Estimation of dielectric properties of clay loam and silty soil with different salinity levels over low frequency range

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The dielectric properties of clay loam and silty soil moistened with various proportions of distilled water and saline solutions over the frequency range from 20 Hz to 2 MHz were estimated. It was observed that the dielectric constant ε' and dielectric loss ε'' increased with increase in volumetric moisture content in the soils. Frequency-dependent dielectric constant ε' and dielectric loss ε'' were found to decrease rapidly with increase in frequency. For moist soils, the dielectric loss increased more rapidly with increase in salinity compared to the corresponding dielectric constant. The complex impedance Z^* ($= Z' - JZ''$) was also calculated from the measured values of ε' and ε'' for the soils. The complex impedance plots (Z'' against Z') for clay loamy and silty soils with moisture content of distilled water and saline water solutions revealed that bulk resistance of the soil decreased with increase in salinity in the wet soil, indicating an increase in conductivity of the soil.

Keywords: Clay loam and silty soil, dielectric properties, low frequency range, saline water.

SOIL is a complex material, with the micro–macro structure of pore spaces between the soil particles that vary widely with soil particle size and shape, density, salinity, organic matter content and porosity of the soil[1]. Different types of soils have different physical, chemical and electrical properties[2]. Physical properties of the soil consist of sand, silt and clay contents, bulk density, colour as well as porosity. Chemical properties of the soil include macronutrients and micronutrients like N, P, K, Ca, Mg and Fe, Mn, Zn, Cu respectively. Electrical properties of the soil include conductivity, permeability and permittivity (complex dielectric constant). Electrical properties of the soil provide information about moisture content and salinity of the soil, which is useful in many branches of science and technology, agriculture, hydrology, meteorology, etc. The dielectric behaviour of geological mate-rials can provide useful information about the presence of water in the soil, subsurface properties of the soil and characteristics of adsorbed pore fluid on the soil particles[3,4].

In this study, we have estimated the dielectric properties of two different types of soil with water of different salinities over the frequency range from 20 Hz to 2 MHz using a Precision LCR meter. We have used clay loam and silty soil to estimate the effect of distilled water, 10,000 ppm saline water, 20,000 ppm saline water, 30,000 ppm saline water and Dwarka Sea bank saline water (38,270 ppm) with different moisture content in the soils. It has been observed by researchers that the dielectric constant ε' and dielectric loss ε'' increase with decrease in frequency over the radiofrequency range[5–9].

Materials and method

The experimental set-up and methodology given by Gadani et al.[8] and Chaudhary et al.[10] have been followed in this study to obtain the electrical properties.

Sample preparation

The soil samples were collected from two different locations, namely Undai (Bhabhar-Banaskantha, Gujarat) and Udhamsingh Nagar (Uttarakhand). Stone and gravel fraction was removed from the soil samples, and the remaining finer grained part of the soil samples was oven-dried at 110°C for 24 h. Then distilled water was added to the soil in different proportions and allowed to saturate for 24 h. To observe the effect of saline water on the dielectric properties of the soil, saline solutions of 10,000, 20,000 and 30,000 ppm were prepared by adding NaCl (AR-grade) in proportions of 10, 20 and 30 g/l of distilled water respectively. Saline water (38,270 ppm) was also collected from the Dwarka Sea bank. The saline water was mixed with soils in different proportions and allowed to saturate for 24 h.

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Table 1. Texture of soil samples and their analysis. The analysis of Dwarka Sea bank saline water is also shown

Textures	Undai (Bhabhar, Banaskantha, Gujarat)	Udhamsingh Nagar (Uttarakhand)	Dwarka Sea bank water (Dwarka, Gujarat)
Sand	46.8%	34%	–
Silt	20.9%	63%	–
Clay	32.3%	3%	–
Soil type	Clay loam	Silty	–
Dry density (g/cm^3)	1.4043	1.4113	–
Wt	0.2592	0.1946	–
Porosity	0.4701	0.4674	–
TDS/ppm (salinity)	124	–	38,270
pH at 25°C	7.91	–	7.34
Calcium	15 (ppm)	–	500 (mg/l)
Sodium	14 (ppm)	–	11,150 (mg/l)
Chloride	36 (ppm)	–	20,000 (mg/l)
Magnesium	6 (ppm)	–	1,500 (mg/l)
Potassium	1.1 (ppm)	–	800 (mg/l)
Sulphate	9 (ppm)	–	3680 (mg/l)
Electrical conductivity (mmho/cm)	190 (ppm)	–	65,500
Total hardness (as CaCO$_3$)	–	–	7500 (mg/l)
Total alkalinity (as CaCO$_3$)	–	–	1600 (mg/l)
Latitude	24°01′47.1″N	NA	22°14′06.9″N
Longitude	71°38′15.7″E	NA	68°57′54.3″E
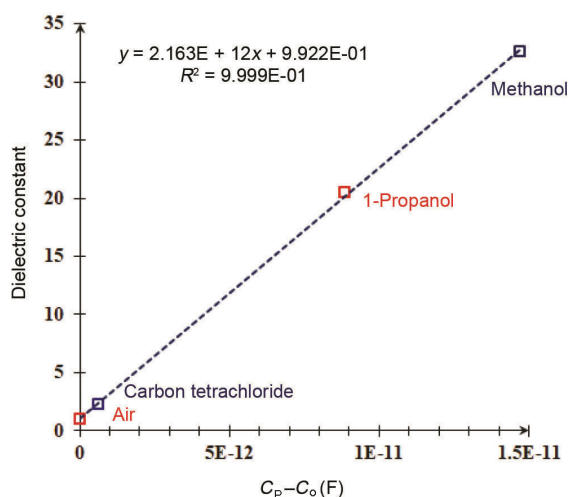
Figure 1. Dielectric constant plotted against $C_P - C_o$ in F.

