonded strain gage, with other two ends of attached lead wires soldered onto tabs previously mounted on a cap pre-installed on one end of porous material (for easy handling of sensor). To adjacent ends of the tab were soldered a length of wire to be connected to a strain indicator. The exposed surface of the strain gage was then water-proofed by applying a thin and even layer of molten wax. The installed strain gage was thereafter tested in order to ensure proper installation using Model 1300 gage installation tester (Intertechnology, Don Mills, ON). The Poroelastic sensor (Figure 1) was connected to a 3800 Wide Range strain indicator (Vishay Measurements Group, Raleigh, NC), setting the gage factor to that of the strain gage attached to poroelastic sensor and properly zeroing the strain indicator.

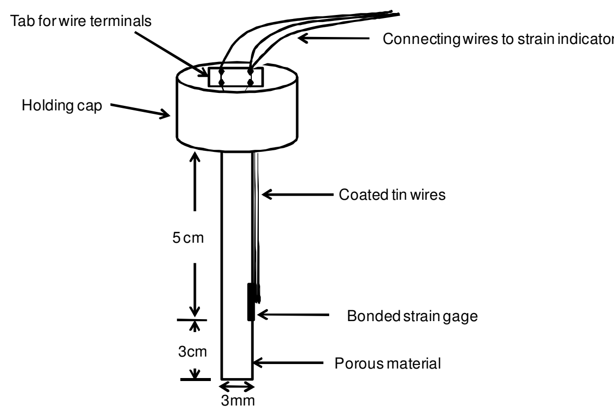

Figure 1. Schematic of Poroelastic sensor after construction and coating

The Young Modulus, E of the bulk sensor was also determined by tracking the strain observed when a given load is placed on a length of the saturated material, given as:

$$E\ (\text{kPa}) = \frac{\text{Axial Stress}}{\text{Axial Strain}} \qquad [5]$$

During the course of our investigations, it was found that using this E to calculate K directly (from equation 2) before substituting in equation (1), rather than calculating K from K_s and E_s (from equation 3) gave more accurate predictions at higher values of matric suction. It is not surprising that using the actual bulk modulus, rather than the bulk modulus calculated from the stiffness of the backbone material obtained from the literature, gave a more accurate prediction.

3.2 Shrinkage Curve, Estimated SWCC, Saturation, Drying and Resaturation Tests of Poroelastic Sensor

The shrinkage curve of porous material of sensor was determined by tracking the changes in moisture content of previously-saturated material as well as indicated strains as it dried on a weighing scale (Figure 2). Volume change measurements were converted to matric suctions using previously-discussed equations to generate an estimated SWCC. It was observed that the AEV of porous material is indeed approximately 7 - 8 MPa.

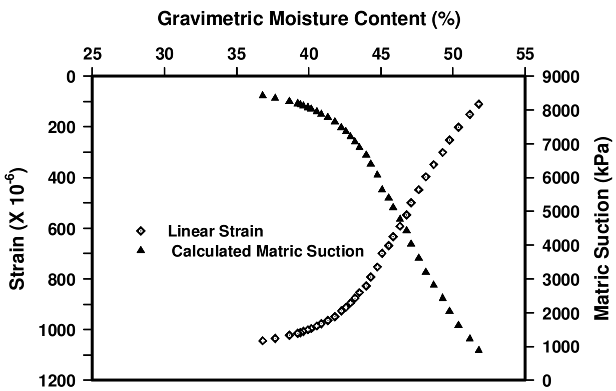

Figure 2. Drying curve and estimated soil water characteristic curve of porous material in Poroelastic sensor

The poroelastic sensor was tested for repeatability by initially saturating the sensor under applied vacuum inside a desiccator, and subsequently subjecting it to repeated cycles of drying and wetting. “Wetting” involved sticking the exposed tip of poroelastic sensor inside distilled water in a beaker and monitoring the change in strain with time until change in strain approached zero. The prototype was then taken out of water, left to stand in ambient air while change in strain was also monitored until the change in strain approached zero. This wetting and drying test was repeated over three cycles and the result is presented in terms of strain and matric suction calculated using the poroelasticity equations (Figure 3). It was promising to note that the prototype returns to the same reference strain upon rewetting, showing no evidence of hysteresis for this range of matric suctions, which are well below the estimated AEV of the porous material. It is also interesting to note the decrease in the rate of drying as the calculated matric suction approaches 4000 kPa. This value of suction corresponds to when the relative humidity at the surface of the poroelastic sensor would begin to drop and Stage II evaporation would commence (Wilson et al. 1991).

