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Toward a new technology for monitoring of pore pressure using MEMS pressure sensor

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Abstract

Pore water pressure monitoring is an important task in mining and civil engineering projects. The success of monitoring results is partly driven by the reliability and performance of the installed instrument in terms of simplicity, accuracy, conformance, precision, stability, and installation process. Despite recent developments in sensing technology, pore pressure monitoring instruments remain less advanced compared to other types of geotechnical instruments. Technological advances in recent years provide an unique opportunity to have new instruments which are cheap and more accurate. Micro-Electro-Mechanical Systems (MEMS) technology is a relative newcomer in the field of geotechnical monitoring, which has shown promising results for current in-situ operational challenges ranging from ground deformation to geo-structural health monitoring. MEMS sensors are tiny, cheap, and able to provide advanced, low-cost, robust, and real time sensing measurements. However, in most practical applications of MEMS-based instruments, there is a large difference between the predicted and actual performances due to the error induced during the manufacturing process. MEMS sensors show different types of errors that require specialised test equipment and thus high-test costs to propose a reliable calibration technique. In this paper, the basics of MEMS pressure sensors are briefly discussed, and the laboratory results of a newly developed piezometer based on a MEMS piezoresistive pressure sensor are discussed.

Keywords: Pore pressure monitoring, MEMS Technology, MEMS piezometers, Sensor calibration, Geotechnical Instrumentation

1. Introduction

Pore pressure distribution and magnitude provide a measure for stability and failure analysis in ground engineering designs. Pore pressure data also provides an indication of the depth of the groundwater table, which is very important for hydrogeologists to determine the properties of an aquifer (McMillan *et al.*, 2019) and for geotechnical engineering to find the depth of the unsaturated layers (Nistor *et al.*, 2020).

The success of monitoring results is dependent on the reliability and performance of the sensor. At present, vibrating wire piezometers (VWPs) are common for the long-term in-situ measuring of pore pressures. However, their components are prone to corrosion and creep under constant tension (Zhu, Shi and Zhang, 2017; Iskander, 2018). Additionally, the size and cost of these devices restricts the number of piezometers in a borehole, which is problematic since the properties of geomaterial are heterogeneous. Moreover, geotechnical instrumentation is now moving towards using wireless sensors and wireless network systems (WSNs) to reduce the cost of monitoring, and complexity of installation (Sabato, Niezrecki and Fortino, 2017). To date, there is no VWP that has been developed with this capacity. Therefore, there is a need to apply new technology.

Fibre-optic and MEMS sensors are gaining attention for in-situ geotechnical monitoring. MEMS technology has been successfully introduced in geotechnical monitoring for ground deformation and ground vibration sensing (Barzegar *et al.*, 2022). Benefiting from a low sensing cost and their small size, MEMS-based instruments are able to provide real-time dynamic measurements, low energy consumption, higher reliability, and simpler installations compared to traditional monitoring equipment (Barzegar *et al.*, 2022). In this study, a MEMS piezometer has been developed and results from laboratory installations are presented to provide an indication of the technologies reliability and accuracy.

2. MEMS Technology & Pressure Sensing

MEMS technology refers to a class of small devices ranging in size from millimetres to microns that combine electronic and micromechanical components on a single substrate, most frequently silicon. The use of silicon makes it possible to batch fabricate inexpensive and high-functioning microsensors with a very low coefficient of thermal expansion and high resistance to compression and dynamic shock (Petersen, 1982). The integration of electrical and mechanical components using IC batch fabrication also provides the following hardware benefits:

- tiny device size ranges from microns to millimetres
- high resolution, sensitive and precise measurements
- large batch quantity fabrication of sensor and actuator components
- lower consumption of energy and material
- ability to control large parallel sensor array
- highly resistant to vibration, shock and radiation