The gravimetric moisture content (W_m) and volumetric moisture content (W_v) in the soil were calculated using formula as follows[8]

$$W_m = \frac{\text{Weight of wet soil} - \text{Weight of dry soil}}{\text{Weight of dry soil}},$$

$$W_v = \rho_{dry} \times W_m,$$

where ρ_{dry} is the dry density of the soil.

Physical properties

The texture of the soil samples and data on the analysis of saline water of Dwarka Sea coast were obtained from the Vishal Analytical Laboratory, Ahmedabad (Table 1).

Experimental set-up and measurements

A precision LCR meter (Agilent E-4980A) was used for measurements in the frequency range from 20 Hz to 2 MHz. A standard four-terminal probe (Agilent 16089A) with Kelvin clip was connected to the LCR meter. A coaxial capacitor with four vertical cuts on the outer cylinder was used[8], which gives almost *in situ* dielectric properties of the soil sample. The compensation and calibration of the LCR meter and coaxial capacitor were done in two steps: (i) open and (ii) short. Thereafter, the coaxial capacitor was standardized using samples of air, carbon tetrachloride, 1-propanol and methanol, whose dielectric constant is known.

Figure 1 is a plot of dielectric constant against capacitance ($C_P - C_0$), which is a straight line represented by linear trend line equation

$$y = 0.9922 + 2.163 \times 10^{12} x,$$

where $x = (C_P - C_0)$; F and $y = \varepsilon'$ with $R^2 = 0.9999$. C_P is the capacitance of capacitor with dielectric, C_0 the capacitance of capacitor with air as dielectric, $C_P - C_0$ is the difference of capacitance. Hence this equation can be used to calculate the dielectric constant ε' of unknown soil samples as

$$\varepsilon' = 0.9922 + 2.163 \times 10^{12} (C_P - C_0),$$

where $(C_P - C_0)$ is in F.

The above equation was used to estimate the dielectric constant of acetone for verification of the result, by measuring $(C_P - C_0)$ for acetone. The estimated value of ε' for acetone is 20.79 at 2 MHZ, which agrees well with the literature value of 20.7 (ref. 10), with less than 1% error.
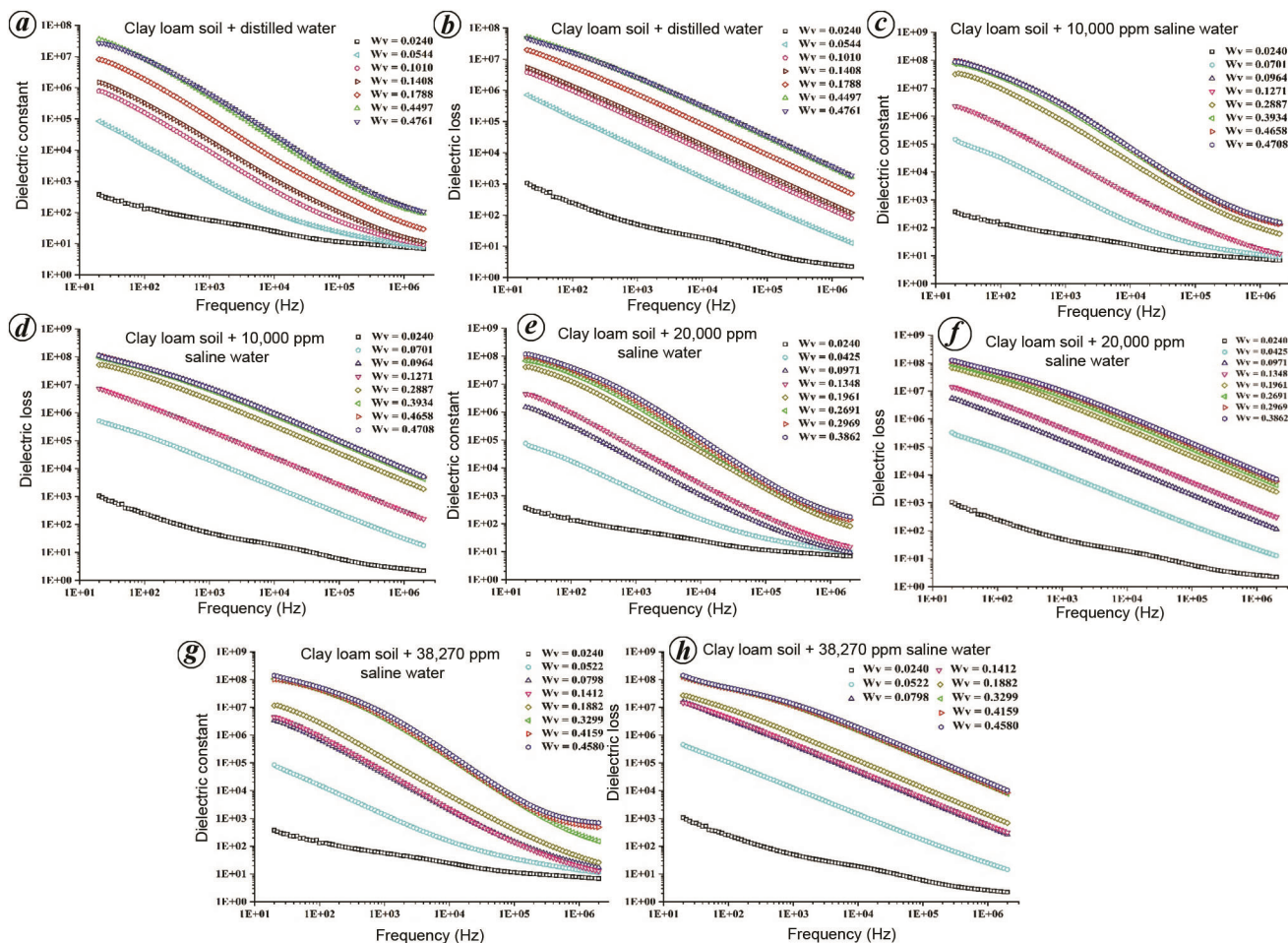
Figure 2 _a–h_. Frequency-dependent dielectric constant ε' and dielectric loss ε'' of clayey loam soil with different concentrations of Dwarka Sea bank saline water, Dwarka, Gujarat.

