Visakhapatnam Chapter

*Proceedings of Indian Geotechnical Conference 2020*
*December 17-19, 2020, Andhra University, Visakhapatnam*

# Performance of an Electromagnetic Sensor for Field Monitoring of Volumetric Water Content in Water Absorbing Polymer Amended Soil

Abhisekh Saha[1], Sreedeep Sekharan[1] and Uttam Manna[2]

[1] Department of Civil Engineering, Indian Institute of Technology Guwahati, Assam-781039, India, abhisekh@iitg.ac.in & srees@iitg.ac.in

[2] Department of Chemistry and Center for Nanotechnology, Indian Institute of Technology Guwahati, Assam-781039, India,
umanna@iitg.ac.in

**Abstract.** Water absorbing polymer (WAP) is gaining a lot of attention because of its potential applications in agriculture, green infrastructure, and ecological restoration of arid lands. Because of its higher water absorbency (more than 100 times its weight), the application of WAP can increase water retention characteristic (WRC) of soil. Accurate measurement of volumetric water content (VWC) of the polymer amended soil is essential to measure the WRC of soil and appraise those observations. The utilization of electromagnetic (EM) sensor (such as ECH$_2$O 5TM) for the determination of VWC, is common practice in different geo-environmental projects. The accuracy of this sensor for the measurement of VWC in WAP amended soil needs to be ascertained before deploying it in the field. The objective of this present study is to evaluate the performance of the EM sensor for the measurement of VWC in WAP amended soil. For this purpose, an experimental methodology has been proposed under controlled laboratory conditions using a cohesionless soil with four different concentrations (0, 0.1%, 0.2%, and 0.4% on w/w basis) of WAP. The accuracy of the EM sensor is found to be very good in the case of bare soil. However, with the increasing concentration of WAP, the error in the VWC measurement also increases. Two different approaches, including polynomial calibration and linear calibration, were proposed to calibrate the EM sensor for accurate measurement of VWC in WAP amended soils. The results indicate the significance of material-specific calibration of the EM sensor for improving the measurement accuracy.

**Keywords:** Water absorbing polymer (WAP), ECH$_2$O 5TM sensor, dielectric permittivity, calibration, soil amendment.

## 1 Introduction

Water absorbing polymer (WAP) are crosslinked three-dimensional (3D) network with various hydrophilic groups (such as carboxyl, hydroxyl, amide) attached to its polymeric structure [1-3]. Due to the presence of hydrophilic groups, WAP can absorbs water/solute molecules more than 100 times of their own weight [4,5]. The application of WAP could be very effective for different geo-environmental problems such as bioengineered slope stability, urban green infrastructure, landfill covers where the development of plant root is an essential parameter for the stability of these projects. In addition, WAP was proven to be an efficient soil amendment material for dryland farming and mitigating the negative impact of water stress conditions [6]. In most of these applications, a real-time field monitoring of the soil-water retention curve (SWRC) of the amended soil is very important to appraise the efficacy of WAP as an amendment material. Continuous and accurate measurement of soil volumetric water content (VWC) is necessary to establish the SWRC in field conditions. It is quite explicit form the literature [7,8] that the non-destructive VWC ($\theta$) measurement is always preferable than the conventional water content measurement, which is destructive and time-intensive, and hence may not be suitable for field conditions.

There are several sensors available in the market for real-time field monitoring of VWC in applications such as agriculture, water resource management, hydrology, waste management, and slope stability [9,10]. Most of the available sensors work on the concept of electromagnetic wave propagation to measure different soil properties such as dielectric constant, electrical conductivity, impedance or electrical resistivity, and indirectly correlate these properties with VWC of soil using some calibration equation [11]. Therefore, the accuracy of these electromagnetic (EM) sensors largely depends on the accuracy of these factory calibration equations. It was observed from the literature that the accuracy of the EM sensor could be affected by soil texture, salinity, temperature, clay content, soil mineralogy, bulk density, installation procedure, and measurement range [12-14]. Several past studies have highlighted the significance of soil-specific calibration for accurate measurement of VWC using EM sensors [15-17]. However, there are not many studies that reported the accuracy of the EM sensors for WAP amended soils. Moreover, there are no guidelines available in the literature related to the corrective procedure for accurate VWC measurement in field conditions for WAP amended soil.

