A COMPARATIVE STUDY OF VH400 SENSOR READINGS WITH GRAVIMETRIC MOISTURE CONTENTS USING DIFFERENT DIELECTRIC EQUATIONS

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Abstract: The study of soil moisture plays a crucial role in determining the optimum quantity of water to be applied in agricultural fields. There are many methods to estimate optimum amount of water application in the agricultural fields, however, in past few decades, the development of soil moisture sensors have played a major role in the efficient use of water. The gravimetric method is the best method used for calibrating soil moisture sensors. In this study, volumetric moisture content from VH400 sensor as well as gravimetric method were measured at 100 points in the study area. The dielectric constants derived from VH400 soil moisture sensor were compared with that obtained from gravimetric method readings by plotting linear curves using different dielectric equations. The results show that among the equations independent of bulk density, the Topp equation yielded slightly better correlation, whereas the equation of Gardner *et al.*, 1998 gave slightly better correlation among all the equations dependent on bulk density. The behaviour of the equation of Gardner *et al.*, 1998 with other equations showed poor correlation and maximum variation of the equation developed by Skierucha *et al.*, 1996.

Keywords: correlation, dielectric equation, gravimetric, soil moisture sensor, VH400.

Introduction: Judicious use of water, particularly in irrigation systems has become a major problem in today's world. The reason is that the major portion of water consumption is dedicated to agriculture and irrigation. As per the report of FAO (2010), in India, out of total water withdrawal, about 91% was consumed for irrigation and livestock. Therefore, measurement and study of efficient use of soil moisture is critical. Some of the benefits of measuring soil moisture are [1]:

- Efficient irrigation management; Increased crop yield and quality
- Monitoring health of soil; Drought monitoring
- Minimizing leaching; Groundwater recharge estimation
- Minimizing the impact of climate change

There are various soil moisture sensors available for a user and it becomes a complicated process for selecting the appropriate one. The principle, criteria for selection, advantages and disadvantages of various sensors are given in [2, 3]. Capacitance sensors are based on the principle of dielectric constant or relative permittivity. A voltage is applied at an end of the plate and the capacitor between the plates stores the energy in the form of dielectric constant. The dielectric constant of air is 1 whereas the dielectric constant of water is approximately 80. Higher water content in capacitance sensors is indicated by higher dielectric constant [4].

VH400 Soil Moisture Sensor and Gravimetric Method: The VH400 soil moisture sensor is used in this study (Fig. 1). The sensor, manufactured by Vegetronix is an example of a capacitance soil moisture sensor. The probe is small, portable, accurate and inexpensive. The most unique feature of this probe is that it can record readings rapidly, it is waterproof, rugged and corrosion free [5].

Fig. 1 VH400 Probe

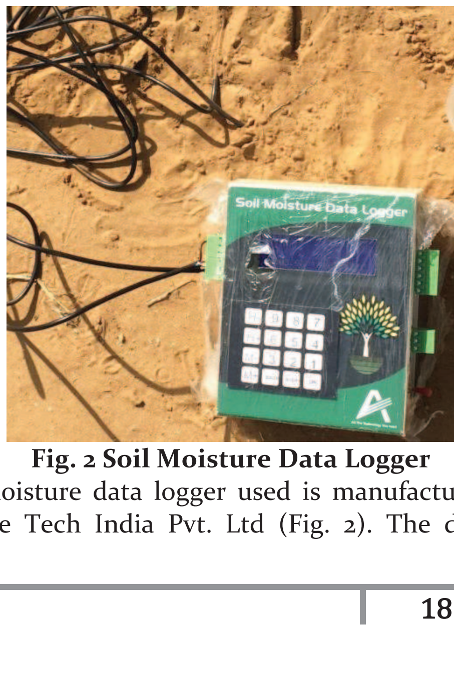

Fig. 2 Soil Moisture Data Logger

The soil moisture data logger used is manufactured by Advance Tech India Pvt. Ltd (Fig. 2). The data logger can take inputs from eight channels and can log data from interval of 600 sample per sec to 1 sample per week [6].