The dielectric loss was calculated using equation

$$\varepsilon'' = \frac{\varepsilon'}{\omega C R},$$

where we used $C = C_P - C_0$ and $R = R_P$ to calculate ε'' of the soil samples[8,11,12].

The frequency-dependent complex conductivity $\sigma^*(\omega)$ of the soil systems was calculated as follows

$$\sigma^*(\omega) = \sigma' + j\sigma'' = \omega\varepsilon''\varepsilon_0 + j\omega\varepsilon'\varepsilon_0,$$

where $\varepsilon_0 = 8.854 \times 10^{-12}$ F/m is the free space dielectric constant.

Results and discussion

Low frequency dielectric behaviour of wet soil

Figures 2 and 3 show the variation of frequency-dependent dielectric constant ε' and dielectric loss ε'' over the low frequency range from 20 Hz to 2 MHz at room temperature (25°C) for clayey loam and silty soil respec-

tively, with moisture contents of distilled water, saline water and Dwarka Sea water (38,270 ppm). The dielectric constant and dielectric loss increase with decrease in frequency from 2 MHz to 20 Hz. Similar behaviour has been observed by other researchers[1,6,8,13–15]. The large increase in the values of dielectric constant and dielectric loss with decrease in frequency for moist soil is due to the effect of electrode polarization and Maxwell–Wagner polarization[16]. At lower frequency, dipole moment of molecules has sufficient time to accumulate and orient in the direction of the field, because of which charge can be stored and its conductive system is improved. Whereas at high frequency, the required time for orientation and to align in the direction of the electric field is comparatively less. So the dipole orientation does not reach proper alignment in the direction of the field, which can reduce the storing of charge. The dielectric constant of moist soils increases with increase in concentration of salinity, which is due to the presence of Na$^+$ cations. The orientation of the ions towards the electrodes contributes to the capacitance, which gives rise to the dielectric constant and dielectric loss. The electrode polarization (EP) occurs
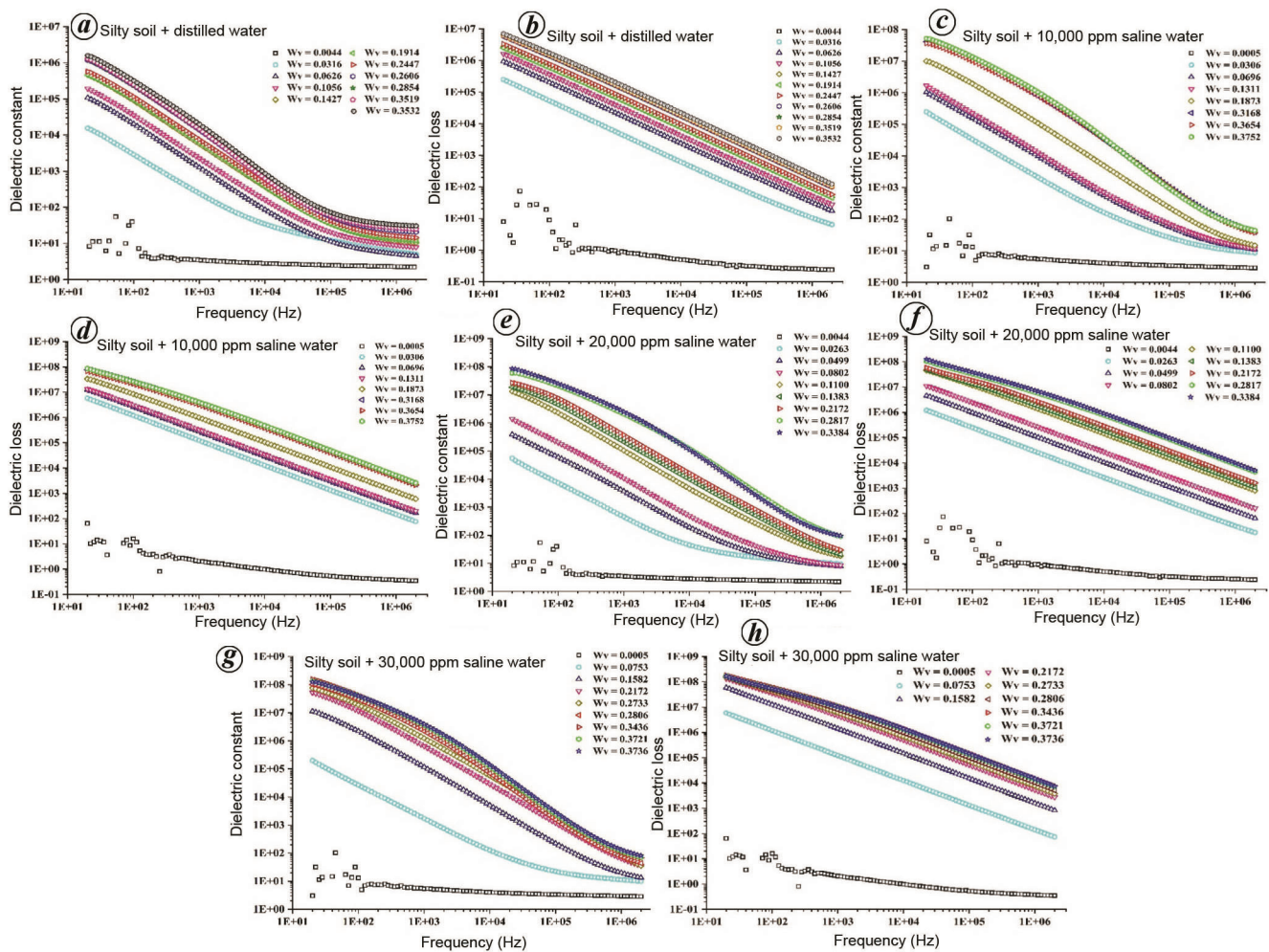
Figure 3 *a–h*. Frequency-dependent dielectric constant ε' and dielectric loss ε'' of silty soil with different concentrations of 30,000 ppm saline water.

