Measurement 54 (2014) 92–105

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Review

A critical review of soil moisture measurement

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ARTICLE INFO

Article history:
Received 23 November 2013
Received in revised form 6 April 2014
Accepted 11 April 2014
Available online 26 April 2014

Keywords:
Soils
Moisture content
Measurement techniques
Advance instrumentation
Nano-sensors

ABSTRACT

Soil moisture content has paramount importance in dictating engineering, agronomic, geological, ecological, biological and hydrological characteristics of the soil mass. Though earlier researchers have employed various techniques of moisture content determination of soils, both in laboratory and in situ conditions, ascertaining the applicability of these techniques to soils of entirely different characteristics and the 'types of moisture content', which they can measure, is still a point of debate. As such, a critical review of all the established and emerging soil moisture measurement techniques with respect to their merits and demerits becomes necessary. With this in view, efforts have been made in this paper to critically evaluate all the soil moisture measurement techniques, limitations associated with them and the influence of various soil-specific parameters (viz., mineralogy, salinity, porosity, ambient temperature, presence of the organic matter and matrix structure of the soil) on the measured soil moisture content. This paper also highlights the importance of various innovations based on Micro Electro Mechanical Systems (MEMS) and nano-sensors that are emerging in this context.

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http://dx.doi.org/10.1016/j.measurement.2014.04.007
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Nomenclature

θ	volumetric moisture content	ε_0	free space permittivity
w	gravimetric moisture content	ΔT_m	the maximum raise in temperature
γ_τ	soil bulk unit weight	f	frequency
γ_d	dry unit weight of soil	L	length
γ_w	unit weight of water	M	mega
η	porosity	M_1 M_2	percentage of minerals present in the material
σ_{dc}	conductivity corresponding to zero frequency	m	meter
°C	degree Celsius	mA	milliampere
atm	atmospheric pressure	mm	millimeter
g	gram	n	nano
eV	electron-volt	Hz	hertz
dS/m	deci Siemen per meter	q	energy applied per unit length
k	dielectric constant	Sr	saturation
k_a	apparent dielectric constant	ERI	electrical resistivity imaging
k_{M_1} k_{M_2}	dielectric constant of minerals	DPHP	dual probe heat pulse
K^*	complex dielectric constant	FDR	frequency domain reflectometry
K'	real dielectric constant	GPR	ground penetrating radar
K''	imaginary dielectric constant	MEMS	micro electro mechanical systems
kPa	kilopascal	NMM	neutron moisture meter
t	time	SWCC	soil water characteristic curve
ω	angular frequency	TDR	time domain reflectometry

1. Introduction

Soil moisture (water) is an inevitable part of the three-phase system of the soil, which comprises of soil minerals (solids), moisture and air [1,2]. Hence, soil moisture content has quite significant influence on engineering [3], agronomic [4,5], geological, ecological, biological and hydrological behavior [6–8] of the soil mass. Mechanical properties of the soil viz., consistency, compatibility, cracking, swelling, shrinkage and density are dependent on the soil moisture content [3,9]. Furthermore, it has a major role to play as far as the plant growth [5], organization of the natural ecosystems and biodiversity [10] is concerned. In agriculture sector, application of adequate and timely moisture for irrigation, depending upon the soil-moisture-plant environment, is essential in crop production [11–14]. Space–time evolution of the soil moisture content is controlled by topography, landscape position, slope, vegetation, soil structure and texture and human-made structure above the soil. Moreover, according to the environmental conditions, soil state can be varied from the dry to saturated state [3,6,7,9,10]. Considering the aforementioned facts, determination of the amount of moisture in the soil (i.e., the soil moisture content) becomes quite crucial in the field of agricultural, geotechnical, hydrological and environmental engineering. Soil moisture content is also used as an important parameter for water balance studies, slope stability analysis and performance evaluation of various geotechnical structures such as pavements, foundations, earthen dams, retaining walls, compacted clay liners, hazardous and toxic waste disposal repositories and wherein contaminant transport within the vadose zone is of utmost importance. [1–3,6,10,15]. In short, physical, chemical, mineralogical, mechanical, geotechnical, hydrological and biological properties of the soils are heavily dependent on the soil moisture content.

In this context, earlier researchers have developed several techniques for measuring the soil moisture viz., thermo gravimetric [10,16–19], neutron scattering [20–25], soil resistivity [26,27], dielectric techniques like time domain reflectometry, frequency domain reflectometry and capacitance etc. [28–47]. However, these techniques are quite intricate, expensive (due to quite elaborate circuitry and paraphernalia) and hence beyond the reach of many. Also, ascertaining the applicability of these techniques to soils of entirely different characteristics and the ‘types of moisture’, which they can measure (viz., hygroscopic moisture, free/gravity moisture, bound/capillary moisture etc.) is still a point of debate among the researchers. Though, these techniques are being employed by researchers and scientists, their limitations associated with the influence of various soil-specific parameters (viz., mineralogy, salinity, porosity, ambient temperature, presence of the organic matter, matrix structure etc.) has not been established yet.

With this in view, efforts have been made in this paper to critically evaluate all the soil moisture measurement technologies and limitations associated with the influence of various soil-specific parameters viz., mineralogy, salinity, porosity, ambient temperature, presence of the organic matter and matrix structure of the soil. This review emphasizes that why it becomes imperative to evaluate various techniques employed by the researchers for determination of the soil moisture. Also, requirements for developing new soil moisture measurement techniques or modifying the existing techniques has been assessed.

2. The soil moisture content

Briggs [48] and Terzaghi [3] made quite significant contributions in understanding the soil-moisture interactions. Briggs [48] has reported that the soil moisture exists in three forms viz., gravitational moisture, capillary moisture and hygroscopic moisture. *Gravitational moisture* is defined as the free moisture that moves through the soil due to the force of gravity. It is found in the macro-pores and its movement is quite rapid in well-drained soil and hence, it is not considered to be available moisture. Normally, gravitational moisture drains out of the soil in 2–3 days after the rainfall. *Capillary moisture* is the moisture present in the micro-pores of the soil and is held within the soil due to cohesion and adhesion against the force of gravity. This moisture is available as pore moisture and is responsible for all physico-chemico-mineralogical–biological interactions between the soil and the environment. *Hygroscopic moisture* forms a very thin film around the surface of the soil particles. Since, it is not held in the pores of the soil, but is on the surface of these particles, it is very difficult to remove due to the presence of extremely high forces of adhesion. Clayey soil retains more amount of hygroscopic moisture as compared to sand due to its higher surface area. For understanding the soil moisture-plant interactions, Widstoe and McLaughlin [49] differentiated capillary moisture into field water capacity, i.e. the available moisture to plants, and wilting point. Field water capacity is the water retained in the soil after the excess gravitational water drained away, but not necessarily available to plants. Wilting point (permanent wilting point) is the water content of the soil below which plants start to wilt. Available water for the plants is the soil water that can be absorbed by plant roots and is obtained by subtracting the permanent wilting point from the field water capacity.

