Capacitance Soil Moisture Sensor Discussion – ES/VH499 Version

By D. Wobschall, Esensors Inc.

Background

Of the electronic sensors for measurement of soil moisture, the capacitance sensors based on the increase in dielectric constant with moisture are the most accurate, although far from perfect. The reason that the dielectric constant of soil, which is a mixture of solid components, air voids and water, increases with water content is that the dielectric constant of water is very high (80) while that of the solid components is low (about 3) and that of air is 1. However, as many studies have shown, including those by this author [1, 2, 3], the composite dielectric constant is not a simple function of the water fraction, but increases non-linearly and also depends on the soil type and conductivity. The empirical equation by Topp [6] (see below) is the most often used to relate the dielectric constant (ε) to the moisture content by volume (Mv) but there are many others which have a lot of similarity [4, 5]. If the moisture content by weight or mass is needed, the density of the soil must be taken into account.

$$\theta_v = -5.3\times10^{-2} + 2.92\times10^{-2}\varepsilon_r - 5.5\times10^{-4}\varepsilon_r^2 + 4.3\times10^{-6}\varepsilon_r^3$$

Topp Equation – volume fraction of water in soil as a function of the dielectric constant

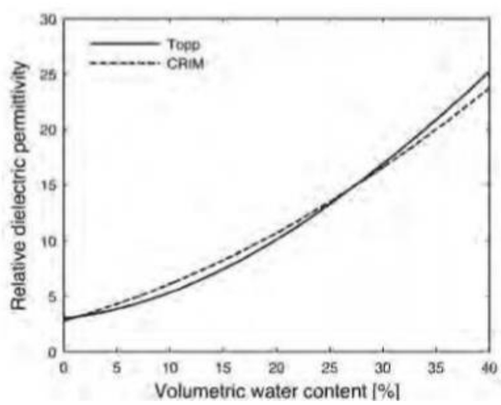


Fig. 1 Topp equation plotted as inverse (ε vs Mv)

The manufacturer of the VH400 soil moisture sensor [10] soes not describe the princple of sensor operation but it appears to be a capacitance or frequency shift sensor similar to one which I developed previously [1]. It operates at about 80 MHz, which is a region where the conductivity effects on dielectric constant are fairly low, but not completely neglibible. The sensor output is scaled so that when in air the voltage is near 0.0 and it close to 3.00 v when in 100% water. The sensor output is expected to follow the Topp equation, at least approximately.

Soiil is porous so the added water goes into the pores and does not change the volume of the soil much. If the pores are completely filled with water the soild is saturated (typically for a Mv of 40% to 50%). The Topp equation is best for an Mv between about 5% and 30% (with less accuracy up to saturation), which is also the range of interest for most agricultural and structural (building) applications. The 3rd order curve (Tropp) will be used between 0% and about 45% for the Esensors calibration. Between 45% and 100% a linear interopolation will be used, although inaccurate.

Published VH400 Calibrations

The manufacturer (Vegetronix) [10] provides a calibration curve but it is crude (piecewise) and was given only for potting soil (which is not a typical soil but is mostly organic material such as peatmoss), see Fig. 2A. Other published curves are shown in Fig. 2B,C. They do not agree well with each other, possibly because they use different soil types.

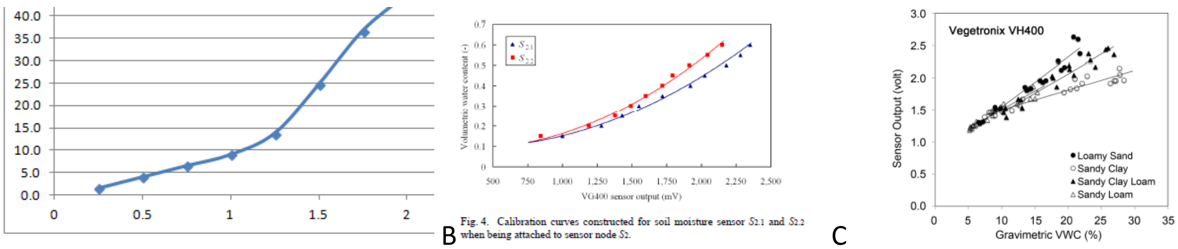


Fig. 2 Published Calibration Curves for the VH400
A. Manufacturer [10], B. Smarsly [11], C. Clemson [12]