due to the formation of electric double layer (EDL) capacitances as free charges build up at the interface between the electrode surface and the wet soil medium[16,17]. The building-up of free charge at the interfacial boundaries between various components of heterogeneous wet soil medium is responsible for the Maxwell–Wagner polarization. In the EP process, when electric field is applied to the material, anions are attracted towards the positive pole and cations towards the negative pole, due to which the poles face the electrode of opposite charge. In the EP region, the slope of logarithmically varying frequency-dependent dielectric constant values close to –1 represent the leakiness of the EDL capacitance to the moving charges, whereas values approaching towards 0 for drier soil as well as for wet soil above ~100 kHz frequency suggest blocking of the charge movement through the layers. From Figures 2 *a*, *b* and 3 *a*, *b*, it can be observed that at 0.14 cm³/cm³ moisture content of distilled water in the soils, the dielectric constant and dielectric loss of clay loam soil are higher than those of silty soil over the whole frequency range. Larger area of soil–fluid interface

increases spatial polarization at low frequency[13]. Further, clay particles have larger water-holding capacity compared to sand, due to larger surface area to volume ratio. Hence the dielectric constant of clayey loam soil is higher than that of silty soil. Further, clay particles contain more cations and dissolved salts. Hence for same moisture content of distilled water in the soil, the conductivity of clayey loam soil is higher than that of the silty soil, which is responsible for higher dielectric loss in clayey loam soil. It can also be observed that as salinity increases, the dielectric loss increases for the same moisture content in the soils, which is associated with increase in the concentration of Na+ ions.