The present study aims to evaluate the performance of an EM sensor (ECH$_2$O 5TM) for real-time field monitoring of VWC in WAP amended soil. The amended soils are often exposed to the real climatic conditions and undergo cyclic changes in VWC, influencing its hydraulic characteristics. Hence, it is necessary to verify and improve the accuracy of the EM sensor before employing it in the field. For this purpose, a simple experimental methodology was proposed for performance evaluation of EM sensor in a cohesionless sandy soil with three different WAP concentrations (0.1%, 0.2%, 0.4% on w/w basis). Based on the experimental results, a correction factor was proposed for the accurate measurement of VWC using the EM sensor based on a material-specific calibration procedure.

## 2 Materials and methodology

### 2.1 Materials

A locally available cohesionless soil (BS) was collected from Brahmaputra river bank located at Kamrup district, India. It is reported in the literature that the performance of WAP is better suited for cohesionless soil as compared to fine-textured soil [18]. Hence, the performance of the EM sensor was also evaluated in cohesionless sandy soil. The collected soil was characterized for its basic geotechnical properties, including specific gravity, particle size distribution, plasticity following the guidelines provided in ASTM codes [19-21] and presented in Table 1. Based on these properties, the selected soil was classified as per the Unified Soil Classification System (USCS) [22] and the United States Department of Agriculture (USDA) standard [23] and included in Table 1.

**Table 1.** Basic geotechnical properties of the used soil

| Properties | Brahmaputra sand (BS) |
|---|---|
| Specific gravity | 2.62 |
| *Particle size distribution* | |
| Coarse sand (2-4.75 mm) | 14 |
| Medium sand (2-0.425 mm) | 40 |
| Fine sand (0.425-0.075 mm) | 38 |
| Silt (0.075-0.002 mm) | 8 |
| Clay (<0.002 mm) | 0 |
| Coefficient of uniformity (Cu) | 5.8 |
| Coefficient of curvature (Cc) | 1.4 |
| Plasticity | Non-plastic |
| USCS classification | SP |
| USDA classification | Sand |

A commercially available WAP (Stockosorb), supplied by SargaGreen, Kerela, India, was used in the present study. The chemical composition of the WAP includes partially neutralized crosslinked potassium polyacrylate (anionic nature). The basic characterization in terms of its water absorbing capacity, equilibrium swelling time, and composition of the used WAP was presented in Table 2. The functional groups of the used WAP were identified using Fourier transform infrared (FT-IR) spectroscopy operated in the range between 4000 $cm^{-1}$ to 450 $cm^{-1}$ and reported in Table 2.

**Table 2.** Basic characterization of the used WAP

| Parameters | Characteristics |
|---|---|
| Composition | Crosslinked potassium polyacrylate |
| Functional groups (FTIR analysis) | Hydroxyl, carboxyl |
| Particle size | 0.8 mm-1 mm |
| pH | 7.5-8.0 |
| Water absorbing capacity (g/g) | 282 (in distilled water) |
| Equilibrium swelling time (min) | 120 |
| Eco-compatibility | Non-toxic to human and plant |

## 2.2 Experimental methodology

An EM sensor, namely ECH$_2$O 5TM (METER Group, Inc., USA), was used in the present study for continuous measurement of VWC for WAP amended soil. The sensor measures the dielectric permittivity ($\varepsilon_a$) of the surrounding soil, which changes with the amount of water present in the soil [24]. The $\varepsilon_a$ value for water is 80, while for dry soil and air, it is around 4 and 1, respectively. This broad range of permittivity helps in measuring the VWC of soil from saturated state to dry state condition. The sensor is equipped with an oscillator working at a frequency of 70 MHz, which generates an electromagnetic field. The electromagnetic field charges the soil around the probe. This stored charge is proportional to permittivity and VWC and is measured by the copper traces of the prongs. The 5TM microprocessor outputs a value of $\varepsilon_a$ from the sensor, which was converted to the VWC by manufacturer calibration equation.