Esensors Calibration Procedures

A mixture of sand and potting soil is used for soil sample #1 (later samples will include some silt and clay, which is more typical of soils). The oven drying method described above is used. The results are shown in Fig. 3. Data was obtained from 4 sensors and averaged.The data is fitted with a 3rd order polynomial between about 1% and 45% moisture (approximating the Tropp equation) and this is the reference calibration curve. The stated range is from 2% to 45% with best accuracy between 10% and 30%. The 3rd order polynomial fit is:

$$y = -4.6062x^3 + 21.152x^2 - 6.7886x + 1.1615$$ (x is sensor voltage, Vs --- y is Mv)

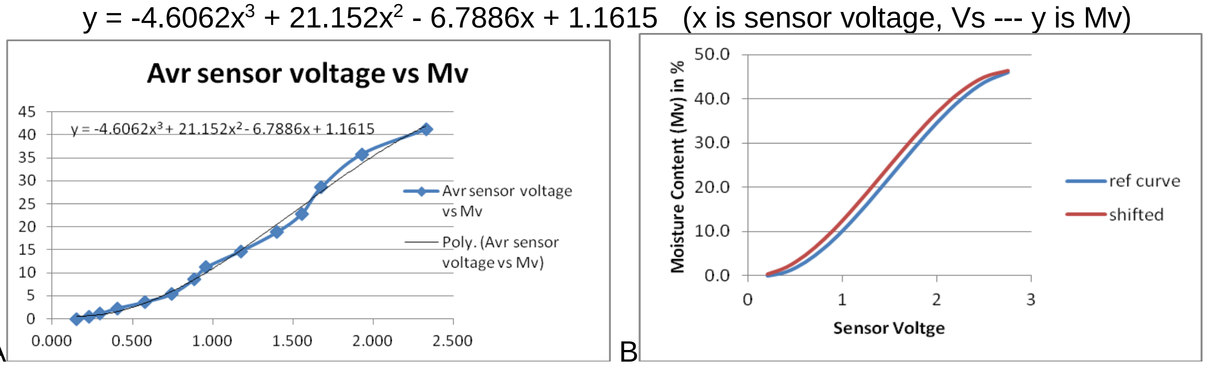
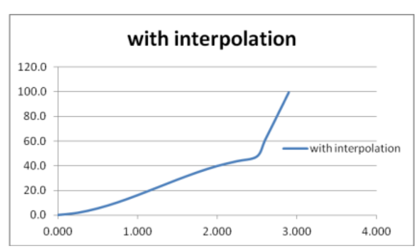


Fig. 3 Calibration curve (sample #1)
A. Averaged Data with polynomial reference curve, B. Reference curve shifted for calibration

For calibration a two-point method is used. A zero (Z), usually between -0.15 and +0.15, plus a fixed number (0.15) is subtracted from the measured sensor voltage (Vs) which is then multipled by a scale factor (F) which is between about 0.8 and 1.2. The Z parameter shifts the whole curve wich compensates for the residual dielectric constant of the dry soil. The F parameter shifts mostly the higher Mv values and compensates for the different soil types.

The calibration (and the useful range of the sensor) is good only below soil saturation (approx 45%-50%). Above this point, a rough linear interpolation is used:

Mv = 48*130*(Vx – 0.15 – Z).



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Appendix A. ES/VH400 Moisture Sensor Calibration

The moisture sensor which is used by Esensors is the Vegetronic VH400 with an analog output of 0 to 3v. The Esensors version converts the analog signal to a calibrated digital output to the Internet in units of % moisture by volume (Mv) based on a generic conversion curve. The sensor is a capacitance type based on the increase in dielectric constant of soil with increasing water content. However the functional relationship varies with soil type and therefore re-calibration of the sensor to fit a particular soil will result in better accuracy.