MEMS technology gain attention in geotechnical and mining engineering in the mid-2000s, with the goal of lowering monitoring costs while improving data accuracy and reliability. They showed pleasing results by enhancing accuracy and reducing the cost of operations in the form of seismic, tilt, flow, pressure, and strain gauge sensors (Barzegar *et al.*, 2022):

Pressure sensors are the most successful MEMS technology in the market and are designed for a wide variety of industries including biomedical, weather forecasting, and aerospace. They are available in three main measurement modes: absolute, gage, and differential; and three sensing techniques: piezoresistive, capacitive, and piezoelectric. Piezoresistive are the most popular due to their highly reliable batch-fabrication. They operate on the principle of piezoresistive effect, in which changes in the resistance of a conductive element provide a measure of the applied pressure (Bao, 2005).

3. Description of the MEMS Piezometer

A MEMS piezometer has been developed based the piezoresistive sensing technique and operates in the range of 0-100 psi (0–689Kpa) and over a temperature range of -40 °C to 150 °C (represented in Figure 1). It cost only 80 AUD with size of 8cm. For signal processing, the piezometer is equipped with an analogue-to-digital converter (ADC) with 10-bit resolution. It is a smart sensor based on the Internet of Things (IOT), where pressure data is transmitted over the internet. Real-time data is accessed through an IP address.

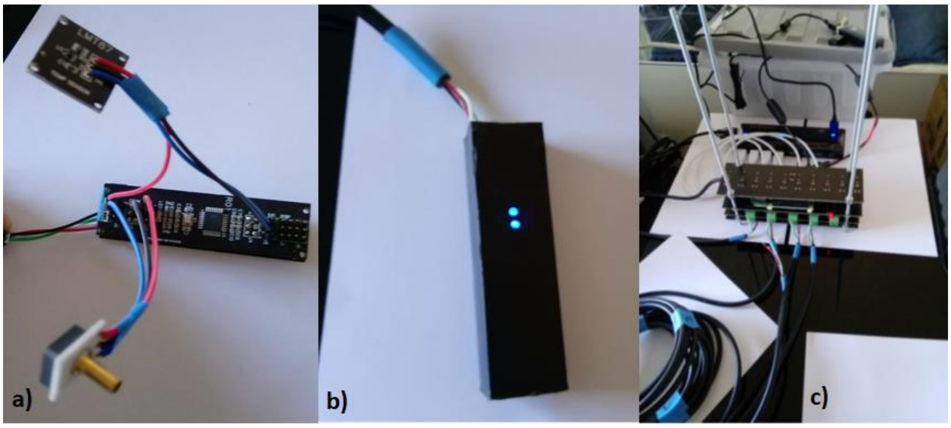

Figure 1: a) TR series pressure sensor (Merit Company, 2020) along with temperature sensor, b) MEMS piezometer encapsulated in clear polyurethane , c) data logger

4. Laboratory Tests and Results

To ensure accurate piezometric data readings, monitoring information must be evaluated in the context of the physical setting and the findings of the research phase (Eberhardt and Stead, 2011). Thus, a series of tests in a laboratory environment have been conducted before field installation to obtain a true understanding of how the developed piezometer responds to known pore pressure fluctuations. The process that was undertaken is described below.

4.1. Calibration

Calibration is a critical stage in the development of a measuring instrument. It is used to correct the sensor output signal to minimise instrument imperfections. In general, any instrument will encounter two types of errors: systematic and random (Joint Committee for Guides in Metrology, 2008). Random errors are unpredictable stochastic temporal and spatial fluctuations around the true value due to difficulty in taking measurements. These are almost impossible to correct, but can be minimised through repetition and averaging, which can improve the reliability of the result of an experiment. Systematic errors are predictable and are a result of uncertainty in the design of the instrument (Joint Committee for Guides in Metrology, 2008). They can not be eliminated easily, but it can be reduced using adequate calibration techniques. There are six systematic errors that must be considered when developing a measurement instrument (Horn and Huijsing, 1998):

Offset: occurs when the minimum (or zero) output signal is not matched with a minimum (or zero) physical input.