3.3 Application of Poroelastic sensor in Artificial Silt and Gold Tailings: Comparison to Tensiometer, Axis-translation Technique and Psychrometer.

The proposed matric suction sensor was deployed to measure the matric suction of a test material. The test material chosen is artificial silt-sized glass beads, an inert material which had been previously characterized by Fisseha et al (2007), with its geotechnical properties and particle size distribution shown in Table 1 and Figure 4, respectively. The artificial silt was prepared at a gravimetric water content of about 30% and placed inside an open aluminum container with dimensions as shown in Figure 5. The poroelastic sensor and a previously-saturated T5 Tensiometer (UMS) were both inserted to the same depth (3cm) inside the artificial silt, with the T5

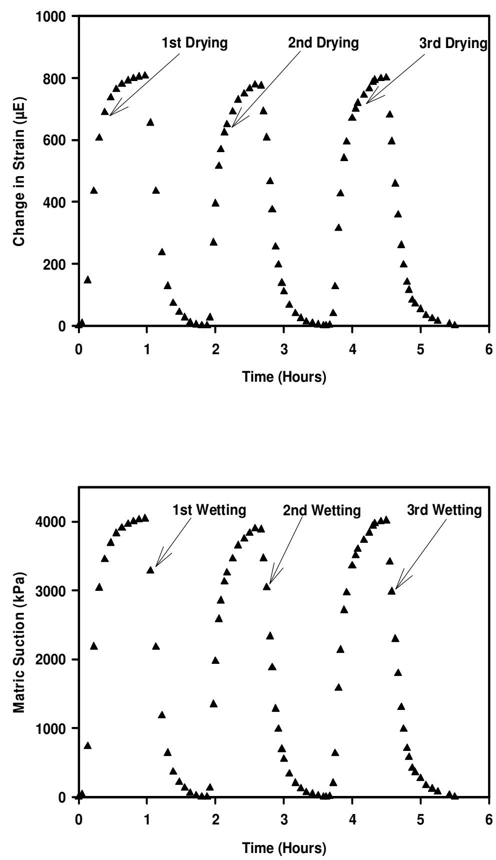

Figure 3. Repeated wetting and drying cycles of Poroelastic sensor in terms of strains and matric suction

tensiometer connected to a multi-meter for reading the matric suction of test material (Figure 5). The change in strain on Poroelastic sensor and tensiometer readings were concurrently monitored over time until the latter failed and cavitation was observed at around 80kPa.

Table 1. Geotechnical properties of artificial silt and gold tailings (from Fisseha et al. 2007 and Simms et al. 2007)

Property	Silt	Gold Tailings
Specific Gravity	2.48	2.9
D_{10}, D_{50}, D_{60} (micron)	1, 31, 41	2, 35, 55
D_{60}/D_{10}	41	27.5
Liquid limit (%)	19	20
Plastic limit (%)	13	19
Shrinkage limit (%)	-	20
K_{sat} (m/s)	1.7E-6	2.0 E-7

Also, the Poroelastic sensor was employed in gold tailings, with geotechnical properties shown in Table 1. The experimental set-up is similar to that previously described for the artificial silt, but with the initial gravimetric water content of tailings being 32%. The matric suction of drying tailings was determined over time using previously-saturated T5 Tensiometer (UMS) and poroelastic sensor.

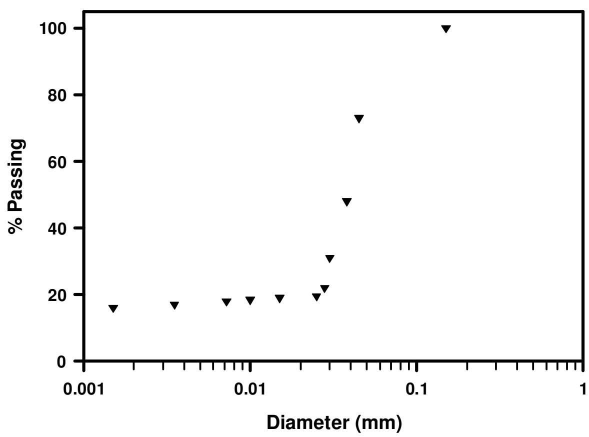

Figure 4. Particle size distribution of artificial silt (from Fisseha et al. 2007).