Buckingham [50] and Gardner [51] conducted initial research on the amount of water with respect to the energy level with which water is held into the soil and the relationship is known as soil water characteristic curve (SWCC). SWCC is a relationship between the moisture content in the soil and soil suction (soil moisture potential) and is unique for each soil type. It can also be referred as soil moisture retention curve since the curve is used to predict soil moisture storage, field capacity, wilting point and which will be useful for irrigation purpose. It can also be used to understand the drying and wetting characteristics of the soil and its pore structure [4,52]. Moreover, the amount of moisture held in the soil depends on the particle size distribution, structure of the soil, porosity, specific surface area, depth of the soil, mineralogical composition, salinity, pore fluid characteristics, degree of compaction, presence of contaminants, organic content, temperature and humidity [8,53,54]. However, the influence of aforementioned parameters on soil moisture content requires exhaustive studies.

3. State-of-the-art on soil moisture measurement techniques

For determining the soil moisture content (in volumetric and gravimetric forms), researchers have employed various techniques, which can be categorized into (i) classical and (ii) modern techniques for both the laboratory and in situ measurements. The classical soil moisture measurement techniques include thermo-gravimetric and calcium carbide technique [10,16–19] while the modern techniques utilize soil resistivity sensor [26,27], tensiometers [55–59], infrared moisture balance [10], [19], dielectric techniques viz., Time Domain Reflectometry (TDR), Frequency Domain Reflectometry (FDR) and capacitance technique [28–47], heat flux soil moisture sensors [60,61], micro-electro mechanical systems and optical techniques [10,26,62–65] as described in the following. However, both classical and modern techniques exhibit uncertainty related to the accuracy, precision, coverage and volume of measurements [22,70].

3.1. Classical soil moisture measurement techniques

Classical soil moisture measurement involves removing moisture from the soil sample by evaporation or chemical reaction. This category comprises of thermo-gravimetric and calcium carbide techniques. The *Thermo-gravimetric technique* (oven-drying) is widely used for measuring the soil moisture content and has been employed as the standard reference for determining soil moisture content. In this technique, wet soil sample (usually 100 g or less) is subjected to oven drying for 24 h, at 105 °C, and subsequently the dry soil weight is recorded [16]. However, for organic soils and gypsiferous soils, the temperature is usually decreased to 50–70 °C, since organic matter may be lost due to volatilization at elevated temperatures. This technique ensures accurate measurement of the moisture content and is not dependent on salinity and the soil type. However, it is a destructive test since the soil sample subjected to oven drying cannot be used for repetitive measurements as its soil structure gets disturbed [26]. On the other hand, the c*alcium carbide technique* is a rapid soil moisture determination technique, employed either in laboratory or in field. Soil moisture content of a specified wet or moist soil is determined by the gas pressure developed due to the chemical reaction of calcium carbide reagent with the moisture present in the soil. Acetylene gas is produced in proportion to the amount of available moisture present in the soil and is measured by confining the resultant gas in a sealed chamber. The apparent moisture content can be obtained from a pressure gauge of the apparatus and is calibrated with the gravimetric soil moisture content. Some highly plastic clay soils or other soils not friable enough to break up may not produce representative results because some of the moisture may be trapped inside soil clods or clumps which cannot come in contact with the reagent. Moreover, 20 g sample requires approximately 22 g of reagent and competence of personnel performing is required for the testing [17].

The amount of moisture present in the soil can be expressed in percentage either as gravimetric soil moisture content, w or as volumetric soil moisture content, θ. The w is defined as the ratio of the mass of moisture present in the soil sample to the dried mass of the same, whereas, θ is defined as the ratio of the volume of moisture present in the soil to the total volume of the soil [10]. Both these parameters are related as per the Eq. (1).

$$\theta = w \cdot (\gamma_d / \gamma_w) \quad (1)$$

where γ_d is the dry-unit weight of the soil mass and γ_w is the unit weight of water.

Hillel [18] has reported that the standard method of oven drying itself is arbitrary, as some clay may still contain perceivable amounts of moisture even at 105 °C (degree celcius). On the other hand, some organic matter may oxidize and decompose at this temperature so that the weight loss may not be entirely due to evaporation of moisture. However, the author has suggested that the errors associated with this method can be reduced by increasing the number of samples as well as by obtaining samples with minimum disturbances from the site.

3.2. Modern soil moisture measurement techniques

Modern soil moisture measurement techniques employ electrical properties of the soil (viz., dielectric constant, impedance, capacitance and soil resistivity), soil moisture potential, infrared rays, and radioactive techniques such as neutron scattering, gamma attenuation and optical techniques. These techniques, except for the application of 'infrared waves' for determining the moisture content can be used for both laboratory and in situ applications. Infrared moisture balance technique works based on the principle of electro balancing combined with the infrared heating technique to ascertain the moisture content present in the soil. It is powered by the integrated advanced microprocessor, for achieving high accuracy, reliability and rapid measurement (approximately 15–20 min) of soil moisture content. The small sample weight (2–5 g), high cost of the instrument and the application only for laboratory measurements are the major limitations of this instrument [10,19].

3.3. Neutron scattering technique

Neutron moisture meters (NMM) employ neutron scattering technique [20], which has been found to be quite versatile for estimating the volumetric soil moisture content, θ in the field. NMM employs a source of fast neutrons (mean energy 5 Mega electron volt, MeV) and a detector of slow neutrons (~0.025 eV at 27 °C). Although, the source strength is relatively small (0.37 or 1.85 Giga Becquerel) and sources are sealed, the radioactivity of these sources leads to requirements for safety training, monitoring and regulation of shipping and handling. The NMM is available as both surface meter and profile meter. Former lies flat on the soil surface, but the latter consists of a cylindrical probe connected by a cable to a case containing power supply, display, keypad and microprocessor [20]. As shown in Fig. 1, the probe is inserted into an access tube in the soil for data acquisition, while the case remains at the surface. When not in use, the probe is locked inside the case, which contains a high density plastic shield [21]. Profile NMM is useful for agricultural and environmental uses whereas the surface NMM has not proved to be fruitful for the same [22]. Fast neutrons (high energy) emitted from a radioactive source are thermalized or slowed down by collisions with hydrogen nuclei present in the soil. Since, most of the hydrogen atoms present in the soil is components of moisture molecules; the proportion of thermalized neutrons is related to soil moisture content [23,24].