Prior to the VWC measurement, the collected soil sample was mixed with dry WAP at four different concentrations (0, 0.1%, 0.2%, 0.4% on w/w basis). The WAP amended soils were mixed with deionized water to prepare five different water content samples from a dry state to a relatively wet state. The soil samples were kept in a polyethylene bag for 24 h to ensure uniform distribution of water. Thereafter, the soil samples were packed at a specific bulk density in a PVC mold of 20 cm diameter, and the EM sensor was inserted horizontally at the center for VWC measurement (Fig. 1). The sensor was connected to Em50 datalogger, and the unprocessed raw data along with the measured VWC ($\theta_m$) was recorded. After the VWC measurement, the EM sensor was removed, and soil surrounding the sensor tip was taken for gravimetric water content (GWC) measurement. The accurate VWC ($\theta a$) was then computed from the GWC ($w$) and the dry density ($\gamma_d$) of the compacted soil using Eq. (1). All the measurements were repeated three times to ensure the repeatability of the data and the average value was reported.

$$\theta_a = \frac{w \times \gamma_d}{\gamma_w} \quad (1)$$

where $\gamma_w$ is the density of water.

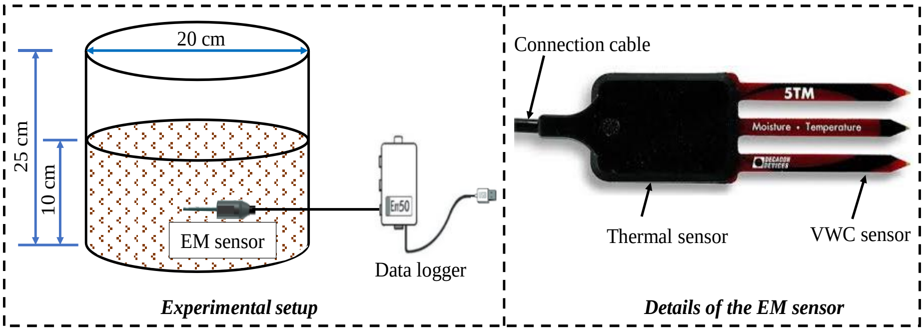


**Fig. 1.** Details of the EM sensor and experimental methodology used in the present study

## 3 Result and Discussion

The recorded $\varepsilon_a$ value and VWC ($\theta_m$) at five different water contents of WAP amended soil were presented in Fig. 2 to establish the factory calibration curve of the EM sensor. The experimentally obtained variation in $\varepsilon_a$ and $\theta_m$ was fitted to a third-degree polynomial with nonlinear regression analysis. The factory calibration curve of the EM sensor [with a regression coefficient value ($R^2$) close to unity] was presented in Eq. (2).

$$\theta_m = 3 \times 10^{-6} \times \varepsilon_a^3 - 5.5 \times 10^{-4} \times \varepsilon_a^2 + 0.03 \times \varepsilon_a - 0.063 \quad (2)$$

