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 $\varepsilon'$ and dielectric loss $\varepsilon''$ increased with increase in volumetric moisture content in the soils. Frequency-dependent dielectric constant $\varepsilon'$ and dielectric loss $\varepsilon''$ 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 $\varepsilon'$ and $\varepsilon''$ 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.

Materials and method

The experimental set-up and methodology given by Gadani et al. and Chaudhary et al. 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 Udham Singh 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/cm³)       | 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 CaCO₃) | –                                    | –                             | 7500 (mg/l)                            |
| Total alkalinity (as CaCO₃) | –                                    | –                             | 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                           |

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, 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 \( y = \epsilon' \) 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 \( \epsilon' \) of unknown soil samples as

\[
\epsilon' = 0.9922 + 2.163 \times 10^{12} (C_P - C_0),
\]

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 \( \epsilon' \) 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.
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 \( \varepsilon'' \) of the soil samples.

The frequency-dependent complex conductivity \( \sigma^*(\omega) \) of the soil systems was calculated as follows
\[ \sigma^*(\omega) = \sigma' + j\sigma'' = \omega \varepsilon_0 \varepsilon_0 + j\omega \varepsilon_0 \varepsilon_0, \]
where \( \varepsilon_0 = 8.854 \times 10^{-12} \text{ F/m} \) 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 \( \varepsilon' \) and dielectric loss \( \varepsilon'' \) over the low frequency range from 20 Hz to 2 MHz at room temperature (25°C) for clayey loam and silty soil respectively, 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. 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. 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...
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\textsuperscript{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 cm\(^3\)/cm\(^3\) 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\textsuperscript{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\textsuperscript{+} ions.

**AC conductivity spectra**

As shown in Figures 4 and 5, the real part of conductivity \(\sigma'\) for wet soil with distilled water increases slowly with increase in frequency. The values of \(\sigma'\) for wet saline soil increase with increase in frequency and become nearly

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**Figure 3 a–h.** Frequency-dependent dielectric constant \(\varepsilon'\) and dielectric loss \(\varepsilon''\) of silty soil with different concentrations of 30,000 ppm saline water.
Figure 4a–h. Frequency-dependent real conductivity ($\sigma'$) and imaginary conductivity ($\sigma''$) 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 (cm$^3$/cm$^3$) | DC conductivity (S/m) | Volumetric moisture content (cm$^3$/cm$^3$) | DC conductivity (S/m) | Volumetric moisture content (cm$^3$/cm$^3$) | DC conductivity (S/m) | Volumetric moisture content (cm$^3$/cm$^3$) | DC conductivity (S/m) |
| 0.024           | $1.18 \times 10^{-6}$  | 0.024                   | $1.18 \times 10^{-6}$  | 0.024                   | $1.18 \times 10^{-6}$  | 0.024                   | $1.18 \times 10^{-6}$  |
| 0.0544          | $7.47 \times 10^{-4}$  | 0.0701                  | $5.58 \times 10^{-4}$  | 0.0425                  | $3.65 \times 10^{-4}$  | 0.0522                  | $5.25 \times 10^{-4}$  |
| 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 increases, 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 $\sigma'$ with increase in frequency, before the plateau region, is evidence for EP effect which
masks the ionic conduction of the bulk material\textsuperscript{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\textsuperscript{19}.

Variation of Ohmic ($\sigma_{dc}$) 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\textsuperscript{3}. The dc conductivity $\sigma_{dc}$ represents the number of produced/introduced mobile charge carriers in the materials\textsuperscript{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 $\sigma_{dc}$ 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\textsuperscript{17}. According to Dobson et al.\textsuperscript{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 $\sigma$ 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\textsuperscript{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

\[ \text{Figure 5a–h. Frequency-dependent real conductivity ($\sigma'$) and imaginary conductivity ($\sigma''$) of silty soil with different concentrations of water solutions.} \]
Figure 6a–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 (cm$^3$/cm$^3$) | DC conductivity (S/m) | DC conductivity (S/m) | DC conductivity (S/m) |
|-----------------|-------------------------|------------------------|------------------------|
| 0.0044          | $4.27 \times 10^{-4}$   | $7.15 \times 10^{-4}$  | $4.27 \times 10^{-4}$  |
| 0.0316          | $2.96 \times 10^{-4}$   | $0.0064$               | $0.0064$               |
| 0.0626          | $0.0010$                | $0.0120$               | $0.0120$               |
| 0.1056          | $0.0018$                | $0.0148$               | $0.0148$               |
| 0.1427          | $0.0031$                | $0.0369$               | $0.0369$               |
| 0.1914          | $0.0028$                | $0.0856$               | $0.0856$               |
| 0.2447          | $0.0037$                | $0.0761$               | $0.0761$               |
| 0.2606          | $0.0065$                | $0.0962$               | $0.0962$               |
| 0.2854          | $0.0066$                | $0.1386$               | $0.1386$               |
| 0.3519          | $0.0068$                | $0.1879$               | $0.1879$               |
| 0.3532          | $0.0078$                |                       |                       |

Table 4. Variation of $R_d$ 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 (cm$^3$/cm$^3$) | $R_d$ (Ω) | $R_d$ (Ω) | $R_d$ (Ω) |
|-----------------|-------------------------|------------------------|------------------------|
| 0.0544          | 22549.63                | 15148.76               | 26408.19               |
| 0.101           | 2793.06                 | 3861.09                | 1805.28                |
| 0.1408          | 1721.15                 | 1281.82                | 635.51                 |
| 0.1788          | 379.69                  | 95.92                  | 71.33                  |
| 0.4497          | 108.23                  | 41.66                  | 41.43                  |
| 0.4761          | 96.79                   | 34.41                  | 30.10                  |
| 0.3862          | 24.81                   |                       |                       |
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 \( Z''_{\text{min}} \)), the EP effect (lower frequency arc, to the right of \( Z''_{\text{min}} \)) 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 \( f_{\text{EP}} \). This can be used to calculate the EP relaxation time \( \tau_{\text{EP}} = (2\pi f_{\text{EP}})^{-1} \). The extrapolated intercept on the \( Z'' \) axis corresponding to \( Z''_{\text{min}} \) is useful for

**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) | \( R_{dc} (\Omega) \) | Volumetric moisture content (cm³/cm³) | \( R_{dc} (\Omega) \) | Volumetric moisture content (cm³/cm³) | \( R_{dc} (\Omega) \) |
| 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               | 0.3286                      | 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                  | 0.3384                    | 32.88                | 0.3736                      | 22.39                   |
| 0.3519        | 1700.69                | 0.3532                 | 1403.20                |                         |                     |                            |                        |
of the dielectric constant $\varepsilon_0$, also denoted as $R_{dc}$, 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 in 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 $\tau_{EP}$ 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 $\tau_{EP}$ values depicting larger time taken by the EDL for charging and discharging. 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 $\varepsilon'$ and dielectric loss $\varepsilon''$ of clayey loam soil is higher than that of silty soil over the whole frequency range for the same moisture. (3) The values of $\varepsilon'$ 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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