Gain: occurs when the maximum physical input signal does not match with the maximum electrical output signal.

Non-linearity: is a deviation of the output signal from a straight line over the full operating range of the sensor.

Hysteresis: is the maximum difference in the value of the output signal at the same pressure during a sequence of increasing and decreasing pressure loops.

Cross-sensitivity arises when another quantity such temperature affects the output signal.

Long-time drift: represents the gradual degradation of the output signal over time under normal operating conditions.

To obtain calibration parameters for each of the above systematic errors, the sensor needs to be excited with a physical stimulus, which requires specialized, expensive equipment. This is a significant issue for MEMS-based sensors that are cheap to manufacture but may be costly to calibrate. It is estimated that around 75% of the total cost of a sensor is associated with the calibration (Clark, 2018). Thus, the calibration techniques need to be carefully selected to justify the cost and time of operation.

The calibration test is conducted using a pressure calibrator, a pressure chamber, a multimeter, and personal computers. The effect of temperature was not considered at this stage. Since the drift error requires long-time monitoring (it may take 6 to 12 months), it is excluded from calibration. In general, drift error shows the robustness of instruments and gives an insight into the need to re-calibrate them.

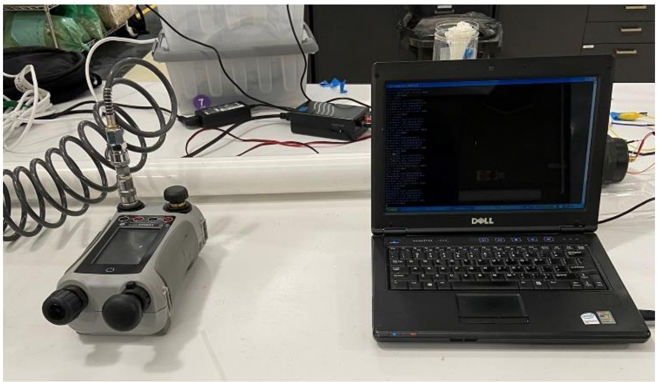

Figure 2: Calibration set up

Analysing the calibration data revealed the existence of gain, offset, nonlinearity, and hysteresis errors in outputs. However, the amount of hysteresis was not significant (below 0.5%) and was neglected. The calibration modelling is focused on gain, offset, and non-linearity.

4.1.1 Gain and offset calibration

Gian and offset errors are compensated by setting up measurements in zero and full span by defining offset and gain coefficients (Rivera, Herrera and Chacón, 2009). For this purpose, it is required to find the output of instrument for two measurement points of $x = [x_1, x_2]$. For input of x, the output is equal to (Rivera, Herrera and Chacón, 2009):

$$y_n = f(x_n) \qquad (1)$$

While the desired or target output is $t_n = f(x_n)$, the offset coefficient is computed by Equation (2):

$$k_1 = t_1 - y_1 \qquad (2)$$

Where the output y_1 , t_1 are actual and desired output at point x_1. Thus, the new input-output mapping function f_1 is defined by Equation (3):

$$f_1 = f(x_1) + k_1 \qquad (3)$$

If there is no offset error in y function, the amount of k_1 is zero and the equation f_1 is equal to y value. The point x_2 is upper limit that is taken to eliminate of the gain, if exist. The gain coefficient k_2 is obtained by (Rivera, Herrera and Chacón, 2009):

$$k_2 = \frac{(t_2 - f_1(x_2))}{f_1(x_2) - t_1} \qquad (4)$$

The new function without gain problem is defined as:

$$f_2 = f_1 + k_2(f_1 - t_1) \qquad (5)$$

The gain coefficient k2 is zero when gain error does not exist in y function and the equation f2 is equal to the equation f1.