In addition, the performance of poroelastic sensor in the artificial silt was also compared with matric suctions established using axis-translation technique. Set up for the axis translation technique is similar to the one described in Oliveira and Fernando (2006). Starting from a gravimetric moisture content (GMC) of about 30%, artificial silt was placed inside air-tight axis translation cell (AEV of ceramic disk being 500kPa) and a 50kPa air pressure was imposed until the air pressure is in equilibrium with the pore-water pressure, at which point the water level in a burette attached to ceramic disk of cell remains constant. At equilibrium, the matric suction of test silt is equivalent to the applied air pressure according to

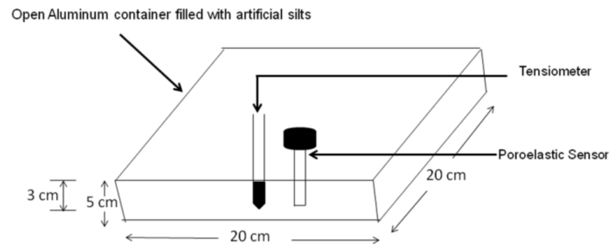

Figure 5. Schematic of drying test for silt and gold tailings for comparing Poroelastic sensor with tensiometer and psychrometer (Not drawn to scale).

principle of axis translation (Hilf, 1956). The matric suction of test silt at this point was determined from readings obtained when previously saturated poroelastic sensor was inserted into test silt after the air pressure has been bled from the axis-translation cell. The water content of the soil was maintained by detaching the axis-translation cell from its water reservoir prior to bleeding applied air pressure and taking sensor reading. This procedure was repeated for 50kPa increments until 300kPa air pressure had been applied. The matric suction values of test silt calculated using strain readings from poroelastic sensor was compared with suctions established by axis translation over time.

The drying soil water characteristic curve (SWCC) of artificial silt was also determined using both the Poroelastic sensor and WP4 Dewpoint PotentiaMeter (Decagon Devices Inc., Pullman WA). The silt was prepared at gravimetric water content of about 33% at the start of drying test. The set-up for the drying test is similar to what was previously described in Figure 5, except that at each sampling event, about 5g silt sample was taken for determination of matric suction using the WP4 Dewpoint PotentiaMeter. The gravimetric water content of the same 5g soil sample was determined by oven-drying method (placement at 105°C for 24 hours). The drying test was continued for several days until the AEV of constituent material of Poroelastic sensor was exceeded, after which the sensor was grossly underpredicting the matric suction of test material compared to the psychrometer. The soil water characteristic curves of the silt obtained from the two devices at the end of drying test was then compared.

4 RESULTS

4.1 Performance of Poroelastic Sensor on Artificial Silt and Gold Tailings.

The proposed poroelastic sensor compared well with other matric suction-measuring devices and technique when used on artificial silt. When the equation previously given (1) was used to convert strain recorded by poroelastic sensor to matric suction values, the matric suction values obtained over time were found to be highly correlated to values concurrently recorded by T5 Tensiometer (Figure 6), with R^2 value of 0.977. Compared to the standard Tensiometer, the poroelastic sensor slightly under-predicted matric suction values over the 20 - 40kPa range and over-predicted matric suctions above 80kPa (Figure 6).

Also, when tested in drying gold tailings, the matric suction values predicted from poroelastic sensor readings correlated well with values concurrently determined from Tensiometer (Figure 7). The matric suction values from both poroelastic sensor and Tensiometer showed good correlation until about 80kPa, when the Tensiometer had cavitated. Beyond 80kPa, matric suctions calculated from poroelastic sensor continued to increase as gold tailings continued to dry (Figure 7).