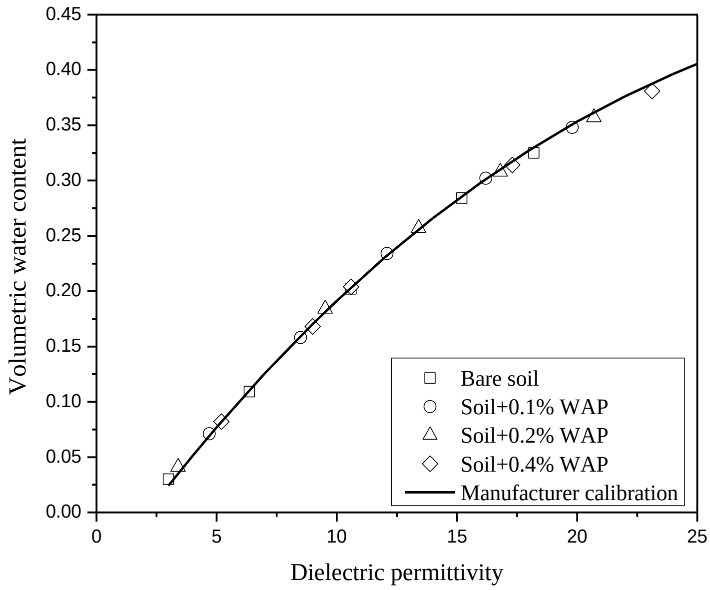


**Fig. 2.** Details of the manufacturer calibration curve of the EM sensor

Figure 3 depicts the EM measured VWC, and the accurate VWC (computed from Eq. 1) of the WAP amended soil at four different WAP concentration. It can be observed that the EM measured VWC and actual VWC are almost same for bare soil. However, with the increasing concentration of WAP, the EM sensor underestimated the VWC (i.e., data points are above the 1:1 line). The figure further indicated that the difference in VWC measurement is higher in the wet state as compared to the dry state. This could be attributed to the higher water absorbing capacity of WAP that may not be reflected during the permittivity measurement. Moreover, the swelling and water absorption behavior of WAP is very different than soil. In bare soil, the water retained in the soil matrix by capillary mechanism and surface adsorption phenomenon [25]. However, WAP particles absorb water due to the osmotic pressure difference between the polymer network and external solution [26]. These observations suggest a material-specific calibration of the EM sensor for different concentrations of WAP to minimize the error during VWC measurement. The calibration was performed in two ways, including (i) fitting a polynomial equation similar to the factory calibration curve to correlate accurate VWC and EM sensor measured permittivity value, and (ii) fitting a linear equation to the accurate VWC and EM sensor measured VWC.

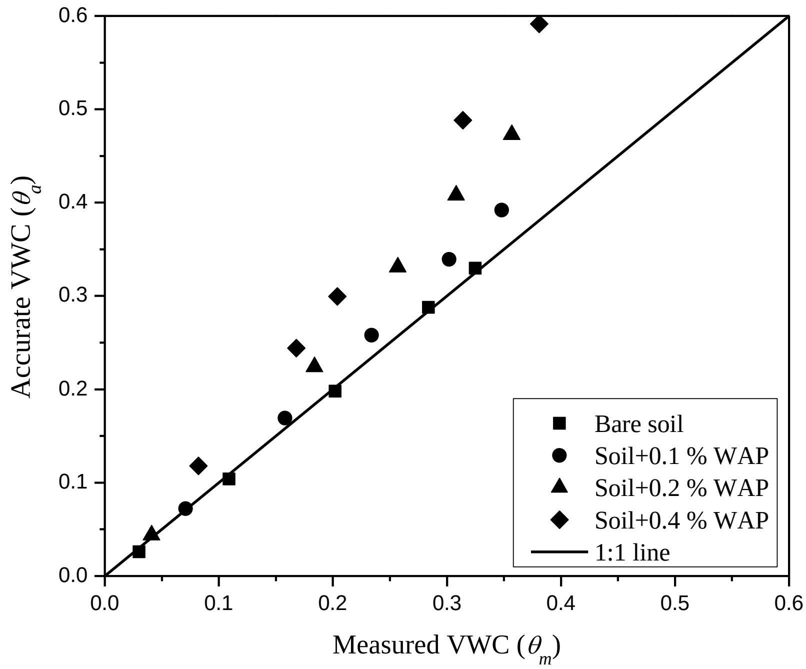


**Fig. 3.** Comparison of EM measured VWC with accurate VWC

In the first approach, a third-order polynomial equation (as presented in Eq. 3) was fitted to the accurate VWC and measured $\varepsilon_a$ and presented in Fig. 4. The obtained calibration parameters (*A*, *B*, *C*, and *D*) along with the regression coefficient ($R^2$) were reported in Table 3. These parameters can be directly used for field measurement of VWC in different concentrations of WAP using the EM sensor.

