Field Dielectric Sensor for Soil Pollution Application

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Abstract. This paper presents a new dielectric sensor which could be used for assessment and evaluation of soil pollution in the field. The new device determines the dielectric properties of soil from the measured soil impedances. The dielectric properties used as indirect method to estimate type and pollution content in soil. The new device was calibrated and validated for accurate measurement of soil dielectric properties in the frequency range of 1 kHz to 30 MHz. The new proposed dielectric sensor was used to measure the dielectric properties of clean and contaminated soil. The measured dielectric properties of soil using the proposed sensor could be used to estimate soil moisture content, hydrocarbon diesel and salinity in sand soil. The results also show that the dielectric properties of clay soil were higher than the dielectric properties of san due to existing bound water in clay minerals. Further testing is necessary to evaluate the effects of other parameters such as temperature and various type of soil prior to adopt the sensor for field testing.

1. Introduction
Pollution of soil and groundwater resources by waste chemicals has become an issue of increasing environmental concern. The human influences on environmental changes affect dramatically on soil by intensive agricultural production like pesticides and herbicides, petroleum hydrocarbon such as diesel, benzene, kerosene, toluene, ethylbenzene and xylene isomers, heavy metals like iron, copper, zinc, lead and cadmium, solid waste leachate, and other treats are changeable in space and time. Whereas these threats effect on engineering, natural ecosystems, and biodiversity [1], crop production [2], plant growth [3], and on geological, ecological, biological, and hydrological behaviour [4-5]. Dangerous health consequences like cancer or neurological diseases will afflict the human being if exposed over an extended period of these compounds [6]. As a result, a continuous and accurate spatially and temporal record of the soil physical properties are required.

Landfill area produces a very high contaminated wastewater known as leachate. The leachate contains very high dissolved and suspended solids, organic and inorganic matters, and heavy metals. Leachate has such characteristic due to the physical, hydrolytic and fermentation process in the landfill. Furthermore, percolation of liquid through the landfill causes the physical and chemical reactions to occur thus, form leachate that has a complex characteristic. Hydrocarbon soil contamination constitutes a serious environmental problem, given the toxicity level and high mobility of these organic compounds. The detrimental effects are not limited only to the deterioration of chemical, physical and mechanical properties of contaminated soils, but also constitute a real risk to human and living species health. The rehabilitation of these soils requires identification and a rigorous characterization of the contaminated site [7-8].
Usual approaches to measuring the soil contamination include a sampling of soil materials followed by analysis in the lab [9-10]. These approaches pose some problems namely, a) the sample will be smashed up while taking out the soil sample; b) costly and time-consuming; c) during taking until analysing the sample it may contaminate, and it is not constant with time. Since those methods regularly require difficult and repeated works, several researchers have tried to build up user-friendly nondestructive in situ methods. Thus, several geophysical methods have been developed which utilizes the contrast caused by the contaminant on physical properties of the soil [11]. Electromagnetic and dielectric methods show high potential for characterization contaminated soil and determination of the type and level of the contaminants [11]. Further, use of this method; rely upon the availability of information about the dielectric properties of the contaminated soil. Development of such information has formed a focus of research by many authors around the world over several years [11-3-20]. Electromagnetic methods depend on the measured dielectric properties of soil. Several techniques and methods were developed to determine dielectric properties of materials including soil material. These methods include ground penetration radar [12], free space method [13-14], coaxial transmission line [15], waveguide method [16], time domain reflectometer [17-18], resonant cavity method [19], parallel plate method, and capacitance electrode method [20-26]. Among these electromagnetic methods, capacitance electrode method possesses several advantages such as low cost, lightweight, simple method, safe, fast, and various setup of electrode could be used to suite the testing condition. Therefore, this method was adopted to develop a surface capacitive sensor for evaluation asphalt pavement material.

In this study, a new filed dielectric sensor was developed. This dielectric sensor uses the concept of parallel plate electrode and capacitance method. This sensor will be simple to use, low cost, light weight, portable and allow to design the sensor for use in the field. The proposed dielectric sensor will be calibrated with capacitance dielectric cell and validated using standard methods. The sensor was used to determine the dielectric properties of water, clean and contaminated soil to show its capability for use in the field for evaluation soil pollution.

