# Using MEMS based RH sensor to measure high total suction

## Utilisation de un capteur d'humidité relative basé sur la technologie MEMS pour mesurer de la succion totale élevée

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ABSTRACT

It is well known that suction is one of the stress state variables that control the behavior of soils and some porous materials. This paper presents a sensor based on Micro electromechanical systems (MEMS) technology that allows the detection of changes in relative humidity (RH) within the soil. By using thermodynamic concepts, the RH can be converted to total suction. The sensor delivers a quick response time, no hysteresis and it is not affected by temperature. The MEMS sensor exhibited a much faster response to changes in relative humidity (total suction) when compared with the non-contact filter paper technique. The MEMS sensor was also used to measure high total suction in two clayey soils and proved to improve the SWCC fit.

RÉSUMÉ

Il est bien connu que la succion est l'une des variables d'état de tension qui contrôlent le comportement des sols et des matériaux poreux. Le présent document présente un capteur basé sur la technologie des systèmes micro électromécaniques (MEMS), qui permet la détection des changements de l'humidité relative (HR) dans le sol. Considérant les concepts de la thermodynamique, les RH peuvent être convertis à la succion totale. Le capteur présent un temps de réponse rapide, pas d'hystérésis et le capteur n'est pas affectée par la température. Les capteurs MEMS ont montré une réponse beaucoup plus rapide aux changements de l'humidité relative (succion totale) par rapport à la technique du papier filtre sans contact. Les capteurs MEMS a également été utilisé pour mesurer la succion totale dans les sols argileux et par rapport à une courbe SWCC ajustée pour le sol.

Keywords: Total suction, relative humidity, MEMS, arid regions, saturated salts.

## 1 INTRODUCTION

It has been proven that many geotechnical challenges are related to the soil suction. Engineering structures that are affected by suction changes include: roads, nuclear waste disposal sites, landfill covers, foundations, and slopes, among others. In many countries, developers in areas with high water deficit face the challenge of designing for soils that present very small amount of water (extremely high suction) and high range of temperature changes. These changes are difficult to detect by using available matric or total suction sensors, due to their limited range of workability. The available matric suction sensors usually measure a maximum suction of about 500 kPa (Agus and Schanz, 2005). Matric suction sensors can be categorized into direct and indirect methods. Direct methods have limitations on the range of suction they can measure (generally they can measure up to 1,500 kPa) and therefore, they are not suitable for field measurements in arid soils. Indirect methods, such as thermal conductivity or electrical resistivity sensors, not only have a limited range, but also are dependent on the high air entry ceramic stone used. These techniques are also limited to measurements up to 1,500 kPa. On the other hand, all the sensors available for measuring total suction are based on indirect techniques. The psycrometer is included in this category and it can measure total suction between 100 and 8,000 KPa. The psycrometer presents two problems for field measurement, both of them related to temperature variation due to changes in environmental conditions. One of the limitations is the relatively long equilibration time with the surrounding soil relative humidity for practical purposes. According to Ridley and Wray (1996), equilibration can take up to one day. The second limitation is its dependence to temperature fluctuations. Case studies reveal that variations larger than ±0.2°C affect the suction measurements. It is, of course, almost impossible to have isothermal condition in the field.

The need arises for a suction sensor capable of measuring extremely high values of suctions with low sensitivity to temperature fluctuations. An extensive literature review revealed that there are not sensors capable of measuring the whole range of suction encountered in arid regions (Siemens and Blatz, 2005). The sensor presented here is a MEMS sensor, originally developed to measure relative humidity. This paper describes the HMX2000-HT sensor in detail, modifications to accommodate for suction measurements, calibration and installation procedures. The testing of the sensor on two soil samples is also described. Finally, recommendations for future development of MEMS sensors for use in the geotechnical field are presented.