It is a very rapid soil moisture measurement technique having response time of 1–2 min. This method offers the advantage of measuring a large soil volume and also the possibility of scanning at several depths to obtain a profile of moisture distribution. NMM is considered as the most accurate technique for measuring the soil moisture content. It is a non-destructive test and moisture can be measured in any phase. However, the high initial cost of the instrument, low degree of spatial resolution and the health hazard associated with exposure to radiation are major disadvantages of this technique [71]. This instrument is insensitive near the soil surface to shallow depth less than 0.3 m. This instrument is very difficult to move from one site of measurement to another [26]. Fityus et al. [25] have used a neutron probe for determining the soil moisture content of an expansive soil. A comparative study on the results of both capacitance probe and neutron probe has been made and it has been opined that capacitance probe fails in expansive soil due to soil cracking, but neutron probe yields better results of total moisture content of surrounding soil volume independent of soil cracking.

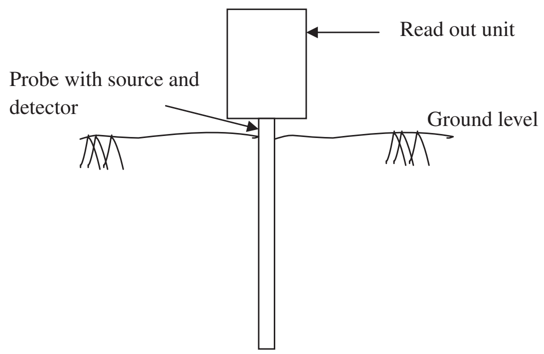

Fig. 1. Schematic diagram depicting moisture measurements using the Neutron probe.

3.4. Gamma attenuation technique

The gamma ray attenuation technique is a radioactive technique that can be used to determine soil moisture content which is restricted to a soil depth of 25 mm or less with high resolution. This technique assumes that the scattering and absorption of gamma rays are related to the density of matter in their path and the specific gravity of a soil remains relatively constant as the saturated density changes with increase or decrease in moisture [72]. Changes in saturated density are measured by the gamma transmission technique and the moisture content is determined from this density change. It is a non-destructive in situ technique having response time of approximately less than 1 min which measures the volumetric moisture content. However, it is likely to be affected by the soil bulk density changes. Though, it is sensitive to the surface soil moisture, gamma rays are more dangerous to work than NMM and the operational cost of gamma attenuation technique is relatively high [26].

3.5. Dielectric techniques

Time Domain Reflectometry (TDR), capacitance technique and Frequency Domain Reflectometry (FDR) are the major techniques which make use of dielectric property of the soil for measuring soil moisture content. The concept behind the utilization of dielectric technique is that there is a huge difference in dielectric constant of dry soil (=2–5) and that of pure water (=81) [28–31,39,73–74]. The negligible influence of temperature on electrical permittivity measurements makes the TDR and FDR more accurate in the determination of soil moisture in shallow soils [29,40].

3.5.1. Time Domain Reflectometry (TDR) technique

Over the years, TDR has become widely accepted for the measurement of soil moisture content [10,40,43,46,74–75]. TDR determines the apparent dielectric constant, k_a, of the soil according to Eq. (2) and is empirically related to the volumetric water content, θ, as expressed by Eq. (3) [74].

$$K_a = [c \cdot t/2L]^2 \quad (2)$$

where c is velocity of the light in free space (=3×10^8 m/s), t is the transit time for an electromagnetic pulse to travel the length of a transmission line and L is the length of the probe.

$$\theta = 4.3 \times 10^{-6}(k_a)^3 - 5.5 \times 10^{-4}(k_a)^2 + 2.92 \times 10^{-2}k_a - 5.3 \times 10^{-2} \quad (3)$$

3.5.1.1. Working principle of the TDR probe. TDR determines dielectric permittivity of the soil mass by measuring the delay in time between the incident and reflected electromagnetic pulses, which propagate along a parallel wave guide, in the form of probes or conductors, inserted in it [28–31,33,39,73]. These wave guides are a pair of stainless steel rods, installed from the surface to a maximum depth of 0.3–0.6 m in the soil mass, as depicted in Fig. 2. The huge difference between the apparent dielectric constant of the water and that of other soil constituents (viz., soil particles, air and water) makes the travel time of the pulse dependent on the volumetric moisture content, θ, of the soil mass [74]. However, the major advantages of TDR are high temporal resolution, the rapidity of acquisition (approximate 28 s) and the repeatability of measurements. It can be operated up to 1 GHz frequency. This technique is independent of the soil texture, temperature, and salt content, helpful in performing long-term in situ measurements and can be automated [76]. The major disadvantages of this instrument are high initial cost, loss of reflection in highly saline soil and increase in conductivity with wetting of the soil mass. As such, quite good wave forms can be obtained in a very dry saline soil as compared to the wet saline soils. TDR has been adapted to fit on mobile platforms, such as tractors, all-terrain vehicles (ATVs), or adapted spray rigs. Most of these mobile TDRs have been designed for agricultural practices. The advantages of these measurements are better spatial coverage and averaging of soil moisture content over 0.3–0.6 m of soil depth. However, it is time consuming to make many repetitive measurements [10]. Giese and Tiemann [77] have demonstrated that TDR can be used for the determination of soil electrical conductivity by retrieving TDR signals. These researchers have related reflection coefficient of TDR signal to soil electrical conductivity.

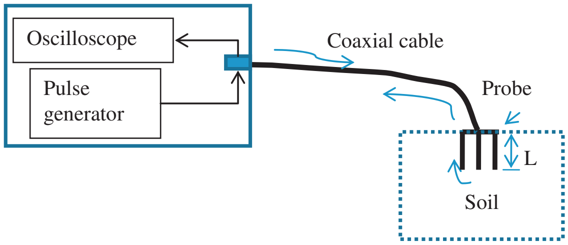

Fig. 2. Schematic diagram depicting soil moisture measurement using the TDR.

