Wave Based Monitoring of Water-Driven Deterioration Process of Unsaturated, Stressed Collapsible Soils

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Abstract

A new approach for monitoring of water caused deterioration process in unsaturated, stressed collapsible soils based on experimental high frequency electromagnetic (HF-EM) investigations with an open ended coaxial line technique is presented. The tests were performed in a one dimensional controlled loading cell under simultaneous measurements of complex dielectric permittivity or conductivity, vertical stress, deformation and other soil hydro-mechanical conditions. In addition, the variation of the complex dielectric permittivity of collapsible soils with changes in soil hydro-mechanical conditions, in particular moisture content and porosity, was studied experimentally and theoretically, as the collapse mechanism is highly influenced by soil hydro-mechanical conditions. Strong correlation between water caused collapse and complex dielectric permittivity of collapsible soils was obtained.

Keywords: Collapsible soils, complex dielectric permittivity, water content, porosity, collapse

1. Introduction

Collapsible soils, widely regarded as problematic soils, are weak soils that appear to be stable in their natural dry state, but deform rapidly during wetting, generating large and often unexpected settlements which often yield disastrous consequences for structures unwittingly built on such deposits. The collapse mechanism is triggered when a critical moisture content is reached in the soil. Determination of the collapse triggering critical moisture content and monitoring of the collapse behavior is vital in the remedial measures of stabilizing and improving of collapsible soils.

In this work, the relationship between water-driven collapse and complex dielectric permittivity of collapsible soils based on experimental studies is presented. In addition, the physical relationship between HF-EM soil properties in terms of the frequency dependent complex dielectric permittivity and soil hydro-mechanical conditions was theoretically analysed by modifying the advanced theoretical HF-EM mixture model suggested by Wagner et al. [1].

2. Soil dielectric behaviour

The broadband theoretical frequency and temperature-dependent mixing rule (Eq. 1) suggested by Wagner et al. [1], based on soil porosity n, volumetric water content \( \theta \) (m\(^3\)/m\(^3\)), complex permittivity of pore water \( \varepsilon^*_w \), structural exponent \( 0 \leq a \leq 1 \) and relative real permittivity of the solid grain particles \( \varepsilon_G \), which is called advanced Lichtenecker and Rother Model (ALRM), was modified by the authors to predict the complex dielectric permittivity of the studied collapsible soil. A linear relationship between the structural exponent \( a \) and the volumetric water content \( \theta \) (m\(^3\)/m\(^3\)), with boundary conditions of \( a_d = 0.2 \) and \( a_s = 0.6 \) for dry and saturated collapsible soils, respectively, has been used, as several authors [2, and others] have shown the reliance of the structural exponent \( a \) on the volumetric water content based on empirical studies of several soils. Moreover, the assumption of a constant structural exponent \( a \) underestimates the dielectric permittivity for volumetric water content below 15% vol. and...
overestimation above [1]. The experimental findings were also verified with prediction of the ALRM model with structural exponent a = 1/2, to represent the version of Lichtenecker and Rother model commonly known as the complex refractive index model (CRIM) [3] or generalized refractive mixing dielectric model (GRMDM) [4], and with a = 1/3, the Looyenga-Landau-Lifschitz model (LLLM) [5, and others].

\[ \varepsilon_{\text{eff}}^{\text{re}}, \theta = \varepsilon_{\text{eff}}^{\text{re}}, \theta (w, T) + (1 - n)\varepsilon_{\text{eff}}^{\text{re}}, \theta (w, T) + (n - \theta) \quad \ldots \quad (1) \]

3. analysed soil

Remolded samples of collapsible soil taken from near Baku area, Azerbaijan, at a depth range of 2.0 m to 2.5 m were used for the experimental program. The common geotechnical and physiochemical characteristics of the studied collapsible soil (obtained following ASTM 2011 [6]) are listed in Table 1. Phase content was determined quantitatively by combined X-ray diffraction (XRD) and X-ray fluorescence (XRF) analysis.

Table 1. Geotechnical and physiochemical properties of the studied collapsible soil

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Property (USCS)*</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific gravity (g cm(^{-3}))</td>
<td>2.735</td>
<td>Classification (USCS)*</td>
<td>CL</td>
</tr>
<tr>
<td>Initial water content w (%)</td>
<td>9.3</td>
<td>Organic content (%)</td>
<td>5.811</td>
</tr>
<tr>
<td>Liquid limit (%)</td>
<td>31.3</td>
<td>Lime content (%)</td>
<td>12.944</td>
</tr>
<tr>
<td>Plastic limit (%)</td>
<td>17.0</td>
<td>Tectosilicates (%)</td>
<td>44</td>
</tr>
<tr>
<td>Plastic index (%)</td>
<td>14.3</td>
<td>Mica (%)</td>
<td>25</td>
</tr>
<tr>
<td>Clay % (&lt; 0.002 mm)</td>
<td>34</td>
<td>Smectite (%)</td>
<td>7</td>
</tr>
<tr>
<td>Silt % (0.002 - 0.063 mm)</td>
<td>51</td>
<td>Chlorite (%)</td>
<td>5</td>
</tr>
<tr>
<td>Sand % (0.063 - 2 mm)</td>
<td>15</td>
<td>Kaolinite (%)</td>
<td>3</td>
</tr>
</tbody>
</table>