## 2 PREVIOUS ATTEMPTS TO MEASURE TOTAL SUCTION WITH RELATIVE HUMIDITY SENSORS

The theoretical concept of soil suction was developed in soil physics in the early 1900's. Soil suction can be measured in terms of the partial vapor pressure of the soil. The thermodynamic relationship between soil total suction and soil relative humidity can be written as follows:

$$\psi = -\frac{RT}{M_v}\ln(RH\% * 100) \tag{1}$$

Where $\psi$ is the total suction of the soil, $R$ is the ideal gas constant (8.314 J/mol-°K), T is the absolute temperature (°K), $M_v$ is the molar volume of water ($1.8\times10^5$ m$^3$/mol), and $RH$ is the soil relative humidity. Some experiments have shown the applicability of relative humidity sensors in the measurement of total suction (Albrecht et al. 2003, Siemens and Blatz, 2005 and Agus and Schanz, 2005). Albrecht et al. (2003) used a sensor

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that makes use of the resistance or capacitance of a polymer film to obtain suction measurements. Their research work showed that the sensor has minimal hysteresis and minimal temperature dependency. The sensor has mainly two disadvantages: it needs a special type of data logger to measure the capacitance which increases the cost of the data acquisition; and it does not keep control of the temperature, which is an important factor when measuring total suction as shown in Equation (1). Siemens and Blatz (2005) tested a relative humidity sensor for total suction measurements. This sensor makes use of silicon strain gauges placed on inert cellulose crystallite structure. The sensor was used successfully inside a triaxial specimen for infiltration tests. Finally, Agus and Schanz (2005) used a capacitive relative humidity sensor capable of measuring both relative humidity and temperature. The response time of the sensor was found to be within 20 to 40 min. span; however, the sensor measurements showed an opposite trend when it was compared with three other techniques that also measures relative humidity, especially at the lower scale range.

## 3 HYGRO-THERMAL MEMS SENSORS

There are several studies that have illustrated different types of MEMS relative humidity sensors (Lee and Lee, 2003, Alex and Govardhan, 2005). The HMX2000-HT used in this study is hygro-thermal, as it is capable of measuring both temperature and relative humidity. The sensor is a commercially available MEMS device, which makes use of shear stress principles for measuring water vapor. It consists of a thin polymer film deposited onto the top surface of four cantilever beams that are micro-machined from the surrounding silicon. The absorption and desorption of the water vapor causes the polymer to expand and contract along with the underlying silicon microbeam. Measurement of the voltage over the bridge is then calibrated with the relative humidity. The process is reversible and regenerative (Fenner et al. 1996) and the sensor is resistant to severe environmental stresses. In addition, the sensor can be easily connected to commercial data loggers which make it relatively inexpensive.

### 3.1 *Equilibrium Time*

It is well established that, if an aqueous solution of suitable concentration is enclosed inside a desiccator, the volume above the solution will equilibrate to a known relative humidity or known partial pressure of water vapor. In order to obtain different relative humidity values above the solution, saturated salt solutions or slurries were prepared. Saturated solution with an excess of solids maintain a very constant vapor pressure even under changing moisture conditions. The gain of water causes some of the solids to go into solution and loss of water causes some of the dissolved water to precipitate. Thus, considerable amount of water can be gained or lost by the soil or porous media, without changing the vapor pressure above it (Winston and Bates, 1960). Five salts were chosen as to meet the following criteria: a) able to cover a broad range of relative humidity values; b) salts were known to have minimal sensitivity of relative humidity above the salt slurry to temperature fluctuations; and c) salts were safe for handling. The salts used in the study along with their relative humidity values above the saturated salt slurry, at different temperatures, are shown in table 1. The values shown represent an average of those found in three main publications: the Union of Pure and Applied Chemistry for Calibrations (1999), Greenspan (1977), and Schneider (1960).

Table 1. Salt solutions and relative humidity at three temperatures

| t (°C) | ($K_2SO_4$) | (KCl) | (NaCl) | (MgCl) | (LiCl) |
|---|---|---|---|---|---|
| 15 | 97.84 | 86.0 | 75.40 | 33.54 | 11.31 |
| 22 | 97.18 | 84.47 | 75.40 | 33.13 | 11.31 |
| 35 | 96.65 | 83.25 | 75.07 | 32.3 | 11.31 |

The sensor was hanged above the salt slurry at a distance of 5cm. The test was conducted inside an environmental chamber with a controlled temperature of ± 0.1 °C. All tests were conducted at 22 °C. The desiccator was kept inside a cooler to minimize any possible temperature fluctuation.