The gravimetric method serves as the base for calibration of all sensors. In this method, known volume of soil sample is collected in an air tight container, weighed, and dried for 24 hours at constant temperature 110°C ± 10°C to determine moisture content in soils. The disadvantage of using this method is that it is destructive and time-consuming [7].

Dielectric Constants and its Equations with Moisture Content: Various researchers have worked on dielectric constant using TDR instruments and have derived equations based on their study. These equations are dependent on either one parameter or multiple parameters but are related to moisture content, Θ. Dielectric equations are used to correlate moisture readings using capacitance sensors and time domain reflectrometry (TDR) sensors [8]. Even though the TDR is generally regarded as the best technique for determining the moisture content, the high cost of TDR has lead to development of different types of soil moisture sensors that use the principle of measuring dielectric to determine volumetric moisture content [9]. The major advantage of TDR is that it is independent of soil texture, temperature, and salt content which helps in long term in-situ measurements [10]. The capacitance sensors are based on dielectric constant which is directly related to moisture content.

There are numerous dielectric equations available to assess the performance of a soil moisture sensor with the help of dielectric constants. An attempt is made in this paper to compare the dielectric constants obtained from VH400 probe readings and the dielectric constants obtained from equivalent gravimetric readings. This was done by calculating dielectric constants using different dielectric equations which directly relate to moisture content. These equations depend on one parameter or more than one parameter. However, in this study, eight dielectric equations are taken into account for comparing the performance of VH400 sensor. The various dielectric equations used in this study are derived by Topp [11, 12], Jacobsen [13], Ferré [14], Rohini [15, 16], Malicki [17], Skierucha [18], and Gardner [19]. Attempts are also made to compare the dielectric values obtained by some of these methods with one another.

Methodology: The tests were conducted at six different locations of MNIT, Jaipur campus. At different locations (fig. 3), soil moisture readings were recorded with the help of VH400 soil moisture probe and data logger.

Fig. 3 Observations at different locations of MNIT, Jaipur campus

In all, 112 soil moisture content values were collected in the field through sensor, out of which 12 readings were discarded as outliers. Moisture readings were taken at different depths of loamy soil which had average bulk density of 1.13. Fig. 4 shows the direct linear correlation between the sensor based soil moisture readings and the corresponding equivalent volumetric moisture content (VMC) readings, taking all the 100 soil moisture values. The R^2, so obtained is 0.78.

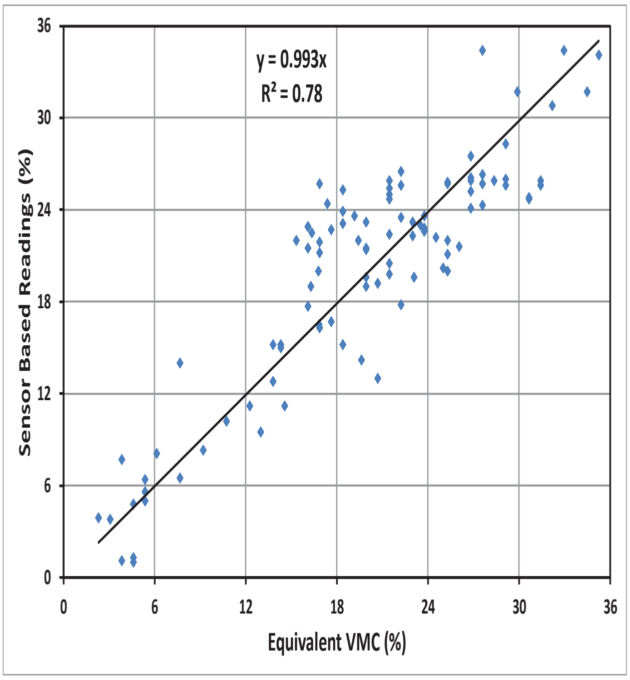

Fig. 4 Linear correlation curve between the sensor based values and equivalent VMC values.