Topp et al. [74] have studied the relation between volumetric moisture content and dielectric constant for the frequency range 1 MHz to 1 GHz. The effect of bulk density, temperature and soluble moisture content on this relationship was also determined. The researchers have opined that the real part of the complex permittivity K' is independent of frequency, but is highly sensitive to soil moisture content. The authors have employed the general expression of complex dielectric constant as given in Eq. (4).

$$K^* = K' + j\{K'' + (\sigma_{dc}/\omega\varepsilon_0)\} \quad (4)$$

where K^* is the complex dielectric constant and K'' is the imaginary part of dielectric constant, σ_{dc} is the conductivity corresponding to zero frequency, ω is the angular frequency and ε_0 is the permittivity of the free space.

Topp et al. [74] have observed that the parameters such as texture, structure, soluble salts, moisture content, temperature, density, and measurement frequency affect the electrical response of the soil. However, it has been demonstrated that over the frequency range of 1 MHz to 1 GHz, the real part of the dielectric constant is independent of the frequency and temperature. Further, it has been opined that the dielectric loss, K'' is considerably lesser than K' in the said frequency range and hence the apparent dielectric constant $k_a \approx K'$. In this study, various techniques such as TDR and coaxial transmission line column have been employed. Authors have reported that k_a increases with volumetric moisture content θ for all the soils used in the study, as depicted by Eq. (3). Further, this study reveals that the temperature has negligible effect on this relationship and k_a depends mainly on the volumetric moisture content rather than the soil type, its density and frequency. However, the limitation of these investigations is that k_a has been shown to be independent of the salt content/contamination.

Topp et al. [29] have conducted a study on TDR in a one meter column of silty loam soil in the laboratory and opined that it can be employed to measure the soil moisture content during infiltration, drainage, evaporation, and rising moisture conditions. Comparison of volumetric moisture content of TDR with the gravimetric moisture content was also carried out and it has been shown that the difference is less than 3%. These researchers also demonstrated that the variation in the soil density affects TDR soil moisture measurements with time. Evett and Steiner [78,38,42] have opined the techniques which utilize electromagnetic waves viz., TDR and capacitance allow data logging and un-attended operation. However, the authors have also revealed the uncertainty in precision and accuracy of these techniques. Pepin et al. [79,80,81] have opined that the prominent source of error in estimating soil moisture content using TDR is the uncertainty in determining the propagation time. These researchers have reported that high soil electrical conductivity in clay or saline soils can also significantly affect the propagation of the waveform which leads to erroneous estimation of the real part of the dielectric permittivity, K'. Rohini and Singh [43] have attempted to show the utility of an impedance cell and a TDR probe for determining electrical properties (resistivity, capacitance, and dielectric constant) of the soil mass with known physical properties such as dry density and moisture content. The study highlighted that the TDR probe can be used for determining dry density, γ_d, saturation, S_r, and porosity, η of the soil mass. Yu et al. [82] have conducted a study to obtain the effect of variations in soil property along the length of the probe and its influence in soil moisture content measurement. The researchers have employed constrained optimization technique in inversion analysis to determine the soil layer properties and have derived a simplified a dielectric model for cohesionless soil. However, the applicability of this model to cohesive soil was not explained. Hence it is not sure that this model is applicable to cohesive soil. Bhat et al. [44] have reported that dielectric constant of soil is dependent on its type (viz., coarse grained, fine grained), mineralogy, volumetric moisture content and the frequency of AC used for its measurement. The researchers have been made efforts to overcome the limitations regarding the correlations of dielectric constant of soils with their physical properties such as density and porosity given by previous researches. The authors have also proposed a generalized equation as given in Eq. (5) which is applicable in any frequency range and found to be quite efficient for determining the dielectric constant of any type of soil.

$$\sqrt{k} = \left[(1-\eta)\cdot\left(M_1\cdot\sqrt{k_{M_1}} + M_2\cdot\sqrt{k_{M_2}}\right) + \eta\cdot\left(S_r\cdot\sqrt{k_{PF_1}} + (1-S_r)\cdot\sqrt{k_{PF_2}}\right)\right] \quad (5)$$

where M_1 and M_2 are percentages of the minerals present in the material, k_{M1} and k_{M2} are dielectric constants of these minerals, k_{PF1} and k_{PF2} are dielectric constants of the pore-fluids (moisture and air, respectively), η is the porosity and S_r is the degree of saturation of the material.

Hilhorst et al. [40] have proposed that a change in the constituents of porous soil will cause change in its electrical permittivity, as the measured permittivity reflects the impact of the permittivity of the individual constituents. The authors have proposed a new theoretical mixture equation, which relates the measured permittivity as the weighted sum of the permittivity of the individual material constituents and depolarization factors which account for electric field refractions at the interface, using the principle of superposition of electric fields. The authors have evaluated the developed equation by using fine sand and glass beads. The depolarization factors were derived from data measured for glass beads and soils. Predicted calibration curves of fine sand and glass beads were in reasonable agreement with the measured data and the data published by Topp et al. [74]. The authors have opined that the developed equation allows correction for porosity which was not included in the Topp's equation (refer Eq. (3)). Schwartz et al. [45] have reported that large scale (greater than 10 m) two dimensional distribution of moisture is difficult to obtain using TDR because installation is difficult and is applicable only for small scale measurements. The authors have proposed new model coupling electrical resistivity imaging (ERI) and TDR moisture measurement results. Using this model and incorporating relevant physical and chemical data obtained from a field site with heterogeneous soils, it was converted to field scale two dimensional ERI profiles into two dimensional moisture profiles. The authors have claimed that this model can be applied to any field site where a quantitative assessment of two dimensional soil moisture distributions is desired. The proposed model produced useful results in heterogeneous soil and small scale soil moisture variation in the subsurface soil can also be detected. However, the authors have highlighted that this model of soil moisture do not resolve small-scale (lesser than 0.1 m) heterogeneities in soil moisture as measured with TDR. Lin et al. [83] and Huisman et al. [84] have pointed out that TDR technique is not suitable for determining the frequency dependence soil electrical properties. Mittelbach et al. [47] have made a comparative study on three low cost soil moisture sensors and a high accuracy-high cost TDR sensor over a period of two years in a clay loam site. The authors have evaluated these sensors based on the daily volumetric soil moisture content data and the temperature dependency of the measurements. The researchers have demonstrated that all the evaluated low-cost sensors had an inconsistent performance, insensitivity in certain soil moisture regimes and/or spurious dependency on soil temperature. From the study, the authors have concluded that site specific calibration is vital for the interpretation of soil moisture measurements with low cost soil moisture sensors for obtaining better accuracy of measurements.