$$\theta_a = A\varepsilon_a^3 + B\varepsilon_a^2 + C\varepsilon_a + D \tag{3}$$

In the second approach, a simpler process was followed by fitting a linear equation (Eq. 4) to correlate the measured $\theta_m$ value and $\theta_a$ value (Fig. 5). It can be observed that all the fitted lines are passing through the origin, and hence, the value of y is equal to 0. The parameter *x* can be termed as a correction factor that needs to be multiplied to the EM measured VWC to obtained the accurate VWC.

$$\theta_a = x\theta_m + y \tag{4}$$

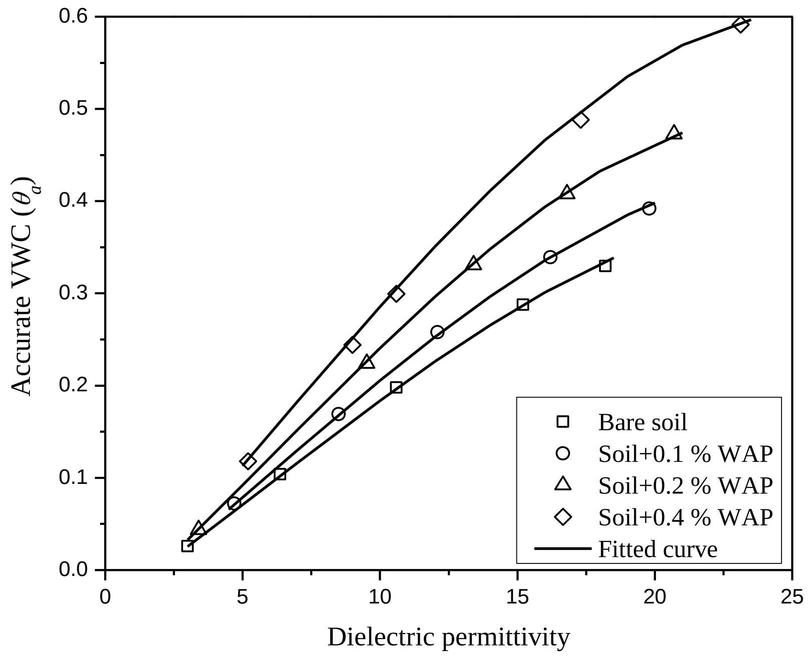


**Fig. 4.** Comparison of EM measured VWC with actual VWC

**Table 3.** Obtained calibration parameters for the bare soil and WAP amended soil

| WAP concentrations | A | B | C | D | $R^2$ |
|---|---|---|---|---|---|
| Bare soil | $-2 \times 10^{-5}$ | $3.5 \times 10^{-4}$ | 0.021 | -0.039 | 1 |
| Soil+ 0.1% WAP | $-2 \times 10^{-5}$ | $3 \times 10^{-4}$ | 0.024 | -0.048 | 1 |
| Soil+ 0.2% WAP | $-3 \times 10^{-5}$ | $5.5 \times 10^{-4}$ | 0.027 | -0.051 | 1 |
| Soil+ 0.4% WAP | $-3 \times 10^{-5}$ | $5.5 \times 10^{-4}$ | 0.032 | -0.055 | 1 |

The obtained correction factor ($x$) for different WAP concentrations were presented in Fig. 6, which showed a linear variation between the parameters. Therefore, a straight line was fitted to the data point ($R^2$ =0.99) to obtain the correction factor corresponding to any WAP concentrations. The obtained relationship between $x$ and WAP concentration was presented in Eq. (5), which can be directly used to determine the accurate VWC from the EM measured VWC.

$$x = 1.35 \times WAP\ concentration\ (\%) + 1 \quad (5)$$

The corrected VWC using the aforementioned two approaches were compared with the accurate VWC in Fig. 7 to verify the efficacy of the approaches. It can be observed that all the corrected VWC (using polynomial and linear calibration) and accurate VWC were lie on the 1:1 line, indicating both the approaches can be applied for field monitoring of VWC using the EM sensor.