4.1.2 Non-Linearity calibration

Calibration models for correcting non-linearity are based on providing a linearization function for pressure deviations over the full operating pressure range. To do this, measurement of the output signal is required at different points over the full pressure range and are implemented in the Polynomial Equation (6):

$$y = a_0 + a_1x + a_2x^2 + a_{n-1}x^{n-1} + a_nx^n \qquad (6)$$

Where y and x are normalized and applied pressure, the coefficient is constant of the pressure sensor. Polynomial equations can be solved via different methods such as Least Square (LS) and interpolation.

In MEMS-based instruments, the result of measurement is mainly dependent on the appropriateness of the calibration scheme and method. A low-cost calibration scheme may be beneficia since MEMS-based instruments usually use cheap microprocessors. This is achieved by choosing a small number of points in the full range. For this study, the nonlinearity error is corrected by mean of optimal Lagrange interpolation via choosing 6 measurement points, including endpoints in the full range of pressure measurement.

4.2. Calibration results

Generally there are no two MEMS sensors that are able to perform identically due to the nature of design, and sensor exhibits different output results (Clark, 2018). In this case, three MEMS piezometers are prepared, and the calibration results are compared (table 1).

	Offset coefficient	Gain coefficient	Mean of Absolute error before calibration (KPa)	Mean of percentage error before calibration	Mean of Absolute error after calibration (kPa)	Mean of percentage error after calibration (%)	Average error in water level (cm)
Piezometer A	5.537	0.018	11.77	4.787	1.020	0.460	10.40
Piezometer Y	6.878	0.015	15.60	5.949	1.116	0.541	11.38
Piezometer R	5.725	0.020	14.69	4.642	0.889	0.309	9.06

Table 1: calibration results: comparing three MEMS piezometers

The result from calibration confirms that each MEMS sensor provides a different degree of error. Although each MEMS sensor was chosen from the same manufacturing batch, the errors are significantly different. After calibration, the percentage error was reduced more than 10 times for each sensor. The percentage error represents the accuracy of piezometers. Piezometer R provides the highest accuracy at an error of 0.309 % after calibration. The accuracy of a VWP is 0.1% over the same range. This is a good outcome since the MEMs piezometer costs less than $80 AUD. It should be noted here that the calibration result is a result of the optimum interpolation technique applied. Other techniques (Polynomial curve fitting, linear piecewise polynomial, and Splines approximation) should be investigated to find the best possible outcome.

4.3. Test for accuracy and precision

To determine the precision and accuracy of the sensors, Piezometer A has been embedded in a column of water with height of 1.5 m (Figure 5). The pressure variation has been evaluated for a period of 1000 hours (6 weeks)

– both before and after calibration. The data acquisition system is programmed to take readings at an interval of 1 hour. The height of water for measurement was maintained to compensate for evaporation. The test followed the procedure for accuracy testing for vibrating wire piezometers conducted by (Choquet *et al.*, 1995). But, due to limitations on size and time, a shorter column size and timeframe are considered.

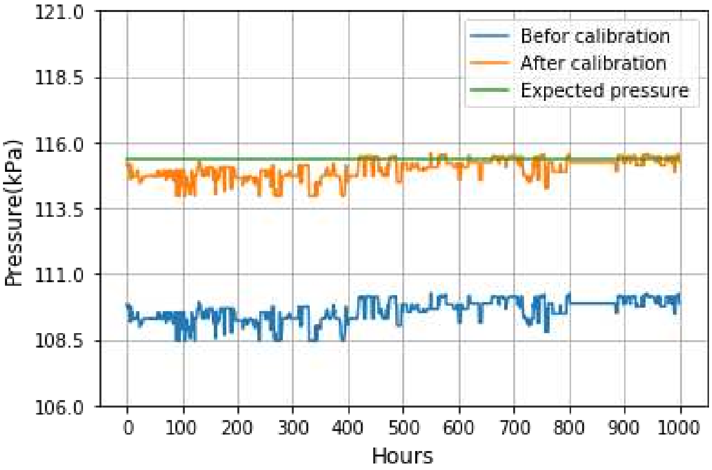

Figure 3: Piezometer A pore pressures measured over a period of 1000 hours in a 1.5m column of water