The matric suctions of drying silt calculated using strain readings from poroelastic sensor showed very high correlation (R^2= 0.98) with values established by axis-translation over time (Figure 8). The poroelastic sensor underpredicted the matric suction of silt at 50kPa and 300kPa pressure equivalents of the axis-translation technique (Figure 8). At other data points however, the poroelastic sensor either precisely or very slightly overpredicted the matric suction of silt when compared with values established by axis-translation (Figure 8).

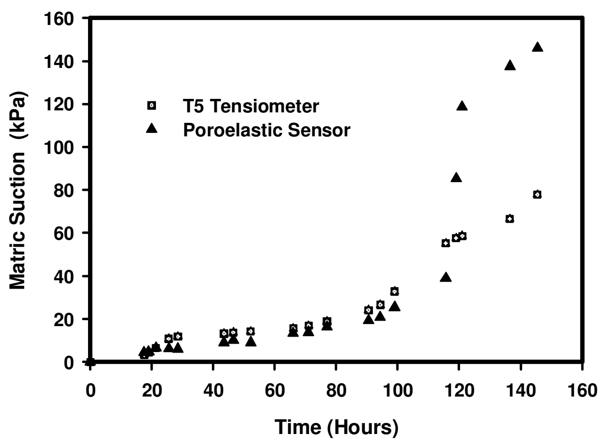

Figure 6. Matric suction values from poroelastic sensor and T5 Tensiometer in drying test for artificial silt.

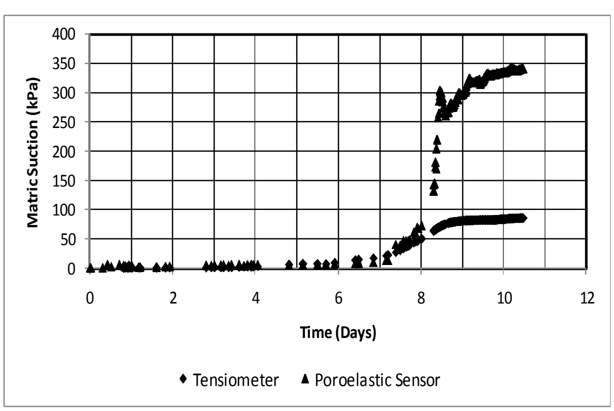

Figure 7. Matric suction values from poroelastic sensor and T5 Tensiometer for drying test of gold tailings.

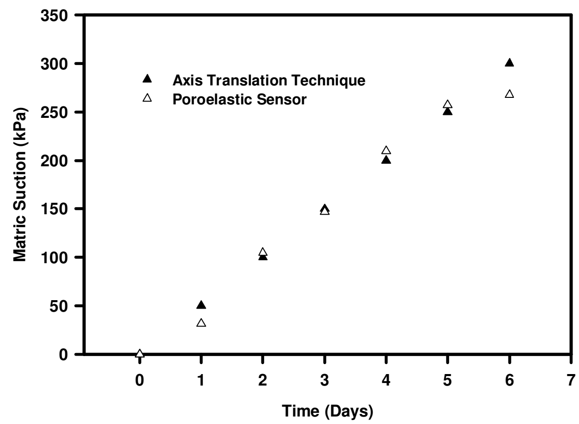

Figure 8. Matric suction values of artificial silt obtained using Poroelastic sensor and as established by axis translation over time.

The soil water characteristic curve (SWCC) of artificial silt obtained using both the poroelastic sensor and psychrometer (WPT4) is shown in Figure 9. Even though the psychrometer typically measures the total suction of test material, the suction values of silt determined in this study is matric since there is no osmotic component of total suction of silt, being a chemically- inert material. The SWCC of silt obtained using proposed sensor was very similar to that obtained using psychrometer (R^2 value of 0.821) as shown in Figure 9. Compared to values obtained from psychrometer, the poroelastic sensor underpredicted the