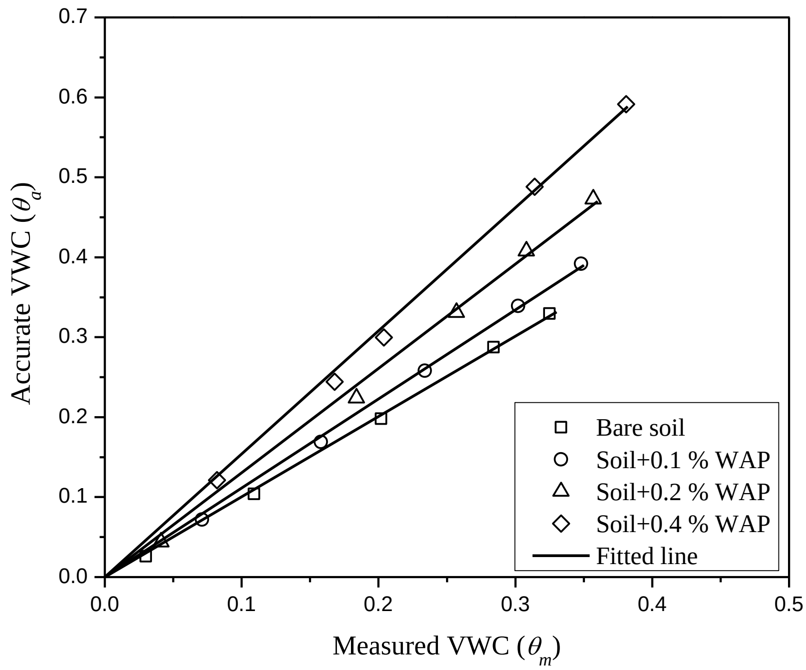


**Fig. 5.** Comparison of EM measured VWC with actual VWC

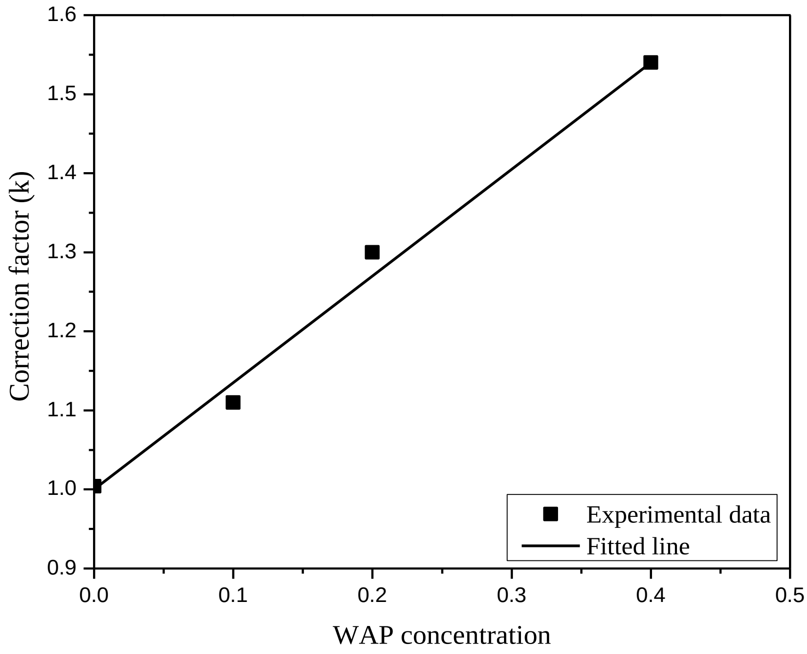


**Fig. 6.** Variation in correction factor with the WAP concentrations

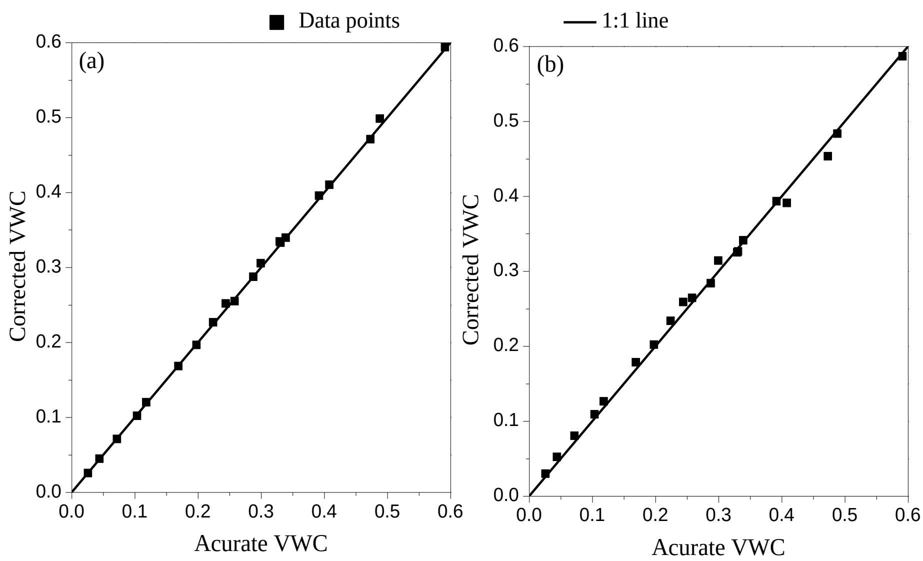


**Fig. 7.** Comparison of corrected EM measured VWC using (a) polynomial calibration and (b) linear calibration

## 4 Conclusions

The present study evaluates the performance of an electromagnetic (EM) sensor ($ECH_2O$ 5TM) for continuous field monitoring of volumetric water content (VWC) of water absorbing polymer (WAP) amended soil. The effectiveness of the manufacturer calibration equation for the EM sensor was investigated in a locally available cohesionless soil with four different WAP concentrations (0, 0.1%, 0.2%, and 0.4% on w/w basis). The experimental results indicated the EM sensor measured VWC matches the accurate VWC for bare soil, whereas the EM sensor underestimates the VWC in WAP amended soil (i.e., manufacturer calibration equation may not valid for WAP amended soil). The error in measured VWC was higher on the wet side as compared to the dry side. The higher water absorbing capacity of WAP could be a possible reason for this error during the EM sensor measurement. Two different approaches, including polynomial calibration and linear calibration, were demonstrated in the present study to calibrate the sensor for accurate measurement of VWC. Both the material-specific calibration procedures were very effective and can be used for continuous field monitoring of VWC in WAP amended soil. However, the linear calibration approach was found to be more simple and robust, as compared to the polynomial calibration approach. A similar methodology can be repeated for a wide range of soil texture to obtain soil-specific calibration equations for WAP amended soils.