3.5.2. Capacitive technique and Frequency Domain Reflectometry (FDR) technique

The capacitance based techniques have an oscillating circuit and a sensing part which is embedded in the soil. The operating frequency depends on the dielectric constant of soil. This technique determines the dielectric permittivity/dielectric constant of a medium by measuring the charge time of a capacitor which uses that medium as a dielectric [32,34,36,85]. As shown in Fig. 3, the capacitance sensors consist of a pair of electrodes (either an array of parallel spikes or circular metal rings) which form a capacitor with the soil as the dielectric. This capacitor works with the oscillator to form a tuned circuit, and changes in soil moisture content are detected by the changes occurring in the operating frequency (10–150 MHz). Despite the working principle of FDR is similar to that of capacitive technique, it uses *swept frequency* (collecting the data over a wide range of frequency). However, both the techniques are soil specific and hence, frequent calibration is required while implementation. The initial cost of these instruments is relatively lower than that of TDR.

Seyfried et al. [86] have opined that obtained calibration relationships from experimental results are not matching with the manufacturer supplied relationships. Authors have investigated the performance of hydraprobe, which is a capacitance based technique, in terms of inter-sensor variability and applicability of data from the calibration equations. The researchers have stated that complex dielectric constant is dependent upon temperature, especially imaginary part of dielectric constant is much more sensitive to temperature than real part and it would give variations in the soil moisture measurement. Lin [86] has reported that frequency domain techniques permits increase of the bandwidth and, thereby, increases the accuracy of the soil moisture measurement data. The author concluded that, frequency domain analysis offers more potential than the time domain reflectometry techniques for the determination of soil moisture content. However, Rao and Singh [46] have conducted a comparison study on both TDR and FDR techniques for the soil moisture measurement and have reported that Topp's equation for TDR soil moisture measurement is valid up to $\theta = 50\%$ as Topp's calibration equation is based on experimental results for mineral soils with $\theta < 50\%$. The authors have also found that measurement repeatability of FDR probe is better in soils having volumetric moisture content lesser than 5% and hence, opined that its sensitivity is high for volumetric moisture content measurement in relatively dry state of soils. The researchers have also reported that the FDR probe has a limitation of showing erroneous results, being sensitive to air gaps between soil, access tube and probe.

3.6. Electrical impedance sensor

As depicted in Fig. 4, electrical impedance sensor consists of probes that use coaxial impedance dielectric reflectometry for measuring dielectric constant of the soil and subsequently dielectric constant is related to moisture content employing Eq. (3). It employs an oscillator (100 MHz sinusoidal oscillator) to generate an electromagnetic signal which is propagated into the soil. Part of the signal will be reflected back by the soil and the sensor will measure amplitude of the reflected and incident signals in volts. This volt is related to the impedance and dielectric

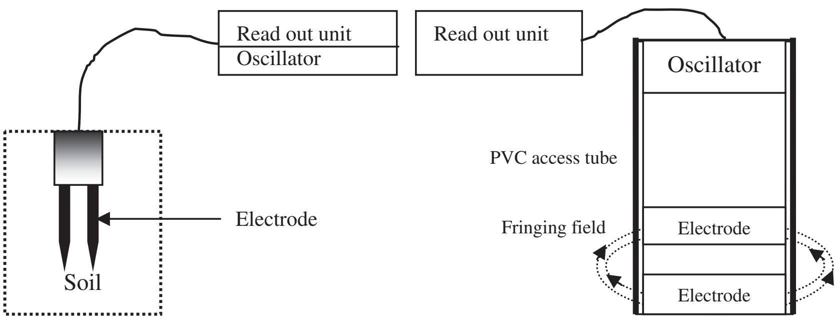

Fig. 3. Schematic diagram depicting soil moisture measurement using (a) capacitance technique and (b) FDR probe.

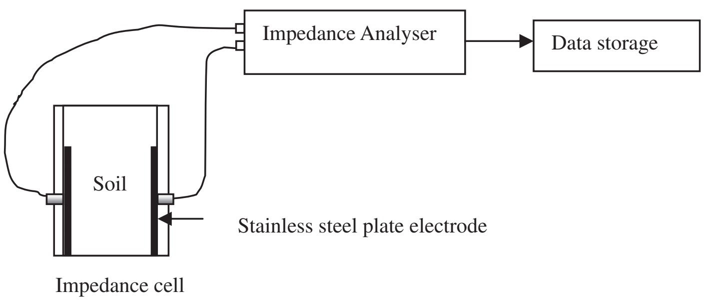

Fig. 4. Schematic diagram depicting soil moisture measurement using impedance analyzer.

permittivity for measuring the soil moisture content [35,37]. However, the field applicability of this instrument has yet to be explored.

3.7. Ground Penetrating Radar (GPR)

GPR uses the transmission and reflection of high-frequency (1 MHz–1 GHz) electro-magnetic waves within the subsurface. The measurements provide information about the permittivity of subsurface materials. GPR measures the travel time of the direct ground wave, which travels from the source to receiver antenna through the topmost layer of the soil and is correlated to the dielectric constant for the soil moisture measurement. It is a high-resolution, non-invasive form of measurement that can be used to estimate the variation in dielectric properties over large regions of the surface and subsurface. The disadvantage of GPR is the high end user knowledge to obtain good-quality data and valid interpretations. Furthermore, GPR fails to get good results in saline soils as signal attenuation happens due to increase in bulk electrical conductivity greater than 1 dS/m [10,88,89].

3.8. Micro Electro Mechanical System (MEMS)

Nanotechnology based MEMS consists of collection of microsensors, nanosensors and actuators which can sense its environment with the use of micro-circuit control. The MEMS used for soil moisture measurement consists of micro-cantilever beam and microsensor chip which combines a proprietary nano-polymer sensing element and Wheatstone's bridge piezoresistor circuit. Using shear stress and stress sensitivity of the nano-resistor, the change on the cantilever surface can be studied. MEMS cantilever is equipped with an expanding film and nano-moisture vapor polymer film on its top surface. When soil moisture molecules comes in contact with this thin film, cantilever bends downwards and expands until the cantilever beam's stress balances the stress in the thin film induced by the moisture molecules. This produces shear constraint which causes deflection of cantilever beam. Deflection is measured as change in resistance in the embedded strain gauges, and is linearly proportional to the shear stress and moisture molecule concentration, which is transduced into a proportional differential voltage change. Temperature is monitored by sensing the temperature of the moisture vapor using an on-chip temperature sensor [64]. Jackson et al. [64] have conducted a theoretical and experimental study on the feasibility of using inexpensive nanotechnology based devices viz., MEMS for the field measurement of soil moisture. The researchers have found that the change in the resistance of the sensor due to moisture depends mainly on the cantilever beam thick-ness and modulus of elasticity, and the quantity of moisture. The authors have concluded that only the cantilever beam thickness and stiffness influence the MEMS sensitivity, and this sensitivity is independent of the cantilever length and shear stress at the cantilever/polymer interface. However, the practical implementation of this device and the effect of different soil components on MEMS response are yet to be studied.