Figure 3 clearly shows that the piezometer provides more accurate results after calibration. The expected pressure for the 1.5m column of water was calculated based on the atmospheric pressure of 100.65 KPa (14.60 psi). The average amount of pressure after calibration was 114.975. This suggests a 0.372 KPa absolute error. Average pressure values before calibration were 109.583 KPa which means a 5.764 KPa absolute error prior to calibration. This represents a more than 11 time increase in accuracy achieved by the calibration process. Figure 4 shows the distribution of pressure data over the 1000 hours of the experiment for the calibrated response.

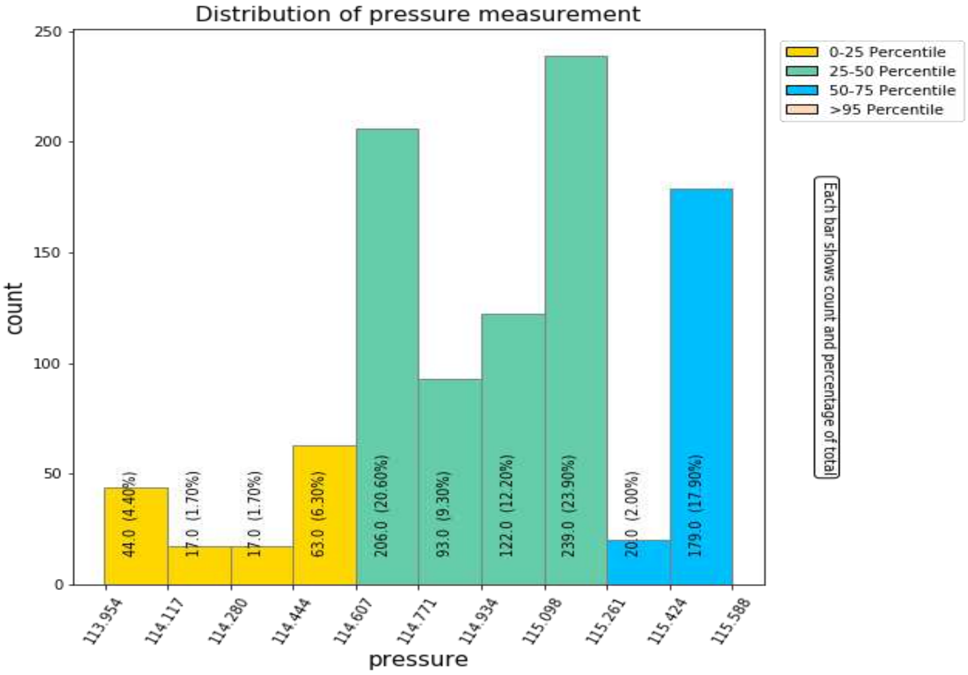

Figure 4: Histogram for precision & repeatability of piezometer A

The maximum deviation and standard deviation were 1.644 and 0.389 respectively. The maximum deviation represents the precision of the instrument. It should be noted that the precision is mainly affected by random errors. The results from Figures 4 shows that with increasing the number of readings the random error decreased as approximately 60% of the output was between 114.600 to 115.100 KPa which is a deviation of 0.500 KPa. Standard error represents the precision of measurement or repeatability. The outcomes presented in Figure 4 suggests high repeatability for piezometer A over 1000 hours of reading.

4.4. Performance Under Water Fluctuation

In this test, two MEMS piezometers (A and R) are placed in two 3.5-meter PVC tubes, and the sensor's performance is evaluated by gradually increasing and lowering the water level in the tube (figure 5).

Figure 5: Two standpipe tube for test performance of MEMS piezometer

The output of piezometer is examined at 6 different heights of water (100 to 350 cm), represented in Figure 7. For each level 6 readings are taken in an interval of 10 minute. The presented data is mean of these 6 readings.