From the curve, it is observed that there are maximum variations in the range of 15 to 25% VMC values but lesser variations in the lower and upper range. To give an overview of the data collected at the site, few observations taken from Aug 2016 to Feb 2017, are highlighted in table I.

Table. I Sample readings and their characteristics

Sample No.	Location	Date	Time (hrs)	Depth of Measurement	Bulk Density (g/cc)	Sensor Based Moisture Content
1	A	08 Aug 2016	1100	0-10 cm	0.81	1.0
6	D	10 Aug 2016	1600	0-10 cm	1.10	12.8
15	E	14 Aug 2016	1130	0-10 cm	1.28	9.5
19	F	17 Aug 2016	1230	0-10 cm	1.04	25.8
70	B	10 Feb 2017	1600	10-20 cm	1.11	15.2
84	C	20 Feb 2017	1410	0-10 cm	1.28	1.3

The six locations are Nursery (A), Near old Director's office (B), Area outside Mathematics department (C), Area surrounding Pump Room No. 5 (D), Near Annapoorna canteen (E) and Behind Prabha Bhawan (F).

Equations Independent of Bulk Density : The first experimental and the most widely used dielectric equation was developed by Topp *et al*., 1980 which is a third-order polynomial relationship between apparent dielectric constant, Ka and the moisture content, Θ. This equation is popularly known as Topp equation.

$\Theta = (-5.3 \times 10^{-2}) + (2.92 \times 10^{-2} Ka) + (-5.5 \times 10^{-4} Ka^2) + (4.3 \times 10^{-6} Ka^3)$ (1)

Since, this equation is based on just one parameter and independent of bulk density of soils, it can give highest correlation error (Mukhlisin *et al*., 2013).

Another equation was developed by Topp *et al*. in the same year which is given as:-

$Ka = 3.03 + (9.3 \times \Theta) + 146 \times \Theta^2) - (76.7 \times \Theta^3)$ (2)

The equation developed by Rohini *et al*., 2004 is a simple, linear equation used to determine Ka of the soil water content. The equation is given as:-

$\sqrt{Ka} = 1.35 + (10.57 \times \Theta)$ (3)

An attempt was made by Jacobsen *et al*., 1993 to calibrate four types of soils using TDR and derived the best-fit third-order polynomial relationship between Θ and Ka, given as:-

$\Theta = (-7.01 \times 10^{-2}) + (3.47 \times 10^{-2} Ka) - (11.6 \times 10^{-4} Ka^2) + (18 \times 10^{-6} Ka^3)$ (4)

A simple Ka-Θ equation given below, developed by Ferré *et al*., 1996 is one of the equations given for performance evaluation of different dielectric equations (Mukhlisin *et al*., 2013).

$\Theta = (0.1181 \times \sqrt{Ka}) - 0.1841$ (5)

Equations Dependent of Bulk Density :

Skierucha *et al*., 1996 developed an equation which takes into account bulk density along with moisture content, which is :-

$K_a = (0.573 + (0.582 \times \rho) + (7.755 + 0.792 \times \rho) \Theta)^2$ (6)

The equation developed by Malicki *et al*., 1996 is an improved version over Topp equations as it includes bulk density along with dielectric constant. The equation is:-

$\sqrt{K_a} = 0.819 + (0.168 \times \rho) + 0.159 \times \rho^2) + (7.17 + 1.18 \times \rho) \times \Theta$ (7)

All the above equations discussed here were derived with help of TDR sensors but the following equation developed by Gardner *et al*., 1998 was formulated using capacitance methods. The dry bulk density of soils in this equation varied between 1.08 to 1.49.