AC conductivity spectra

As shown in Figures 4 and 5, the real part of conductivity σ' for wet soil with distilled water increases slowly with increase in frequency. The values of σ' for wet saline soil increase with increase in frequency and become nearly
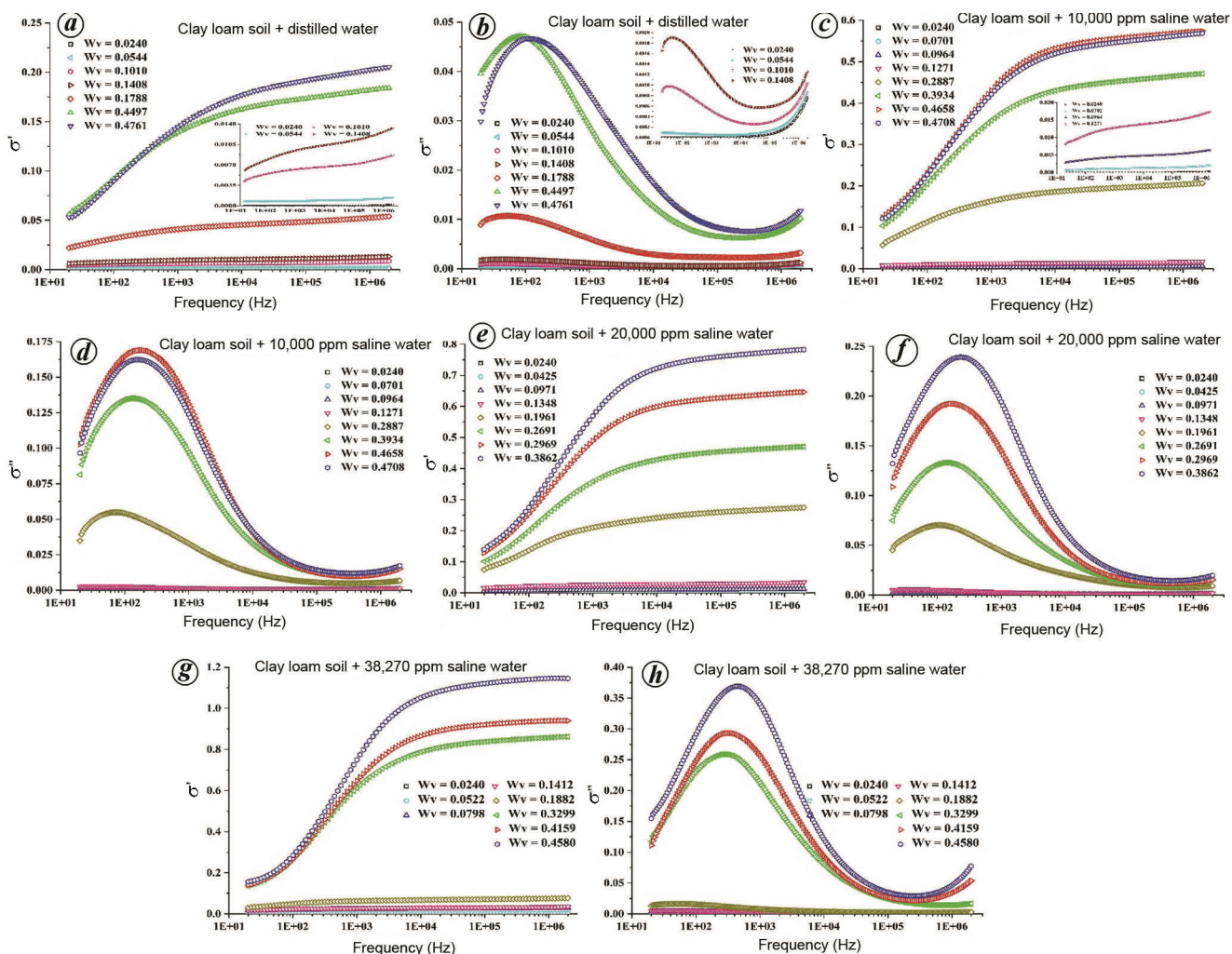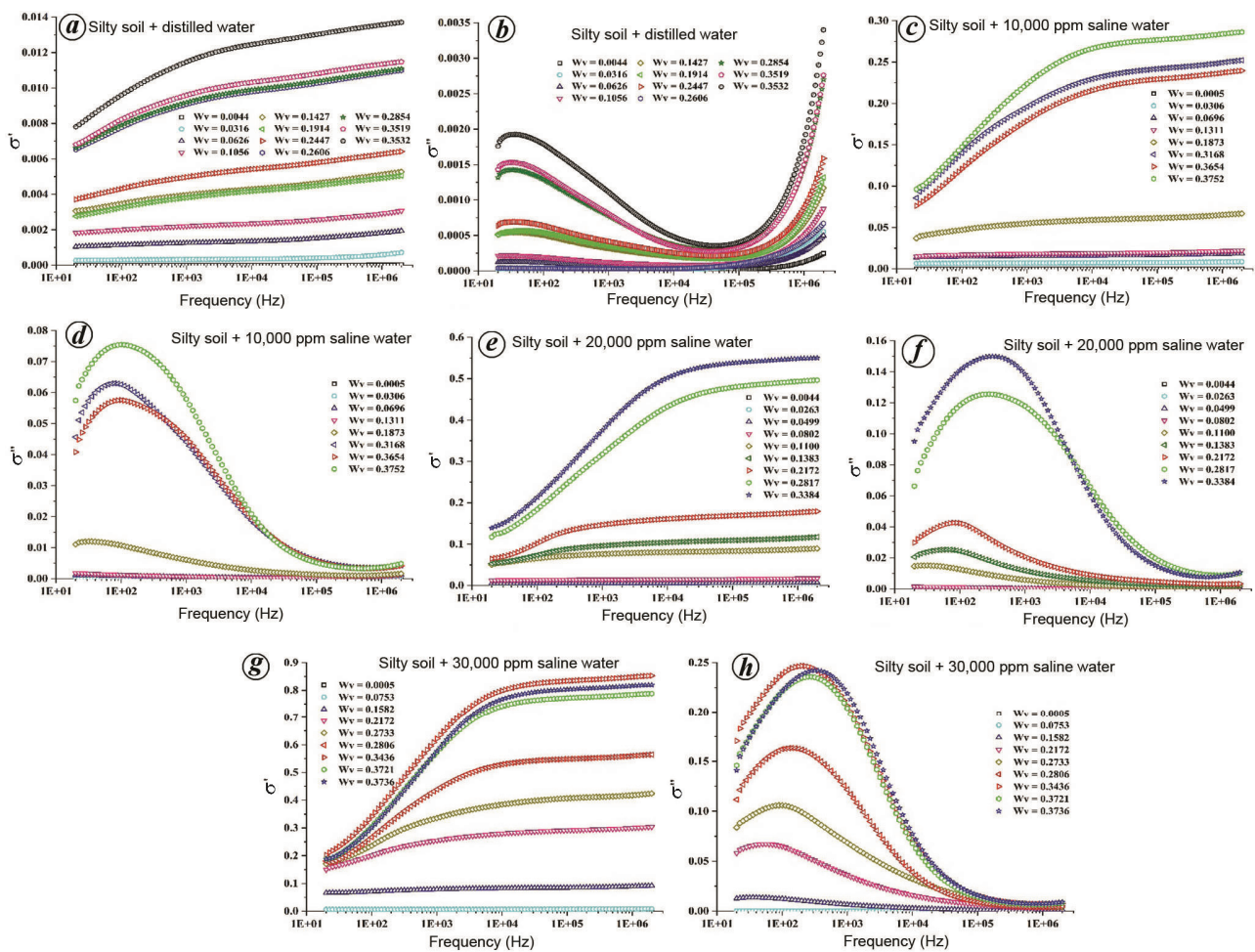
Figure 4 *a–h*. Frequency-dependent real conductivity (σ') and imaginary conductivity (σ'') of clayey loam soil with different concentrations of saline solutions.