2. Development of field dielectric sensor
This section presents the new field dielectric sensor for assessment of soil pollution. The new sensor was calibrated with the parallel dielectric cell developed in previous research work because it proves to measure the dielectric properties accurately of several materials such as soil, water, and concrete. The detail design of the field dielectric sensor and the lab dielectric device were presented in the following sub section.

2.1. Lab parallel dielectric cell
Lab dielectric capacitance cell was developed in previous study to measure the dielectric properties of liquid like water and particulate material such as soil. The schematic diagram and the actual lab dielectric cell are presented if Figures 1 and 2 respectively.

![Figure 1. Schematic diagram of Lab parallel dielectric cell.](image1)

![Figure 2. Actual lab parallel dielectric cell for soil pollution.](image2)
The dielectric properties of water and soil could be used as indirect method to detect and estimate pollution content in soil and water. In this study the capacitance dielectric cell will be used to validate the proposed field dielectric sensor. Both lab dielectric cell and field dielectric sensor determined the complex permittivity of soil from the measured soil impedance. The complex permittivity of soil ($\varepsilon^*$) is a physical property represents the response of soil to the alternative current (AC) passes through soil. The real component of complex permittivity called dielectric constant ($\varepsilon'$) represent the amount of energy stored in soil because of polarization. The imaginary component of complex permittivity called loss factor ($\varepsilon''$) represents the amount of energy loss in soil as current passes through soil material. These two dielectric properties of soil material are given in equation (1). Details of how to measure these two properties of soil using lab dielectric cell or parallel capacitance cell could be found in previous publication [20].

$$\text{Complex Permittivity} = \varepsilon^* = \varepsilon' + \varepsilon'' \quad (1)$$
given in equation (1). Details of how to measure these two properties of soil using lab dielectric cell or parallel capacitance cell could be found in previous publication [25].

2.2. Design of field dielectric sensor
Several designs were developed, and investigation of the suitability of each design to be used on the site was evaluated. At this stage, no attempt was made to measure the dielectric properties, and only suitability for use in site for soil is considered. Four designs setup were investigated. These four designs for field sensor were pin probe, plate probe, cylinder probe and cone penetration rod. The pin probe presented in Figure 3 was easy to insert in soil in the field, but the electric field of AC signal will not be uniform in soil and will be minimum interaction between the electrode and soil therefore this probe was avoided. The plate probe presented in Figure 4 improves the interaction of AC with soil and form space of uniform electric field in soil, but it suffers from fringing of the electrical field at the edge of the plates. This probe also not used. The third design was cylinder coaxial electrodes presented in Figure 5 which make a uniform electric field in soil, but it is difficult to insert it in soil and avoid air bubbles inside the cylinder. This probe was also excluded. The final design was cone penetration probe which form a rod with ring electrodes. The probe is presented in Figure 6 and this probe was chosen because it could provide acceptable level of soil interaction and easy to insert in soil in the field. In addition, the geotechnical engineers are familiar with the cone penetration test which is like this design configuration. The probe allows using multi ring electrodes which could provide the profile of dielectric measurements at different soil depth.
The final design and setup of the field dielectric sensor for soil pollution application was the cone probe which is very easy to insert in soil for field testing. The probe could use multi ring electrodes. The electric field of the probe could be inside and outside of the rode. Inside impedance of the sensor will be constant while the outside impedance changed with soil properties and condition surrounding the rode and ring electrodes. The schematic diagram, the actual sensor and the electric field are shown in Figure 7. The system consists of an LCR meter as source of AC signal and measure the impedance of the soil. The LCR meter connected to the ring electrodes using coaxial cables. The LCR meter connected to personal computer for automation of calculation.