* USCS unified soil classification system

4. Results and discussions

4.1 Variation of \(\varepsilon_{\text{eff}}^{\text{re}}\) with hydro-mechanical conditions of collapsible soil

The results of electromagnetic measurements on collapsible soil samples at natural loose condition (\(\varepsilon_0 = 0.83\)) and lab compacted condition (\(\varepsilon_0 = 0.43\)) are shown in Figure 1. The values of the relative effective complex dielectric permittivity \(\varepsilon_{\text{eff}}^{\text{re}}\) at a particular frequency of 1 GHz were selected from the spectra in order to compare the dispersion and absorption directly. The results were compared to the modified ALRM model presented in this research and the frequently used empirical relationship suggested by Topp et al. [7]. The measured real \(\varepsilon_{\text{eff}}^{\text{re}}\) part of relative effective complex dielectric permittivity of the collapsible soil at loose saturated condition, \(\varepsilon_{\text{eff}}^{\text{re}} @ 1 \text{ GHz} = 29.42\), was much higher than that of the collapsible soil at lab compacted saturated condition, \(\varepsilon_{\text{eff}}^{\text{re}} @ 1 \text{ GHz} = 21.12\), Figure 1 (left and middle). This is primarily due to the fact that the collapsible soil at loose saturated condition (comparatively with a higher void ratio), has a relatively higher amount of liquid phase (pore fluid) at saturated condition, which results in a much better conducting pathway for dielectric permittivity or conductivity [8, 9].

However, the difference between the measured imaginary \(\varepsilon_{\text{eff}}^{\text{re}}\) part of relative effective complex dielectric permittivity of the collapsible soil at loose saturated condition, \(\varepsilon_{\text{eff}}^{\text{re}} @ 1 \text{ GHz} = 22.57\), and the collapsible soil at lab compacted saturated condition, \(\varepsilon_{\text{eff}}^{\text{re}} @ 1 \text{ GHz} =\)
21.34, was relatively small, Figure 1 (right). The $\varepsilon''_{\text{r,\text{eff}}}$ of a soil is mainly influenced by the amount of dissolved solutes in the pore water solution and the corresponding Ohmic and polarization losses [9, 10] when the soil is subjected to an electromagnetic wave, both of which are not significantly affected by changes in soil porosity.

Figure 1. Variation of $\varepsilon'_r, eff$ (left and middle) and $\varepsilon''_r, eff$ (right) with gravimetric water content $w$

### 4.2 Variation of $\varepsilon^*_r, eff$ during a water driven deterioration process of collapsible soil

Figure 2 shows results of electromagnetic measurements conducted during a one dimensional controlled loading test on a collapsible soil initially at natural condition ($w = 0.09 \, \text{g g}^{-1}$), but was later inundated with water at a stress level of 50 kPa, to monitor progression of collapse of the sample with measurements of complex dielectric permittivity or conductivity. It can be seen that the measured complex dielectric permittivity $\varepsilon^*_r, eff$ of the collapsible soil increased rapidly when water was introduced to the sample in the test box. Casagrande [11] has demonstrated that a portion of the fine-grained fraction of the soil exists as bonding material for the larger-grained particles and that these bonds undergo local compression in the small gaps between adjacent grains resulting in the development of strength. When the loaded soil is exposed to moisture, and a certain critical moisture content is reached, the fine silt or clay bridges that are providing the cementation will soften, weaken and/or dissolve to some extent. Eventually, the binders reach a stage where they no longer resist deformation forces and the structure collapses [12]. As the water molecules react and dissolve the clay and/or silt bridges, the concentration of $\text{Na}^+$, $\text{Ca}^{++}$, $\text{OH}^-$ and other alkali ions in the pore water solution rises rapidly, producing a sharp increase in the recorded values of $\varepsilon^*_r, eff$.

Figure 2. Plot of time with $\varepsilon^*_r, eff$ and deformation (left), $\varepsilon'_r, eff$ (middle) and $\varepsilon''_r, eff$ (right) as functions of frequency $f$
5. Conclusions

In this work, a new approach for monitoring of water caused deterioration process in stressed collapsible soils based on experimental high frequency electromagnetic (HF-EM) investigations, conducted by fitting an open ended coaxial line horizontally into a one dimensional controlled loading device, is presented. In addition, the variation of complex dielectric permittivity \( \varepsilon_{r,\text{eff}}^* \) of collapsible soils with changes in moisture content and porosity was investigated, as the collapse behavior is highly affected by soil hydro-mechanical conditions. The work presented in this research can be extended further to enable accurate in-situ and laboratory determination of the collapse potential of collapsible soils using dielectric measurements, providing a platform of widely applicable and easy to use equipments, such as time domain reflectometry (TDR), for the identification and improvement of such deposits.

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References