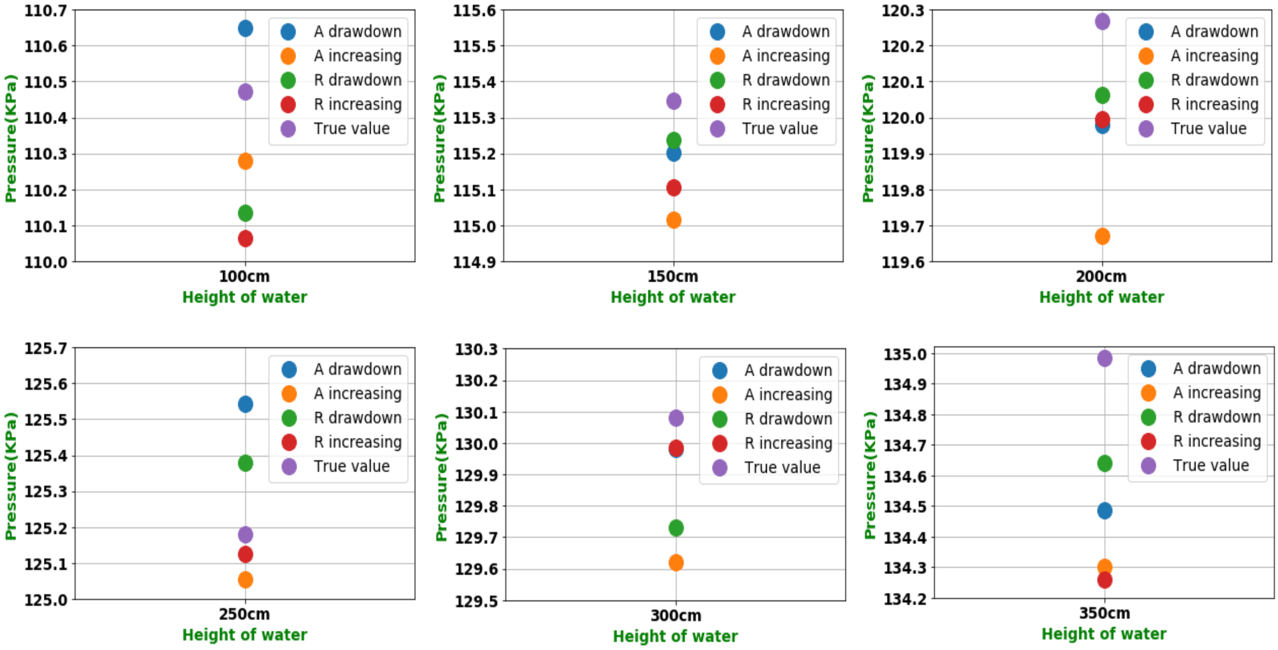

Figure 6: The piezometer performance at different water level

Figure 6 shows that the piezometers did not provide the same output readings for the same water level heights (both increasing and decreasing) which suggests they exhibit hysteresis. However, the severity of hysteresis is not significant and is not considered a concern. Piezometer R provides better accuracy with lower hysteresis compared to Piezometer A. The maximum hysteresis was 0.365 KPa for Piezometer R and 0.489 KPa for Piezometer A.

5. Conclusions

In this research, a series of laboratory tests are conducted to evaluate of the performance of new MEMS based piezometers that have been developed for down-hole pore water pressure monitoring. The results show that a reliable measurement is achievable if the systematic error is compensated though a calibration procedure. MEMS piezometer capable of providing precise measurement, but their accuracy is strongly depended on the calibration. The calibration can be conducted most efficiently when the types and magnitudes of errors are clearly identified. In this case, errors associated with offset, gain and nonlinearity are compensated for. Hysteresis was observed, however, the magnitudes considered negligible. The MEMS piezometer's performance in the laboratory under simulated downhole/in-situ sealed conditions is required next. Different materials such as gravel sand, bentonite-cement grout and cemented paste fill will be considered prior to field installations.

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