![Figure 7. Field dielectric sensor; (a) schematic diagram of multi electrode; (b) actual probe and (c) electric field inside and outside the probe.](image)

The impedance \(Z=Z'+iZ''\) of soil surrounding the dielectric sensor measured by the LCR meter at each frequency is used to calculate the complex admittance of soil. The admittance of soil surrounding the dielectric sensor could be calculated from the soil impedance using equation 2.

\[
Y_{soil} = \frac{1}{Z} = Y_{soil}' + iY_{soil}'' = G_{soil} + iB_{soil} \tag{2}
\]

The dielectric constant and loss factors of soil material determined using equation 3 and equation 4, respectively.

\[
\text{Dielectric Constant} = \varepsilon_{soil}' = \left(\frac{B_{soil}}{\omega C_0} - \frac{\varepsilon_{in}}{C_0}\right) \tag{3}
\]

\[
\text{Loss Factor} = \varepsilon_{soil}'' = \left(\frac{G_{soil}}{\omega C_0}\right) \tag{4}
\]

Where \(\omega\) is the angular frequency which could be calculated from operating frequency (f) of the AC signal in Hertz using equation (5).

\[
\omega = 2\pi f \tag{5}
\]

It is necessary to determine the sensor parameters \(C_0\) and \(C_{in}\) at each frequency to calculate the dielectric properties as stated in equations 3 and 4. These two sensor parameters were determined by performing two measurements on two materials with known dielectric properties. These two measurements could be used to form two linear equations which are given by equations 6 and 7.
Deionized water and methyl alcohol were used to determine the dielectric sensor parameters at each frequency. The complex permittivity of deionized water and methyl alcohol were 80.0 - i0.0 and 9.0 - i7.0, respectively. The field dielectric sensor inserted in both deionized water and methyl alcohol at 25°C. The sensor parameters \( C_0 \) and \( C_{in} \) were determined at each frequency from 1 kHz to 30 MHz and stored to be used to calculate soil dielectric properties.

3. Material and methods
This section presents the new material used for calibration and validation of the proposed sensor. In addition, the properties of soil used in this study are presented. The dielectric properties of soil conducted in this study were measured using both parallel capacitance cell and the new field dielectric sensor. All measurements were performed in room temperature 25°C and in the frequency range from 100 kHz to 1 MHz.

3.1. Standard material
Several standard materials were used in this study such deionized water, methyl alcohol. These standard materials used to determine the sensor parameters at each frequency. The complex permittivity of methyl alcohol and deionized water at 25°C were 9.0 - i7.0 and 80.0 - i0.0 respectively [27]. Diesel was collected from Aramco petrol station with density equal 0.865 g/m\(^3\). Diesel dielectric constant and loss factor was 2.5 and 0.083 respectively. Diesel was used to validate the field sensor to measure the dielectric properties of material accurately.

3.2. Soil samples and condition
Two soil material was used in this study, pure sand, and clay soil. The sand porosity was 40% and specific weight was 2.65. Grading and size distribution of both soils were evaluated using sieve analysis and hydrometer method. The size distribution of both sand and clay are presented in Figure 8.

![Figure 8. Size distribution of both sand and clay soil.](image)

The dielectric properties of sand and clay were measured at different frequency range from 100 kHz to 1000 kHz. Dielectric measurements of sand soil were performed at moisture condition from 0% (oven dry sample) 40% moisture (saturated sample with water) with increment of 2.5% and the results were compared at 500 kHz. Saturated sand soil was contaminated by hydrocarbon diesel at five level 0%, 2.5%, 5% 7.5% and 10%. Dielectric constant and loss factor of clean and diesel polluted soil were compared at 500 kHz. In addition, saturated soil were contaminated with salt by adding NaCl. The salinity of three sample were prepared at 0%, 1% and 2%. The dielectric constant and loss factors of saturated clean sand and saline soil were evaluated at frequency range between 100 kHz and 1000 kHz.
4. Results and discussion

The results of calibration and validation procedure carried out for the field dielectric sensor proposed in this study are presented. The dielectric properties of soil sample measured by the proposed field dielectric sensor were also presented in the following subsection.