Table 2. Variation of dc conductivity of clayey loam soil with moisture content of distilled water and saline solutions

Distilled water		10,000 ppm saline water		20,000 ppm saline water		38,270 ppm saline water	
Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)	Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)	Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)	Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)
0.024	1.18×10^{-6}	0.024	1.18×10^{-6}	0.024	1.18×10^{-6}	0.024	1.18×10^{-6}
0.0544	7.47×10^{-4}	0.0701	5.58×10^{-4}	0.0425	3.65×10^{-4}	0.0522	5.25×10^{-4}
0.1010	0.0042	0.0964	0.0028	0.0971	0.0062	0.0798	0.0175
0.1408	0.0060	0.1271	0.0080	0.1348	0.0155	0.1412	0.0162
0.1788	0.0220	0.2887	0.0569	0.1961	0.0742	0.1882	0.0297
0.4497	0.0562	0.3934	0.1037	0.2691	0.1007	0.3299	0.1374
0.4761	0.0531	0.4658	0.1234	0.2969	0.1285	0.4159	0.1396
		0.4708	0.1211	0.3862	0.1398	0.458	0.1557

constant (plateau region) in the kilo Hertz range in frequency. The plateau region varies with variation in moisture content, salinity of water and the type of soil. The plateau region for clayey loam soil is broader than for the silty soil. Further, as moisture content in the soil increas-

es, the width of the plateau region decreases. Also, for the same moisture content, as the salinity of water in the soil increases, the width of the plateau region decreases. The increase in the values of σ' with increase in frequency, before the plateau region, is evidence for EP effect which

Figure 5 *a–h*. Frequency-dependent real conductivity (σ') and imaginary conductivity (σ'') of silty soil with different concentrations of water solutions.

masks the ionic conduction of the bulk material[18]. The EP phenomenon occurs due to the formation of EDLs (also known as blocking layers) by the free charges that build up at the interface between the wet soil and metallic electrode surfaces[19].

Variation of Ohmic (σ_{dc}) conductivity of soils with moisture content of distilled water and saline solutions

The electrical conductivity of the soil can provide qualitative information about the material[3]. The dc conductivity σ_{dc} represents the number of produced/introduced mobile charge carriers in the materials[8]. Tables 2 and 3 show the variation of dc conductivity of clayey loam and silty soil samples with volumetric moisture content of distilled water and saline water respectively. It can be observed from the tables that the dc conductivity of both soils increases by one order of magnitude with increase in moisture content up to saturation level in the soils. The σ_{dc} values for the soil with distilled water as moisture is lower than the mixture of soil with saline water. Further,

as salinity increases, the dc conductivity of the soil increases. The observed trend for a given moisture content in the soil is

$$\sigma_{dc(\text{soil + distilled water})} < \sigma_{dc(\text{soil + 10,000 ppm saline water})} <$$

$$\sigma_{dc(\text{soil + 20,000 ppm saline water})} < \sigma_{dc(\text{soil + 38,270 ppm saline water})}.$$

In the wet soil medium, increase in ionic conductivity is associated with the number of mobile charge carriers introduced/produced with increase in water content in the soil[17]. According to Dobson *et al.*[20], the adsorbed cations are tightly held with negatively charged dry soil particles, mainly clay. Excess amount of cations, above the required value to satisfy the surface charge density σ of the soil particles, is present in the dry soil as salt precipitate. When water is mixed with soil, the salt precipitates dissolve in the water increasing conductivity of the soil[8]. Thus, the dc conductivity of clayey loam soil is higher than that of silty soil, because of higher clay content in the former soil. Saline water contains a high concentration of dissolved salts. When saline water is mixed with the soils, the salts of the saline water add to the dissolved
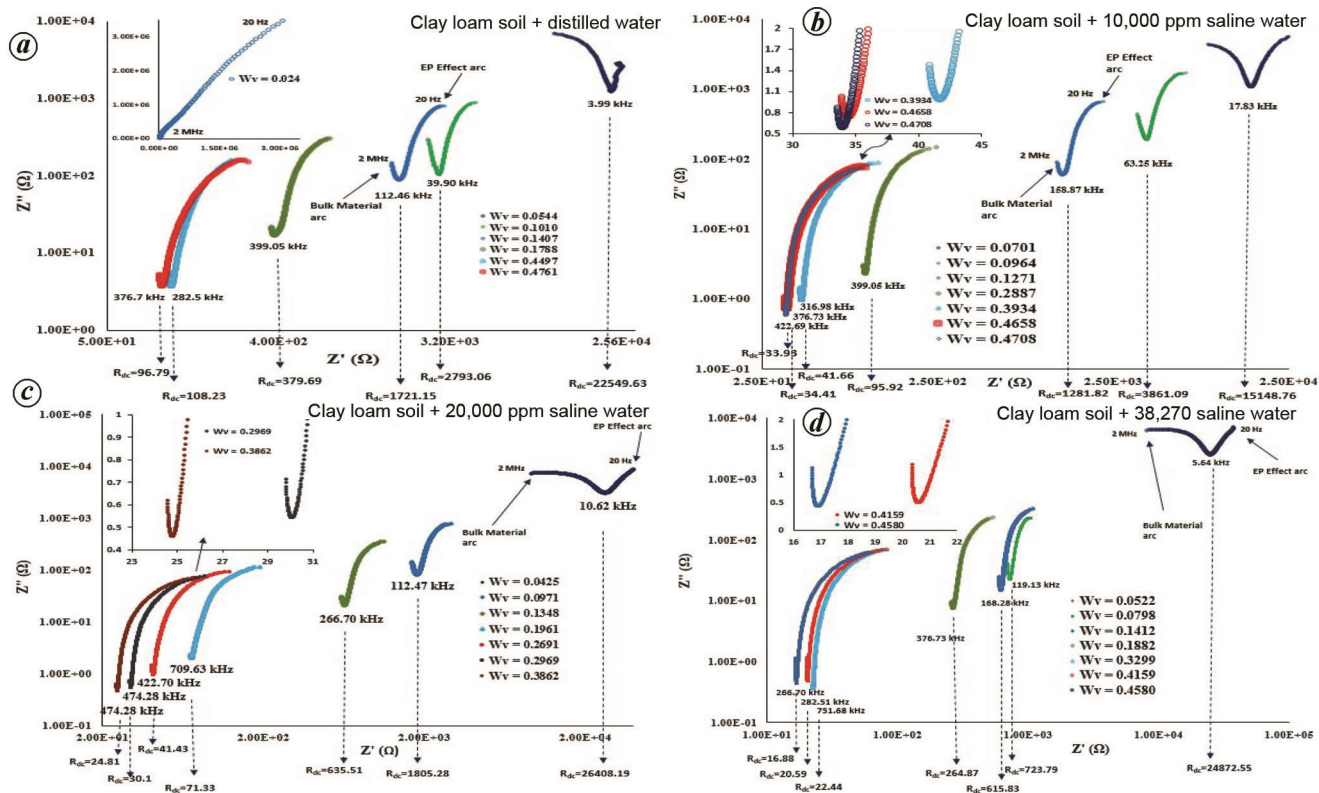
Figure 6 *a–d.* Plot of *Z″* against *Z′* for different moisture content of distilled water and saline solutions in clay loam soil.