In order to verify both the sensor response and the relative humidity equilibration times, the test was run for a period of 4 days. It was found that the time for equilibrium was about one hour regardless the salt solution used. The results can be observed in Figure 1 for the first one-hour period. The procedure was repeated using a smaller container. The results suggested that the equilibrium time for this setup was also of about one hour. Based on the observations, it was concluded that the air volume above the salt solution does not affect the equilibration time of the sensor.

It was reported by the manufacturer that the response time of the sensor is about 5 seconds. Based on the observations, it is believed that the time of salt vapor equilibration is different from the response time of the sensor. This means that the time of the equilibration shown in Figure 1 might actually be the equilibrium time of the salts vapor, and not the response time of the sensor.

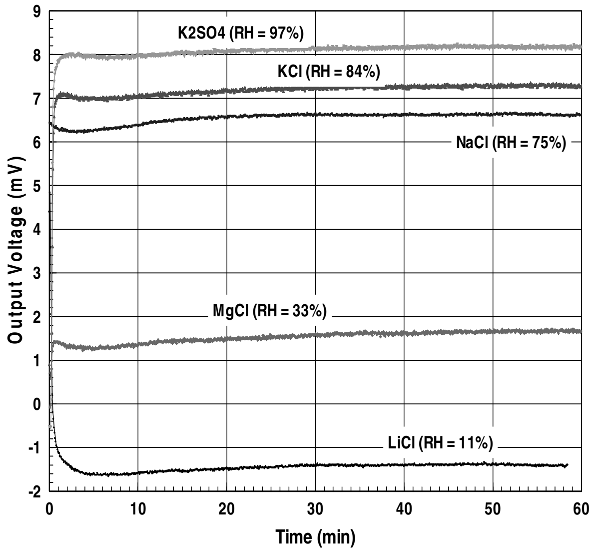


Figure 1. Sensor output versus equilibration time of RH imposed by different salt slurries

### 3.2 *Sensor Calibration*

The same data used for the evaluation of the equilibrium time was used to obtain the calibration curves for 10 sensors. The calibration data was obtained by measuring the output voltage and the relative humidity after the volume above the salt slurry had reached equilibrium. A polynomial model was fitted to the data obtained. It was found that each sensor requires an individual calibration curve. An example of such curve is shown in Figure 2.

### 3.3 *Temperature Sensitivity*

In order to evaluate the sensitivity of the sensor to changes in temperature, the sensor was hanged above the salt slurry inside the desiccator at a temperature of 15°C. The temperature was increased to 22°C and left for 24 hours until temperature and relative humidity equilibrated. Temperature was again increased to 35°C and left for 24 hours until equilibrium was attained.

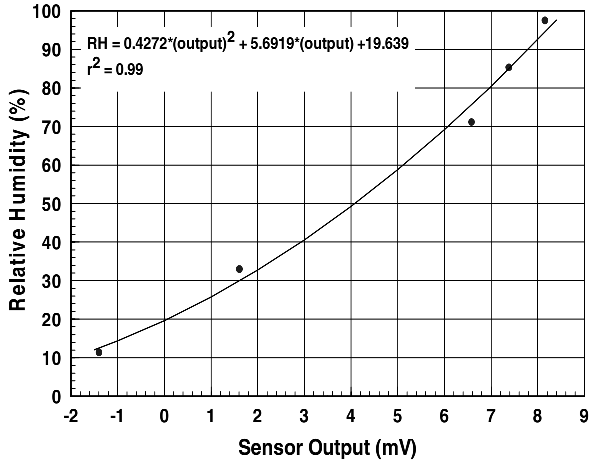


Figure 2. Calibration curve depicting the relative humidity for different salt slurry versus voltage output

The procedure was repeated for each salt and the voltage output plotted against the relative humidity for every temperature was obtained. The results are shown in Figure 3. The data shows small changes in relative humidity for different temperature values at the lower range. The temperature effect was found less significant in the higher relative humidity range.