4.1. Calibration of field dielectric sensor

Two methods were used to calibrate the field dielectric sensor. First method was open/short calibration standard method build in the LCR meter and developed by HP were used to calibrate the field dielectric sensor [28]. After implementing open/short calibration standard the measure impedance of Teflon as standard material was more accurate and the error in the measure value and the actual value reduced from 4% to less than 1% after calibration. The second method used for calibration was the dielectric capacitance cell. Diesel was used as standard material and the dielectric properties of diesel were measure using both capacitance dielectric cell (CDC) and proposed field dielectric sensor (FDS). The results of the dielectric properties of diesel using both FDS and CDC are given in Table 1. The results were compared to calibrate field dielectric sensor. The results obtained indicate that the measure dielectric properties using field dielectric sensor was lower than the value measured by capacitance dielectric cell. This is noticed for several material and the error were very small and almost constant. A correction factor was introduced to make the measured dielectric properties of material is identical (equal value) with the measured values using capacitance cell. The correction factors were used as capacitance cell calibration method. This correction factor is presented in equation (8).

\[
\text{Correction factor} = \frac{\varepsilon'_{\text{using CDC}}}{\varepsilon'_{\text{using FDS}}} \quad (8)
\]

To validate the accuracy of FDS in measuring the dielectric properties of material. The sensor was inserted in water at 25°C and the dielectric properties of water were measured. The results are given in Table 2. The results indicate good agreement with result reported by many researchers. The error in the measured dielectric constant of water from the theoretical value (\(\varepsilon' = 80\)) was less than 2% which is acceptable if we consider that the water may be not pure.

| Frequency (kHz) | Measurements using CDC | Measurements using FDS |
|----------------|------------------------|------------------------|
|                | Dielectric constant (\(\varepsilon'\)) | Loss factor (\(\varepsilon''\)) | Dielectric constant (\(\varepsilon'\)) | Loss factor (\(\varepsilon''\)) |
| 1000           | 2.561                  | 0.151                  | 2.440                  | 0.142                  |
| 900            | 2.531                  | 0.0308                 | 2.517                  | 0.029                  |
| 800            | 2.514                  | 0.028                  | 2.511                  | 0.025                  |
| 700            | 2.537                  | 0.097                  | 2.531                  | 0.093                  |
| 600            | 2.514                  | 0.083                  | 2.510                  | 0.079                  |
| 500            | 2.485                  | 0.069                  | 2.469                  | 0.067                  |
| 400            | 2.461                  | 0.025                  | 2.450                  | 0.022                  |
| 300            | 2.468                  | 0.082                  | 2.459                  | 0.078                  |
| 200            | 2.476                  | 0.036                  | 2.470                  | 0.033                  |
| 100            | 2.442                  | 0.192                  | 2.400                  | 0.190                  |

| Frequency (kHz) | Dielectric constant (\(\varepsilon'\)) | Loss factor (\(\varepsilon''\)) | Error (%) |
|----------------|---------------------------------------|---------------------------------|-----------|

Table 1. Dielectric properties of diesel using both CDC and FDS.

Table 2. Dielectric properties of water using FDS.
4.2. Effect of soil type and moisture

The dielectric constant and loss factor of oven dry sand and clay were measured using the proposed dielectric sensor. The dielectric constant and loss factors of dry sand and dry clay (0% moisture content) over frequency range of 100 kHz to 1000 kHz are presented in Figures 9 and 10, respectively. Both dielectric constant and loss factor of sand and clay decrease with increasing frequency. Polarization of a dielectric material such as clay and sand used in this research is contributed by ionic, electronic, interfacial, and dipole polarization. The electronic and dipole polarization of sand and clay samples occurs in longer interval of time than the time required for alternative current (AC) to change its direction at high frequency. The dipole molecules of soil cannot reorient themselves within a short time available at the high frequency. This will not allow the soil material to store more energy from the applied AC where the AC direction changed very fast. This phenomenon is responsible to decrease both the dielectric constant and loss factor at high frequency for sand and clay. The results also show that both dielectric constant and loss factor of clay is higher than the dielectric properties of sand because clay minerals contain bound water in the microstructure while sand does not have any bound water. The polarization of bound water is very high compared to solid phase of soil. This is the reason behind high dielectric value of clay soil sample.