Table 3. Variation of dc conductivity of silty soil with moisture content of distilled water and saline solutions

Distilled water		10,000 ppm saline water		20,000 ppm saline water		30,000 ppm saline water	
Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)	Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)	Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)	Volumetric moisture content (cm³/cm³)	DC conductivity (S/m)
0.0044	4.27×10^{-8}	0.0005	7.15×10^{-8}	0.0044	4.27×10^{-8}	0.0005	7.15×10^{-8}
0.0316	2.96×10^{-4}	0.0306	0.0064	0.0263	0.0014	0.0753	0.0064
0.0626	0.0010	0.0696	0.0120	0.0499	0.0049	0.1582	0.0660
0.1056	0.0018	0.1311	0.0148	0.0802	0.0073	0.2172	0.1499
0.1427	0.0031	0.1873	0.0369	0.11	0.0497	0.2733	0.1706
0.1914	0.0028	0.3168	0.0856	0.1383	0.0526	0.2806	0.1803
0.2447	0.0037	0.3654	0.0761	0.2172	0.0644	0.3436	0.2021
0.2606	0.0065	0.3752	0.0962	0.2817	0.1172	0.3721	0.1890
0.2854	0.0066			0.3384	0.1386	0.3736	0.1879
0.3519	0.0068						
0.3532	0.0078						

Table 4. Variation of R_{dc} for clayey loam soil with moisture content of distilled water and saline solutions

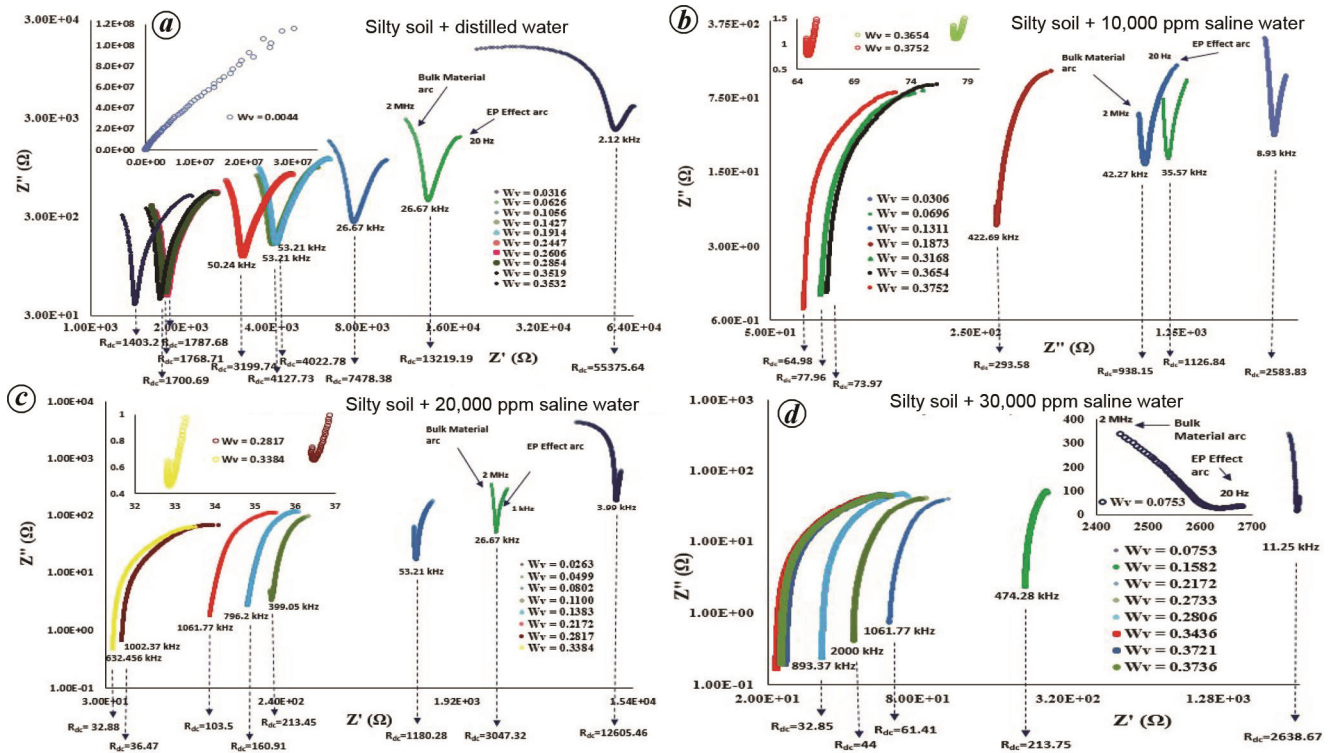| Distilled water		10,000 ppm saline water		20,000 ppm saline water		38,270 ppm saline water	
Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)	Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)	Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)	Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)
0.0544	22549.63	0.0701	15148.76	0.0425	26408.19	0.0522	24872.55
0.101	2793.06	0.0964	3861.09	0.0971	1805.28	0.0798	723.79
0.1408	1721.15	0.1271	1281.82	0.1348	635.51	0.1412	615.83
0.1788	379.69	0.2887	95.92	0.1961	71.33	0.1882	264.87
0.4497	108.23	0.3934	41.66	0.2691	41.43	0.3299	22.44
0.4761	96.79	0.4658	34.41	0.2969	30.10	0.4159	20.59
		0.4708	33.93	0.3862	24.81	0.458	16.88