$\sqrt{K_a} = (9.93 \times \Theta) + (2.454 \times \rho) - 1.208$ (8)

Observations and Discussions: Apparent dielectric constant values were calculated for all the above mentioned equations for all the records using observed moisture content from sensor readings (K_a^1) as well as from volumetric moisture content (K_a^2) determined from soil samples. Table I shows some of the sample points for four methods. From this table, it is observed that the dielectric constants derived by both the methods in the equation of Rohini *et al*., 2004 are initially equal and lower but increases gradually to become more than that obtained by Topp equation. It can also be seen that values obtained by Skierucha *et al*., 1996 are consistantly lower than those obtained by Gardner *et al*., 1998.

Table. II Sample data points and calculated K_a methods for equations with bulk density

Observed Sensor Readings	Observed VMC Readings	Topp *et al.*, 1980		Rohini *et al.*, 2004		Bulk Density (g/cc)	Skierucha *et al.*, 1996		Gardner *et al.*, 1998	
		K_a^1	K_a^2	K_a^1	K_a^2		K_a^1	K_a^2	K_a^1	K_a^2
4.8	4.6	3.7	3.6	3.4	3.3	1.1	2.7	2.6	4.0	3.9
8.3	9.2	5.1	5.5	4.8	5.3	0.8	3.1	3.4	2.7	3.0
15.0	14.3	8.1	7.8	8.4	8.0	1.1	6.4	6.1	9.2	8.8
19.6	19.9	10.4	10.6	11.4	11.6	1.2	8.9	9.0	13.6	13.8
23.6	23.8	12.6	12.7	14.4	14.5	1.2	11.0	11.1	16.5	16.6
28.3	29.1	15.5	16.0	18.3	19.0	1.1	13.5	14.1	19.1	19.9
34.1	35.3	19.7	20.6	23.8	25.0	1.2	18.1	19.0	26.6	27.8

(where K_a^1 is K_a^1 derived from sensor readings, K_a^2 is K_a derived from VMC readings)

The linear curve of correlation for all the equations was plotted. The R^2 values of all equations varied between 0.74 to 0.77. This shows that there is not much variation in dielectric constant by using bulk density in the study equations. Fig. 5 and 6 show the comparison between K_a^1 and K_a^2 values obtained for two equations that gave highest R^2 - Topp *et al.*, 1980 among equations that are independent of bulk density and Gardner *et al.*, 1998 among equations dependent on bulk density.

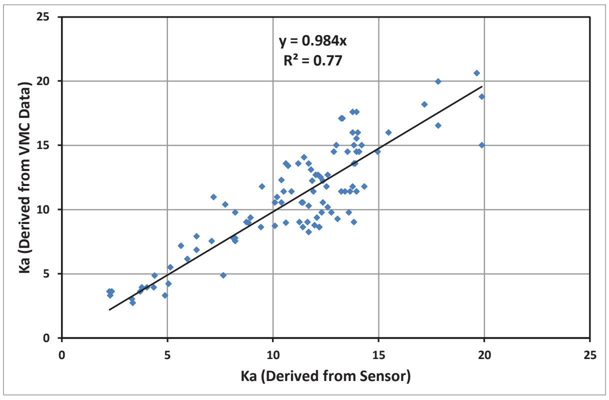

Fig. 5 Linear relationship between K_a derived from VMC and K_a derived from Sensor Values according to equation (1)

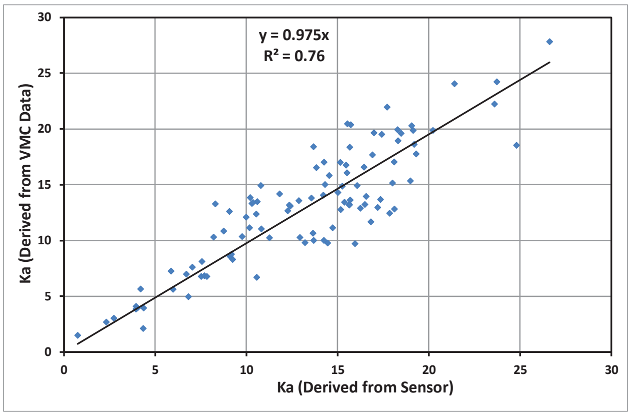

Fig. 6 Linear relationship between Ka derived from VMC and Ka derived from Sensor Values according to equation (8)