| Frequency (kHz) | Dielectric Constant | Loss Factor |
|-----------------|----------------------|-------------|
| 1000            | 78.98                | 237.08      |
| 900             | 79.14                | 247.4       |
| 800             | 79.74                | 256.33      |
| 700             | 80.39                | 289.02      |
| 600             | 81.02                | 336.79      |
| 500             | 81.09                | 405.46      |
| 400             | 81.17                | 533.32      |
| 300             | 81.29                | 724.13      |
| 200             | 81.42                | 1077.5      |
| 100             | 81.04                | 2368.33     |

To evaluate the effect moisture condition of soil, sand samples were prepared at different moisture content range from 0% to 40% (oven dry to saturated condition). The dielectric properties of moist sand soil were measured using the developed sensor at each moisture condition. The results of dielectric constant and loss factor versus moisture condition at 500 kHz are presented in Figure 11 and 12. The results indicate that both dielectric constant and loss factor increase with increasing moisture condition. This is due to high dielectric properties of water molecules compared to low dielectric
properties of solid sand particles. Dielectric constant of water is 80 while dielectric constant of solid sand particles ranges from 2.5 to 4. The relationship between dielectric properties and loss factor was established using nonlinear regression analysis. The relationship was quadratic function as given by equations (9) and (10). The square coefficient factors of the models were 0.9949 and 0.9975 for both dielectric constant and loss factor, respectively. This shows high prediction and of soil moisture using the proposed sensor.

\[
\text{Dielectric constant} = \varepsilon' = \beta_0 + \beta_1 \theta + \beta_2 \theta^2 + \beta_3 \theta^3 \quad (9) \\
\text{Loss factor} = \varepsilon'' = \beta_0 + \beta_1 \theta + \beta_2 \theta^2 + \beta_3 \theta^3 \quad (10)
\]

Where \( \theta \) is the moisture content, \( \beta_0, \beta_1, \beta_2, \) and \( \beta_3 \) are constant parameters. This is in good agreement and similar models developed by Topp et al. using time domain reflectometer [18].

4.3. Effect of pollution type and content
The dielectric constant and loss factor of saturated sand soil at various diesel pollution level were measured and compared at 500 kHz. The results are presented in Figure 13 and Figure 14. The results show that both dielectric constant and loss factor of sand decrease with increasing diesel pollution. This is due to the low dielectric properties of diesel and replacement of good-conducted water by low conductive diesel in soil sample increase the resistivity of soil and decrease the conductivity which resist the AC current to pass through sand soil. This result indicate that the proposed sensor could be used to estimate the level of diesel content and pollution in sand. In addition, the results is agreed with the results obtained by Chenaf and Amara [17].

The dielectric constant and loss factor of sand polluted with salt content were evaluated in the frequency range between 100 kHz to 1000 kHz. The relationships between dielectric constant, loss factor and soil salinity are presented in Figures 15 and 16. The results indicate that dielectric constant decrease with increasing salinity of sand while the loss factor increase with increasing the salinity.
This is due to high conductivity of salt which increase the loss factor. The results indicate that the dielectric sensor could be used to detect salt in sand soil and quantify its salinity.

\[ \text{Figure 15. Dielectric constant versus frequency at different salinity.} \]

\[ \text{Figure 16. Loss factor versus frequency at different salinity.} \]

5. Conclusion
This paper presents a field dielectric sensor developed for determination of soil dielectric constant and loss factor of soil in low the frequency ranges from 100 kHz to 1000 kHz for soil pollution assessment. The sensor was designed and fabricated to suite the field testing of soil. The dielectric sensor was calibrated and validated using parallel capacitance dielectric cell. The sensor shows the capability to measure soil dielectric properties with accuracy less than 2%. The measured dielectric constant shows the potential to estimate the soil moisture content. In addition, the measured dielectric properties using the proposed dielectric sensor could be used to determine the diesel pollution content and soil salinity. Further testing including temperature, various types of soil and different types of pollution is necessary before adapting the use of this sensor. The results of dielectric constant of soil at different moisture content and diesel pollution content is in good agreement with results obtained by other researchers using different techniques.

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Acknowledgments
Authors thank staff of Jadara University, King Khalid University, and Yarmouk University for help to conduct testing and using the lab facilities.