Two-Point Calibration Method

Step 1. Obtain Sensor Readings for Test Samples

- Select a relatively dry sample of the soil (best Mv under 8%)
- Measure the moisture using the ES/VH400 sensor and record the reading.
    - The reading is taken from the website (example 5.5%)
    - Label reading as Wds
- Determine the moisture using a reference method and record the reading.
    - The reading may be taken from another moisture sensor with a known good reading or the oven-drying (gravimetric) method described below can be used.
    - Label reading as Wdr (expected to be close to Wds)
- Select a relatively wet sample of the soil (best Mv in range of 20 to 30%)

- Measure the moisture using the ES/VH400 sensor and record the reading.
    - The reading is taken from the website (example 22.2%)
    - Label reading as Wws
- Determine the moisture using a reference method as accurately as possible and record the reading.
    - The reading may be taken from another moisture sensor with a known good reading or the oven-drying (gravimetric) method described below can be used.
    - Label reading as Wwr (expected to be close to Wws)

Step 2. Enter sensor readings into calibration site

- Go to website page displaying moisture sensor data
- Press "Cal" button – the table (below) should appear
- Insert the 4 numerical values (e.g. 5.5) into the table.

Sample	Sensor (%)	Reference (%)
Dry	Wds	Wdr
Wet	Wws	Wwr

New Cal

Calibration Z = 0.11 F = 1.05

Done

- Press "New Cal" button.
    - The Reference numbers will remain the same but Sensor numbers will change to the reference numbers (meaning sensor is now calibrated to read the same as the reference).
- Press the "Done" button.
    - The table will disappear and the normal sensor readings will appear
    - The internal calibrations factors are shown (Z is zero shift and F is scale factor

For one point calibration, insert only the wet values and type in 0 for the two dry values (the stored values will be used instead).

Oven Drying and Gravimetric Methods

If soil (or other materials) is baked in an oven above 100 ºC for some time, the moisture (unbound water) will be driven off and its moisture content by volume (Mv) will be approximately zero. Chemically bonded water may remain but this is not considered "moisture".

Oven Drying Process

1. Spread soil thinly on metal tray or baking sheet
2. Bake in oven at 120+ ºC (250+ ºF) for an hour or more. Stir occasionally.
3. Cool and store in covered container
4. This is soil with approx 0% Mv.

Determination of Moisture Content by Oven Drying

1. Measure out a soil sample of known volume (Vs) with a moisture content of interest (Example: 345.6 ml)
2. Weigh the sample accurately (e.g. 789.0 grams). Label as S1.
3. Oven dry the sample (see above).
4. Re-weigh the sample (to determine water loss). Label as S2.

5. Calculate water loss. $\Delta S = S1 - S2$. This is the water loss by volume (as well as mass). (example 789.0 – 709.0 = 80.0 ml)
6. If the soil increases (or decreases) in volume as a result of the water addition, correct Vs to this value (the volume changes little for lower moisture content because the water goes into the pores)
7. Calculate Mv in %

   $$Mv = 100^{*}\ \Delta S/Vs$$

   (for example: Mv = 100*80.0/345.6 = 23.1%)

Hydrating soil to Known Mv

1. Start with dry soil (Mv=0) of known volume Vs (e.g. 300 ml)
2. Calculate water volume (Vw) needed for chosen Mv
   (Example: for Mv=20.0% and Vs=300 ml then Vw should be 60 ml, assuming no sample swelling)
3. Add the water slowly with stirring.
4. Allow to soak in for a minute or more and continue to stir
5. This is a soil of moisture content of Mv for testing with the sensor.
6. If, for research purposes a full curve is wanted, add water in small (e.g. 5%) increments and measure at each point. (see curve below).