## References

1. Saha, A., Rattan, B., Sreedeep, S., Manna, U.: Effect of Water Absorbing Polymer Amendment on Water Retention Properties of Cohesionless Soil. In Advances in Computer Methods and Geomechanics (pp. 185-195). Springer, Singapore (2020).
2. Feng, D., Bai, B., Ding, C., Wang, H., Suo, Y.: Synthesis and swelling behaviors of yeast-g-poly (acrylic acid) superabsorbent co-polymer. Industrial & Engineering Chemistry Research 53(32), 12760-12769 (2014).
3. Zhang, M., Cheng, Z., Zhao, T., Liu, M., Hu, M., Li, J.: Synthesis, characterization, and swelling behaviors of salt-sensitive maize bran–poly (acrylic acid) superabsorbent hydrogel. Journal of agricultural and food chemistry 62(35), 8867-8874 (2014).
4. Koupai, J. A., Eslamian, S. S., Kazemi, J. A.: Enhancing the available water content in unsaturated soil zone using hydrogel, to improve plant growth indices. Ecohydrology & Hydrobiology 8(1), 67-75 (2008).
5. Akhter, J., Mahmood, K., Malik, K. A., Mardan, A., Ahmad, M., Iqbal, M. M.: Effects of hydrogel amendment on water storage of sandy loam and loam soils and seedling growth of barley, wheat and chickpea. Plant Soil and Environment 50(10), 463-469 (2004).
6. Saha, A., Rattan, B., Sekharan, S., Manna, U.: Quantifying the interactive effect of water absorbing polymer (WAP)-soil texture on plant available water content and irrigation frequency. Geoderma 368, 114310 (2020).
7. Norris, A., Saafi, M., Romine, P.: Temperature and moisture monitoring in concrete structures using embedded nanotechnology/microelectromechanical systems (MEMS) sensors. Construction and building Materials 22(2), 111-120 (2008).