3.9. Soil resistivity sensor technique

As soil moisture content increases, soil resistivity decreases. The quantification of soil resistivity can be done by measuring either the resistivity between electrodes in a soil or the resistivity of a material which is in equilibrium with the soil [10].

One of the most common methods of estimating matric potential is the application of porous blocks, containing two electrodes connected to a cable. The porous block is made up of gypsum, fiberglass, ceramic or nylon. When the device is buried in the soil, moisture will move in or out of the block until the matric potential of the block and the soil are the same. The electrical resistance is measured between the two electrodes using a meter attached to the cable. The calibration curve, between the electrical resistivity and soil moisture content, can be developed for any particular soil within 2–3 h. Use of a porous electrical resistance block system offers the advantage of low cost and the possibility of measuring the same location in the field throughout the season. Gypsum block are suited for fine textured soils and not with coarse textured soil since gypsum blocks are not generally sensitive below 1 atm (atmospheric pressure). The major disadvantages of this technique are requirement of individual calibration and failure in saline soil [26].

Sreedeep et al. [27] have developed an electrical resistivity box and employed an electrical resistivity probe, for estimating soil electrical resistivity. The authors have developed a calibration chart and by using that, the electrical resistivity of a locally available silty soil and commercially available white clay was determined. The study demonstrated that the soil electrical resistivity obtained from these setups matches quite well with the results available in the literature. The researchers have also determined that the electrical resistivity of soils decreases exponentially with increase in saturation and suggested its application in soil moisture content determination.

3.10. Thermal dissipation block technique

Thermal dissipation blocks are made of porous ceramic material. A small heater is embedded inside the porous block which is inserted into the soil and is attached to a temperature sensor placed at the surface via a cable. By applying a voltage to the internal heater, rate of heat conducted away from the heater (heat dissipation) is measured. This heat dissipation is related to the soil moisture content and hence soil tension. However, this device requires calibration and is more expensive as compared to the resistance block [60].

3.11. Heat flux sensor technique

As shown in Fig. 5, the Dual Probe Heat Pulse (DPHP) sensor technique consists of two probes viz. heater and temperature sensor probes for measuring soil volumetric moisture content. The method is based on the application of an instantaneous pulse of heat to an infinite line source. The increase in temperature that results from the heat pulse is measured. This temperature increase is measured

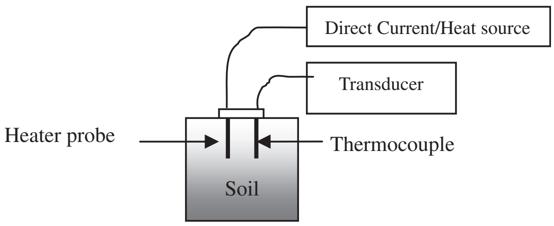

Fig. 5. Schematic diagram depicting soil moisture measurement using DPHP.

at a short distance from the line heat source and is related inversely to the soil volumetric heat capacity, which, in turn is related directly to the volumetric moisture content [61].

Julie et al. [61] have conducted tests in laboratory and at field to determine volumetric moisture content, θ, by using dual-probe heat capacity sensor (DPHP). The authors have reported that dual probe sensors measure volumetric heat capacity, ρc_p (given in Eq. (6)), by using transient heat pulse and temperature and which is converted into θ, [90] which is valid for non-swelling soil of known bulk density as given in Eq. (7).

Volumetric heat capacity of soil from dual probe heat pulse sensor with a temperature sensor positioned at fixed distance from a line heat source can be obtained using De vries equation [90] and is given below.

$$\rho c_p = \frac{q}{\pi e r^2 \Delta T_m} \tag{6}$$

$$\rho c_p = 1.92\,\mathrm{Xm} + 2.50\,\mathrm{Xo} + 4.18\theta \tag{7}$$

where ρ is the soil bulk density, c_p is the specific heat of the soil, e is the base of the natural logarithm, q is the energy applied per unit length of heater, r is the distance between the heater and temperature sensor, ΔT_m is the maximum raise in temperature, Xm, Xo, θ (%) are volumetric contributions of mineral and organic components and moisture, respectively

3.12. Tensiometric techniques

The primary method for measuring matric potential (capillary tension) in soil involves the use of a tensiometer, which directly measures matric potential [55–59,91]. As depicted in Fig. 6, tensiometer consists of a porous ceramic cup which is filled with moisture and buried in the soil at any desired depth. The ceramic cup is connected with a moisture filled air tight tube having a vacuum gauge connected with a tube. When the tensiometer is buried in the soil, moisture inside the porous cup comes in contact with the soil and tends to equilibrate with the soil moisture through the pores in the ceramic cup. This loss in moisture from the air tight tensiometer causes a drop in its hydrostatic pressure, which is indicated by the vacuum gauge.

The main disadvantage of the tensiometer is that it functions only from zero to about 1 atm, which represents a small part of the entire range of available moisture. The lower moisture limit for the good growth of most crops is beyond the tensiometer's range. Hence, it is apparent that the use of tensiometer to schedule irrigation can cause over irrigation, unless tensiometer readings are combined with the information of the soil moisture content. The equipment is well suited in sandy soil where a large part of the available moisture is held at a tension of less than 1 atm, but less suited to fine textured soil where only a small part of available soil is held at 1 atm. Though the tensiometer is inexpensive and easy to install, it requires regular maintenance and disturbs the soil above the point of soil moisture measurement [92].

3.13. Optical techniques

Optical techniques are based on the change in the characteristics of the incident and reflected light when it passes through the soil mass. These methods involve the use of polarized light, fiber optic sensors, and near-infrared sensors [10,26,62,63,65] as explained in the following. However, the practical applications of these sensors for soil moisture measurement are yet to be established.

3.13.1. Polarized light technique

Polarized light technique is based on the principle that the presence of moisture on the surface of reflection tends to cause polarization in the reflected beam. A monochromatic light source is directed at the soil surface and the reflected light passes through a polarizer onto a photocell. As the polarizer rotates, horizontal and vertical polarization signals are formed and can be determined by the photocell. The percentage of polarized visible light is determined from these two measurements and has a relation with soil moisture content. Calibration of this technique is affected by the soil type and roughness of the soil surface [10,62,63].