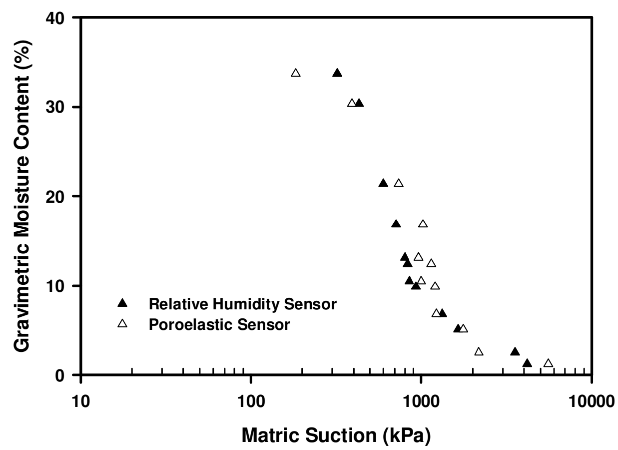

Figure 9. Soil Water Characteristic Curves obtained for 25-50 micron artificial silt using Poroelastic sensor and Relative Humidity sensor.

matric suction of silt at suction values lower than 400kPa, but slightly overpredicted the matric suction at suction values between 400 and approximately 1200kPa (Figure 9). However, the slight discrepancy between the 2 curves may be explained by the accuracy of the psychrometer being ±0.1 MPa for total suction determinations ranging from 0 to 60MPa. The Poroelastic sensor was capable of predicting matric suction values as high as 5500kPa (Figure 9), but for matric suction values beyond its AEV (8000kPa), the sensor grossly underpredicted the matric suction of silt as determined using the psychrometer, as expected (data not included).

5 DISCUSSION

Matric suctions measurements by the prototype poroelastic sensor described in this paper compares well with simultaneous measurements with a standard tensiometer and psychrometer, as well as with suctions established using axis-translation. The laboratory determinations suggest that the proposed sensor has a range at least up to 5500 kPa. In addition, the applicability of the poroelastic sensor was demonstrated in artificial silt as well as in gold tailings. However, there are potential limitations that may need to be addressed in further iterations of sensor design. One limitation to the use of this Poroelastic sensor is that the porous material of sensor is prone to breaking if not properly handled. There is also the need for good contact between the exposed tip of Poroelastic sensor and test material for easy and rapid equilibration. Further investigation is underway to improve the performance of Poroelastic sensor in order to minimize these limitations.

As the Poroelastic sensor is deformable, soil-structure interaction may affect measurements, especially if the sensor is placed relatively deep into the soil: the response of the sensor in this condition is a function of effective stress and stiffness ratios between the sensor and the soil. The authors are presently constructing a modified sensor that has a porous stiff cap on the exterior which may eliminate this problem. The effect of porous material pulling away from soil upon contraction may not be significant on the sensor's compatibility with soil considering the scale of strain (microstrains) being measured.

Irrespective of whether moisture exchange between soil and sensor is in liquid or vapor phase, strain is sensed by poroelastic sensor. Thus, for the application in artificial silt, there is no osmotic component of total suction and suction measured by sensor is matric. For the gold tailings however, there is a significant osmotic suction (~100 kPa before drying begins). It is possible, as it is for all porous material based sensors, that when continuity of the water phase between the sensor and the soil is broken, the sensor will read total suction. The point at which this occurs, for any sensor, is not yet known.

Temperature may also deform the Poroelastic sensor. Under the prevailing laboratory conditions for this study, no significant response to variation in temperature was observed. However, the authors are continuing to investigate the performance of the sensor under more variable climatic conditions.

6 CONCLUSION

A new type of matric sensor, the poroelastic sensor, is proposed in this paper. Preliminary laboratory comparisons with other methods have shown promise, and the new sensor appears to have a good range (up to 5500kPa) as applied on artificial silt and gold tailings. The poroelastic sensor compared favorably with standard Tensiometer, axis-translation technique and psychrometer when tested on artificial silt. Also, when tested on gold tailings, matric suction values obtained from poroelastic sensor and tensiometer showed good correlation. The new sensor was simple to design and relatively inexpensive in terms of the total cost of components. On a theoretical basis and from observations made so far with the newly-designed poroelastic sensor, it is not affected by cavitation, and it promises to have long-term reliability, with no need for constant renewal. Further studies to improve the performance of the poroelastic sensor are underway.

ACKNOWLEDGEMENTS

GCTS Testing Systems is gratefully acknowledged for the support for this project. Scholarship funding for first author from Natural Sciences and Engineering Research Council of Canada (NSERC) is highly appreciated.

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