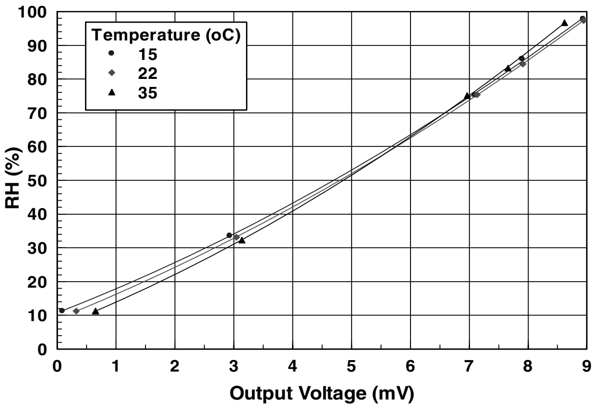


Figure 3. Temperature effect on sensor calibration curve

### 3.4 *Hysteresis*

A set of tests were conducted to assess whether the sensor exhibited appreciable hysteresis. A sensor was installed in a sealed container containing a salt solution of sodium chloride yielding a relative humidity of 75.4% at $22^0$C. After the reading stabilized, the sensor was placed in another container with a salt solution of lithium chloride yielding a relative humidity of 11.8% at $22^0$C. The test was repeated with solutions that impose different relative humidity values. The results are shown in Figure 4. It can be observed that the output voltage of the sensor above the same salt during drying or wetting was approximately the same at the same temperature. The observations imply that the sensor can measure the total suction during wetting and drying paths with relatively good accuracy and minimum hysteresis.

### 3.5 *Using "HMX2000-HT" sensor to measure soil total suction*

In order to verify the ability of the sensor to measure soil total suction, the sensor was used in two types of soils. The direct contact of the sensor with liquid water could reduce the sensor response time and therefore, it was necessary to use hydrophobic caps to keep the liquid water away from the sensor while freely allowing the vapor flow. The caps are shown in Figure 5a along with the sensor.

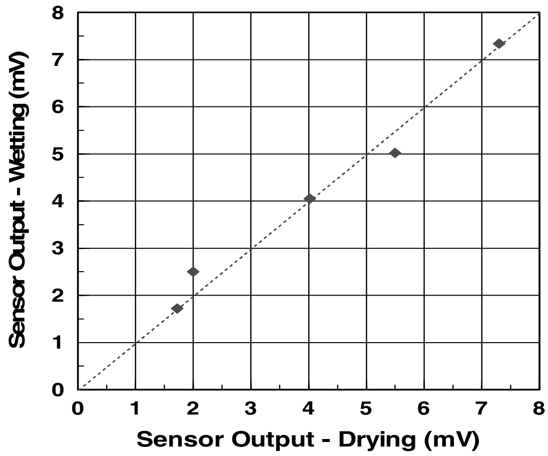


Figure 4. Voltage output of the sensors at drying versus the voltage output of the sensor at wetting

A simple test was performed to evaluate the effect of the cap on the equilibrium time. The cap was inserted into water to verify the hydrophobic characteristic. It was observed the water did not penetrate the cap while the sensor showed a quick increase in relative humidity. This simple experiment demonstrated that the cap allowed only the passing of vapor even though it was soaked in the water. The sensor was also tested with and without the cap in order to check if the cap affected the relative humidity measurements. It was noted that the sensor relative humidity measurements were not affected by the cap presence.

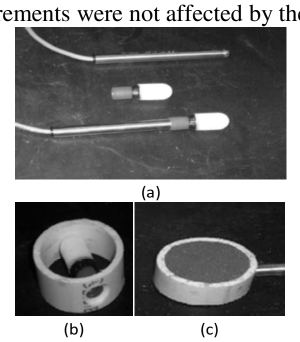


Figure 5. (a) HMX2000-HT sensor and hydrophobic caps (b) Hydrophobic caps inside compaction ring (c) Relative humidity sensor with cap inside compacted soil specimen and the compaction ring