3.13.2. Fiber optic sensor technique

This technique utilizes an unclad fiber which is embedded in the soil. Light attenuation in the fiber varies with the amount of soil moisture which in contact with the fiber. Refractive index and critical angle of internal friction of the light wave change with the soil moisture content [10,62,63].

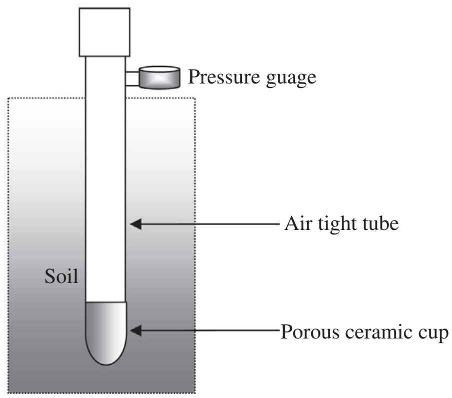

Fig. 6. Schematic diagram depicting soil moisture measurement using Tensiometer.

3.13.3. Near-infrared optical technique

There are several moisture absorption bands in the near infrared, the strongest being at 1450, 1940, and 2950 nm wavelength. Hence, near infrared techniques may be used for monitoring soil moisture content. Such techniques depend on molecular absorption at distinct wavelengths by moisture only on the surface layers. Incidentally, earlier researchers (Sims et al. [66], Eitel et al. [67] and Clevers et al. [68]) have reported the reflection spectrum variation in the Near Infrared Region (NIR), due to the water absorption by targets and its relevance in water content measurement for vegetation, water stress detection and canopy water content determination, respectively. Though, it is a non-contact and rapid moisture sensing technique, results depend upon the characteristics of the soil surface [10,62,63]. Moreover, wide canopy of the vegetation restricts the reflection of the NIR from the soil surface and hence accuracy of the measurement by the sensor might get affected.

Alwis et al. [69] have reported a comprehensive review of the optical fiber based sensor techniques that are employed for humidity and moisture measurements. These authors have highlighted the advantages of such sensors (viz., immunity to electromagnetic interference, chemical inertness, light weight, multiplexing capability, thermal stability and overall suitability for the remote sensing applications) over other electronic sensors. Although, the sensors like fiber grating, evanescent wave based, interferometric and hybrid based (i.e., grating plus interferometric) sensors have been widely employed for humidity and moisture measurement, their applicability to various types of soil moisture content measurement, entirely different characteristics of soils, soil moisture profiling, longevity and dependency on soil temperature are yet to be explored.

4. Critical appraisal

A critical synthesis of the reviewed literature indicates researchers have employed various techniques like classical techniques viz., thermogravimetric and calcium carbide test [18,22,74] and modern techniques viz., neutron scattering, gamma attenuation [22,25,26,45], dielectric techniques [44] including TDR [29,40,43,46,47,74,77,80], FDR [38,86,87,46,47], capacitance probe [38,42,78] and electrical impedance sensor [35] and GPR [10], electrical resistivity box [27], heat pulse sensor [60,61], MEMS [64], tensiometer [92] and optical techniques [10,62,63,66–69] for determining the soil moisture content. Among these techniques, dielectric techniques have been reported to be quite reliable. Furthermore, a summary of recent research in the advanced soil moisture measurement techniques have been illustrated in Table 1 and it must be noted that the researchers have reported the ineffectiveness of these techniques in various types

Table 1
Summary of some recent research in soil moisture measurement techniques.

Year	Authors	Sensor/technique	Remarks
2012	Mittelbach et al. [47]	Comparison of (1) 10HS (Decagon Devices, United States), (2) CS616 (Campbell Scientific, United States), (3) SISOMOP (SMG University of Karlsruhe, Germany) sensors and (4) TDR- based TRIME-IT/-EZ (IMKO GmbH, Germany) sensors	Site specific calibration is vital for better accuracy of soil moisture measurements. Authors also have pointed out that level of performances of sensors are not consistent with that of manufactures' specification.
2011	Rao and Singh [46]	Comparative study between TDR and FDR	Authors have reported that TDR soil moisture measurement is valid up to $\theta = 50\%$, measurement repeatability of FDR probe is better than TDR, but FDR probe has a limitation of showing erroneous results. Authors have also opined that dielectric techniques would give erroneous results in highly saline soils. However the applicability of these techniques in different types of soil has to be conducted.
2011	Fityus et al. [25]	Comparative study between Neutron probe and capacitance probe	Authors have opined that neutron probe is better than capacitance probe in expansive soils. However, it neutron probe is hazardous in handling.
2008	Jackson et al. [64]	Wireless MEMS	The researchers have found that the change in the resistance of the sensor due to moisture depends mainly on the cantilever beam thick-ness and modulus of elasticity, and the quantity of moisture. The authors have concluded that only the cantilever beam thickness and stiffness influence the MEMS sensitivity, and this sensitivity is independent of the cantilever length and shear stress at the cantilever/polymer interface. However the practical implications of this study have to be explored.
2007	Bhat et al. [44]	Dielectric techniques	Authors have reported that dielectric constant of soil is dependent on its type (viz., coarse grained, fine grained), mineralogy, volumetric moisture content and the frequency of AC used for its measurement. The authors have also proposed a generalized equation relating dielectric constant with the minerals present in the soil, porosity and saturation of the soil. However, the implementation of this equation is yet to be done.
2005	Seyfried et al.[86]	Hydraprobe	The researchers have stated that complex dielectric constant is dependent upon temperature, especially imaginary part of dielectric constant is much more sensitive to temperature than real part and it would give variations in the soil moisture measurement.

of soils, lab and field calibration variations with respect to the manufacturers' specifications and the lacunae of the existing calibration equations. It is apparent that none of these techniques provides a holistic approach for obtaining the soil moisture content. For instance, nowadays, dielectric techniques (especially the TDR) are the most commonly employed soil moisture measurement techniques. But, TDR sensor for soil moisture measurement works based on Topp's equation [74,29] which in author's opinion is insensitive to porosity, pore fluid characteristics, saturation and percentage of minerals present in the soil since dielectric constant depends on minerals present in the soil, as also opined by Bhat et al. [44]. However, the generalized relationship proposed by these authors needs to be revised to incorporate the presence of multi-phase mineralogical composition of the soil and the exact quantifications of these minerals is another research to be explored.