8. Žilinjtơ, L., Motiejnjnas, A., Kleizienơ, R., Gribulis, G., Kravcovas, I.: Temperature and moisture variation in pavement structures of the test road. Transportation Research Procedia 14, 778-786 (2016).
9. Ataka, M., Kominami, Y., Miyama, T., Yoshimura, K., Jomura, M., Tani, M.: Using capacitance sensors for the continuous measurement of the water content in the litter layer of forest soil. Applied and Environmental Soil Science 1-5 (2014).
10. Chen, R., Chen, Y., Chen, W., Chen, Y.: Time domain reflectometry for water content measurement of municipal solid waste. Environmental engineering science 29(6), 486-493 (2012).
11. Topp, G. C., Davis, J. L., Annan, A. P.: Electromagnetic determination of soil water content: Measurements in coaxial transmission lines. Water resources research 16(3), 574-582 (1980).
12. Baumhardt, R. L., Lascano, R. J., Evett, S. R.: Soil material, temperature, and salinity effects on calibration of multisensor capacitance probes. Soil Science Society of America Journal 64(6), 1940-1946 (2000).
13. Gong, Y., Cao, Q., Sun, Z.: The effects of soil bulk density, clay content and temperature on soil water content measurement using time-domain reflectometry. Hydrological Processes 17(18), 3601-3614 (2003).
14. Evett, S. R., Tolk, J. A., Howell, T. A.: Soil profile water content determination: Sensor accuracy, axial response, calibration, temperature dependence, and precision. Vadose Zone Journal 5(3), 894-907 (2006).
15. Morgan, K. T., Parsons, L. R., Wheaton, T. A., Pitts, D. J., Obreza, T. A.: Field calibration of a capacitance water content probe in fine sand soils. Soil Science Society of America Journal 63(4), 987-989 (1999).
16. Huang, Q., Akinremi, O. O., Sri Rajan, R., Bullock, P.: Laboratory and field evaluation of five soil water sensors. Canadian Journal of Soil Science 84(4), 431-438 (2004).
17. Visconti, F., de Paz, J. M., Martínez, D., & Molina, M. J.: Laboratory and field assessment of the capacitance sensors Decagon 10HS and 5TE for estimating the water content of irrigated soils. Agricultural Water Management 132, 111-119 (2014).
18. Dorraji, S. S., Golchin, A., Ahmadi, S.: The effects of hydrophilic polymer and soil salinity on corn growth in sandy and loamy soils. Clean–Soil, Air, Water 38(7), 584-591 (2010).
19. ASTM D854: Standard test method for specific gravity of soil solids by water pycnometer, West Conshohocken, PA, USA (2014).
20. ASTM D422-63: Standard test method for particle-size analysis of soils, West Conshohocken, PA, USA (2007).
21. ASTM D4318: Standard test methods for liquid limit, plastic limit, and plasticity index of soils, West Conshohocken, PA, USA (2017).
22. ASTM D2487: Standard practice for classification of soils for engineering purposes (unified soil classification system), West Conshohocken, PA, USA (2011).
23. USDA: Keys to soil taxonomy, Washington DC, 197-240 (2010).
24. Saha, A., Sekharan, S., Manna, U.: Evaluation of Capacitance Sensor for Suction Measurement in Silty Clay Loam. Geotechnical and Geological Engineering, 38(4), 4319-4331 (2020).
25. Lu, N., Likos, W. J.: Unsaturated soil mechanics. Wiley (2004).
26. Huettermann, A., Orikiriza, L. J., Agaba, H.: Application of superabsorbent polymers for improving the ecological chemistry of degraded or polluted lands. Clean–Soil, Air, Water 37(7), 517-526 (2009).