Comparison of the most suitable equation with other equations : The equations developed by Skierucha *et al.*, 1996 and Gardner *et al.*, 1998 are dependent on both moisture content and bulk density, whereas the equations developed by Rohini *et al.*, 2004 and Topp *et al.*, 1980 are dependent on moisture content only. It was also found that there is less variation in dielectric constants obtained by these equations. However, to observe the behaviour of one equation with others, the equation of Gardner *et al.*, 1998 was compared with other equations by plotting linear correlation curves as shown in fig. 7.

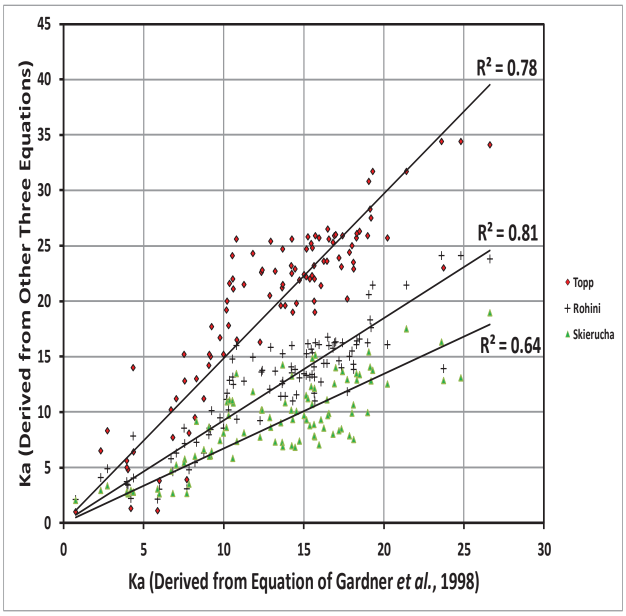

Fig. 7 Comparison of dielectric constants derived from equation of Gardner *et al.*, 1998 with equations developed by Topp *et al.*, 1980; Rohini *et al.*, 2004 and Skierucha *et al.*, 1996.

The correlation curves from fig. 7 show that there is a consistent variation of K_a values derived by Skierucha *et al.*, 1996, which is the reason for its least R^2 value. Also, it is observed that the K_a values from equation of Skierucha *et al.*, 1996 is on the lower side in comparison to other equations. The K_a values obtained from other two equations give better R^2 values than the equation of Skierucha *et al.*, 1996.

Conclusions: The eight dielectric equations, five independent whereas three dependent on bulk density were plotted based on dielectric constants derived from soil moisture sensor and corresponding gravimetric readings. Table III lists out the different coefficients obtained from four equations out of eight equations.

Table. III R^2 values for different dielectric equations

S.No.	Equation	Slope	R^2
1	Topp *et al.*, 1980 (equation (1))	0.984	0.77
2	Topp *et al.*, 1980 (equation (2))	0.981	0.74
3	Rohini *et al.*, 2004	0.979	0.75
4	Jacobsen *et al.*, 1993	0.986	0.74
5	Ferré *et al.*, 1996	0.983	0.76
6	Skierucha *et al.*, 1996	0.977	0.75
7	Malicki *et al.*, 1996	0.975	0.74
8	Gardner *et al.*, 1998	0.975	0.76

The R^2 values are close to each other as they are varying from 0.74 to 0.77. The dielectric constants have yielded good correlation. When these four equations were compared with each other, the equation of Skierucha *et al.*, 1996 showed maximum deviation from the values obtained by Gardner *et al.*, 1998. It must also be noted that this is only an attempt to check the suitability of different equations for the sensor under study. It does not imply that any one of the above equations is the best equation for this sensor. The best dielectric equation can be developed with the help of such dielectric equations in various forms for different types of soils. By calculating dielectric equations directly, one can develop an equation for a particular type of probe which is a future work for such type of sensors.

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