Table 2
Comparison of important soil moisture measuring techniques.

Sensor	Flexibility	Depth of measurement	Principle	Major specifications	Response time	Measured parameter	Cost* (USD)	Remarks
Conventional Thermo gravimetric technique	Lab scale	Any depth	Evaporation/ chemical action	105 °C	24 h	Gravimetric soil moisture content	≈400	No health risk, more time consuming, destructive test
Neutron moisture meter	In situ	< 0.3 m	Neutron scattering	Mean energy 5 MeV fast neutron is the input	1–2 min	Volumetric soil moisture content	≈10,000	Health risk, immediate response, more suitable in subsurface soil
TDR	In situ// lab	0.3–0.6 m	Dielectric constant	Operating frequency up to 1 GHz	28 s	Volumetric soil moisture content	≈8000	No health risk, noninvasive way, immediate response, fails in highly saline soils, frequency dependent
Capacitance technique and FDR	In situ// lab	1 m	Dielectric constant	Operating frequency 10–150 MHz	Instantaneous	Volumetric soil moisture content	100–4000	No health risk, requires individual calibration, fails in highly saline soils, frequency dependent
Resistive sensor	In situ// lab	0.1–0.3 m	Electrical resistance	1–15 atm (100–1500 kPa)	2–3 h	Volumetric soil moisture content	5–30	No health risk, time consuming
Thermal dissipation block	In situ// lab	0.1–0.3 m	Heat dissipation	50–200 mA	2–3 h	Volumetric soil moisture content	≈100–150	No health risk, requires individual calibration
Tensiometer	In situ// lab	0.15–0.6 m	Suction or negative tension created	0–1 atm (0–100 kPa)	2–3 h	Suction	~75	No health risk, more time consuming, indirect method

* Panchard [93].

Table 3
Comparison of commercially available TDR and FDR soil moisture measurement techniques.

Commercially available soil moisture sensor	Accuracy	Measurement range	Repeatability	References
TDR				
TRIME PICO 64/32	Not reported	0–100% θ	0.20%	IMKO devices [94,95]
TRIME PICO IPH/T3			0.30%	
TRIME-IT/-EZ	±1% θ for 0–0.40 m^3/m^3; ±2% θ for 0.40–0.70 m^3/m^3	5 and 15 cm depth	Not reported	
FDR				
CS616	±2.5% θ for 0 and 0.50 m^3/m^3;		Not reported	Campbell Scientific [96]
SISOMOP	Relative accuracy of the permittivity of ±4%	0–1 m^3/m^3		Schlaeger [97]
Capacitance type technique				
5TE soil moisture sensor	±1 k_a for (1–40 k_a) and ±5 k_a for (40–80 k_a)	0–100% θ	Not reported	Decagon Devices [98]
EC 5 soil moisture sensor	±3% θ most mineral soils up to 8 dS/m ± 1–2% θ with soil specific calibration			
10HS	Based on Standard Calibration ±0.03 m^3/m^3 in mineral soils; ±0.02 m^3/m^3 based on soil specific calibration	0% and 57% θ		

Table 4
General specifications of the widely used soil moisture sensors.

Parameter	Conventional techniques	Modern techniques			
	Oven drying	Neutron scattering technique	TDR	FDR	Capacitance technique
Accuracy	±0.01 g of the samples of around 100 g	±0.001 to ±0.002%θ	±0.01 to ±0.02%θ	±0.025%θ	±1 to ±3%θ
Repeatability	Not applicable	±0.01 to ±0.03%θ	±0.2 to ±0.3%θ	±0.3 to ±0.4%θ	±0.2 to ±0.30%θ
Sensitivity	±1.5 °C	±0.011 to ±4%θ	±1 to ±3%θ	±1 to ±3%θ	±1 to ±3%θ
Installation	Only for lab application	Access tube is required for profile meter	Permanently or temporarily burying is possible	PVC access tube is required; permanently buried in situ	Permanently or temporarily burying is possible
Data logging	Possible	Not possible	Possible	Possible	Possible
Reference	[99]	[99]	[46,93–95]	[46,95,96,100]	[97]

Comparisons of various soil moisture measurement techniques are presented in Table 2–4. From Table 2, it can be realized that the requirements for fast, reliable, automated and spatially distributed soil moisture measurement by considering soil specific parameters (viz., mineralogy, salinity, porosity, ambient temperature, presence of the organic matter, matrix structure etc.) are not being fulfilled by the current (read commercially) available techniques. The reasons behind this situation are dependency on frequency (TDR and FDR), time consumption (gravimetric technique, tensiometer), need for site specific calibration (FDR, resistive sensors), problems with saline soils (FDR, TDR and resistive sensors), portability issues (NMM, FDR), issues related to health hazards (NMM, Gamma attenuation technique) and extremely high cost of instruments (viz., neutron probe, TDR, FDR). Table 3 depicts the technical specifications of the commercial available TDR, FDR and capacitance type soil moisture measurement sensors. It can be noted that accuracy range of commercially available TDR, FDR and capacitance sensors are ±1–2% θ, ±2.5% θ and ±3% θ respectively. Another interesting fact is that repeatability and sensitivity of these commercially available sensors are not reported in the manufacturers supplied manual. Table 4 describes the general specifications of the widely used conventional as well as modern soil moisture techniques. From the manufactures' manuals [93–100], it can be observed that installations of modern techniques are quite cumbersome, as probes should completely in contact with the soil and any air gap or excessive soil compaction around the probe can profoundly influence the soil moisture measurement readings. It can be found that accuracy, repeatability and sensitivity of neutron probe are much better than the rest of the techniques. However, the difficulties in installation and datalogging, and insecurity are the major demerits of the neutron probes.

Furthermore, none of the existing studies describes the 'influence zone within the soil mass' for which the moisture content measurement is being made. Validity of the commonly employed techniques based on 'dielectric response' of the soils having organic matter, salinity and its overall physical, chemical and mineralogical should be studied thoroughly. Ascertaining the applicability of these techniques to soils of entirely different characteristics and the 'types of moisture content' (viz. hygroscopic moisture, free/gravity moisture, bound/capillary moisture etc.), which they can measure is still a point to be addressed. Hence, there is a need to study the effect of these parameters on the soil moisture measurement and to probe the utility of these techniques for accurate measurements. In this context, fabrication and utilization of nanoscale soil moisture sensors is the need of the hour to facilitate accurate soil moisture content measurements.

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