### 3.6 *Using the MEMS sensor to measure soil total suction*

To evaluate the ability of the sensor to measure total suction, a comparison was made between the SWCC obtained by using the axis translation technique and the relative humidity sensor. Plastic rings of 40mm diameter and 25mm height with a hole in the ring side were fabricated, as shown in Figure 5b. The cap was placed in the hole and the soil was compacted around the cap. After allowing the sample to equilibrate for a 24-hour period, it was placed above a salt solution inside a desiccator. Two sensors were used: one inside the soil sample and another outside, in order to determine the time the RH imposed above the salt slurry would equilibrate in presence of the soil sample. The soil sample was then weighted after equilibrium was achieved to obtain the degree of saturation. The salts used were NaCl which imposed $\psi$ = 38,376 kPa at 22$^o$C and LiCl, which imposed $\psi$ = 296,337 kPa at 22$^o$C upon saturation. Two soils were tested; the first soil sample from Arizona State University East Campus, research park (ASU-East) was classified as silty clay to clayey silt (CL-ML), while the second soil was classified as silty sand (SM). Both, the relative humidity of the environment above the salt and the relative humidity inside the sample were tracked. Figure 6 shows that the relative humidity above the salt and inside the soil eventually came to equilibrium with the relative humidity imposed by the saturated salt.

Soil water characteristic curves (SWCCs) were obtained for both soils using a pressure cell. The axis translation technique was used to apply air pressure to the soil samples and the soil degree of saturation was obtained after equilibration was achieved. The degree of saturation was plotted versus matric suction ($u_a$-$u_w$) as shown in Figure 7. The data points were then fitted using the Fredlund and Xing fitting equation. It is important to note that the SWCC data is shown in terms of matric suction while the relative humidity measurements are related to total suction. The small differences between measurements obtained by the relative humidity sensor and the pressure cell are probably due to osmotic suction but further testing to validate this fact is undergoing.

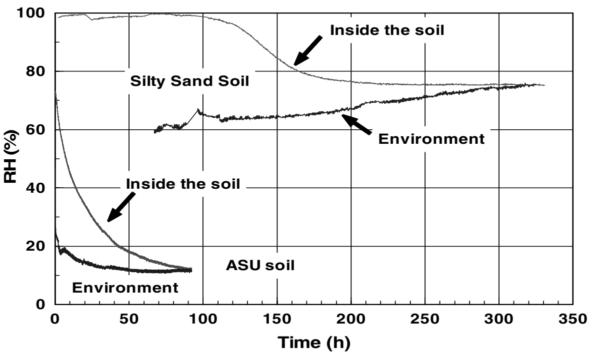


Figure 6. Comparison of the change in relative humidity above the salt slurry and inside the soils.

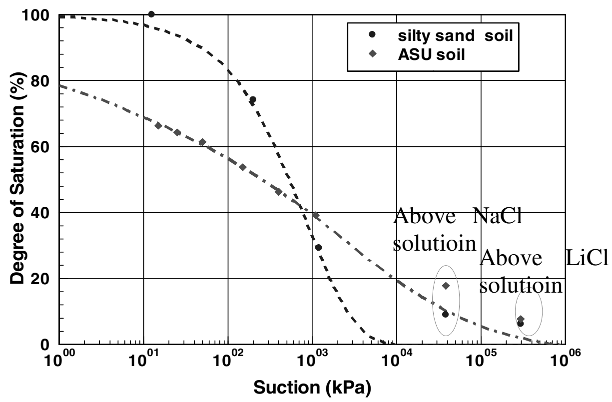


Figure 7. Soil-Water Characteristic Curves for the two soils used in the study, along with the relative humidity sensor total suction measurements.

## 4 CONCLUSIONS

The use of the MEMS relative humidity (RH) sensor presented in this study will enable to measure the total suction using the thermo dynamic relationship between relative humidity and total suction at a specific temperature (Equation 3.1).

The conclusions can be summarized as follows:

- The RH humidity sensor presented in this research study can be used for measuring the total suction in the field within a range of 3MPa to 300MPa.
- Calibration of RH sensors should not require more than one hour per salt solution used.
- The sensor is not significantly affected by temperature fluctuations. However, since temperature is simultaneously measured by the sensor, a correction factor can easily be applied.
- Results exhibited a minimal hysteresis with respect to the drying and wetting paths.
- The sensor exhibited a simultaneous response to the change in the relative humidity.

The effect of the presence of a porous material above the salt for two different soils was investigated. The following results were observed:

- In the presence of an absorbent material, the equilibration time increases and it is dependent on the volume of the absorbent material.
- The ASU soil (CL-ML) took a longer equilibration time along the drying path than along the wetting path; however, the results obtained showed no effect of hysteresis for practical purposes.

These results are preliminary and therefore, further studies need to be performed to validate the presented results.

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