Figure 7 a–d. Plot of Z'' against Z' for different moisture content of distilled water in clay loam soil.

Table 5. Variation of R_{dc} for the silty soil with various moisture content of distilled water, and saline solutions in the soil

Distilled water		10,000 ppm saline water		20,000 ppm saline water		30,000 ppm saline water	
Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)	Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)	Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)	Volumetric moisture content (cm³/cm³)	R_{dc} (Ω)
0.0316	55,400.00	0.0306	2,583.83	0.0263	12,605.46	0.0753	2638.67
0.0626	13,219.19	0.0696	1,126.84	0.0499	3047.32	0.1582	213.75
0.1056	7478.38	0.1311	938.15	0.0802	1180.28	0.2172	61.41
0.1427	4022.78	0.1873	293.58	0.1100	213.45	0.2733	44.00
0.1914	4127.73	0.3168	73.97	0.1383	160.91	0.2806	32.85
0.2447	3199.74	0.3654	77.96	0.2172	103.5	0.3436	21.56
0.2606	1787.68	0.3752	64.98	0.2817	36.47	0.3721	23.32
0.2854	1768.71			0.3384	32.88	0.3736	22.39
0.3519	1700.69						
0.3532	1403.20						

precipitate salts of clay already present in the soil, due to which the conductivity of clayey loam soil increases further. Modi *et al.*[21] observed that the conductivity of pure water is lower compared to saline water. As salinity increases the conductivity also increases, and hence dc conductivity of the soil increases with increase in salinity in the water.

Complex impedance spectra and R_{dc}

To analyse the bulk material effect and EP effect for different moisture content of distilled water and saline water on the soils, the complex impedance plane plots Z'' against Z' were plotted for the soil samples. Figures 6 and 7 show the complex impedance plane plots (Z'' against Z') of clayey loam soil and silty soil for different moisture content of distilled water and saline water of different salinities. For lower moisture content in the soils, mainly the bulk material effect was observed, corresponding to upper frequency arc. As moisture content in the soil increased, along with bulk material effect (upper frequency arc, to the left of $Z''_{minimum}$), the EP effect (lower frequency arc, to the right of $Z''_{minimum}$) was also observed, separated by minimum values of Z''. The frequency corresponding to these minimum values of Z'' separating the bulk material effect and EP effect, represents the EP relaxation frequency f_{EP}. This can be used to calculate the EP relaxation time $\tau_{EP} = (2\pi f_{EP})^{-1}$. The extrapolated intercept on the Z' axis corresponding to Z''_{min} is useful for

the estimation of the dc bulk resistance R_{dc}, also denoted as R_b of the dielectric material[17]. As the moisture content in the soils increases, the corresponding R_{dc} values decrease. Further, it can be observed from the figures that as the salinity in the soil increases the R_{dc} values decrease, which confirms that the conductivity of the soils increases with increase their salinity.

Tables 4 and 5 show the values of R_{dc} for clayey loam and silty soil respectively. From the tables, it can be observed that with increase in moisture content in the soil, the R_{dc} values decrease rapidly. The R_{dc} value at the 0.14 cm^3/cm^3 moisture content for distilled water is higher than that of Dwarka Sea water. Thus, the R_{dc} value decreases with increase in salinity of the soil. Similar results were observed for silty soil. The value of τ_{EP} at moisture content of 0.14 cm^3/cm^3 for clay loam soil with distilled water was lower than that for the silty soil with distilled water, the higher τ_{EP} values depicting larger time taken by the EDL for charging and discharging[17]. We can conclude that the charging or discharging time for clay loam soil is less than that for silty soil, which contributes to the dielectric constant and dielectric loss. This may be one of the reasons for higher dielectric constant of clayey loam than silty soil.

Conclusion

From the results of this study, the following conclusions have been derived: (1) The dielectric constant and dielectric loss of the soil increase with decrease in the frequency from 2 MHz to 20 Hz. (2) The dielectric constant ε' and dielectric loss ε'' of clayey loam soil is higher than that of silty soil over the whole frequency range for the same moisture. (3) The values of σ' for wet saline soil increase with increase in frequency. (4) As the salinity of the soil increases the R_{dc} value decreases, which confirms that conductivity of the soil increases with increase in its salinity.

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