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LOW FREQUENCY DIELECTRIC BEHAVIOR OF NEAR SURFACE COHESIVE SOILS

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Abstract. The frequency (f) and the volumetric water content (θ) dependencies of the real (ε') and the imaginary (ε'') components of the complex dielectric permittivity, of the six cohesive soil samples extracted from the near surface of the Banat area, Romania, in the frequency range 500 Hz to 2 MHz, was investigated. The results indicated the relaxation and conduction loss. The experimental dependence $\varepsilon'(\theta)$ at 100 kHz, 500 kHz, 1 MHz and 2 MHz were compared using the theoretical soil texture independent models of Topp and Wensink, and the theoretical soil texture dependent model of Wang-Schmugge. The results obtained, for all samples, shown that the experimental dependence $\varepsilon'(\theta)$, fits reasonably well with the theoretical models, for frequencies in the range of 500 kHz to 2 MHz, and for volumetric water contents, greater than 10%, but are dispersed at frequencies around and less 100 kHz.

Key words: soils, complex dielectric permittivity, volumetric water content, topp and Wensink model, Wang-Schmugge model.

1. INTRODUCTION

Soil is a heterogeneous multiphase porous system with three natural phases: (a) the solid phase (consisting of mineral particles and solid organic materials); (b) the liquid phase, represented by water; and (c) the gaseous phase, which contains air and other gases. The volume size and distribution of the three phases are specific to each type of soil, determining its water content and strength [1].

When interacting with an electric field, cohesive soils show a specific electrical behavior that can be used to investigate their characteristics [2]. In the past decades some empirical and semi-empirical dielectric mixing models have been developed for the determination of the dielectric behavior of cohesive soils as a function of the complex dielectic permittivity [3, 4, 5].

The frequency of the electrical field, the volumetric water content θ, the salinity and clay content of soils, are all factors that influence both the real, ε' and imaginary ε'_{eff}, components of the complex dielectric permittivity and determine dielelectric losses [6].

In this paper we determined the frequency (f) and the volumetric water content (θ) dependencies of the real, ε' and the imaginary, ε''_{eff}, components of the complex dielectric permittivity in the frequency range 500 Hz–2 MHz, of cohesive soil samples from the Banat area of the western part of Romania.

Furthermore we made a comparison between the Topp, Wensink, and Wang-Schmugge theoretical models and the $\varepsilon'(\theta)$ experimental dependence.

2. SAMPLES AND EXPERIMENTAL INVESTIGATIONS

Six soil samples were extracted from different locations belonging geographically to the Banat area and geologically to the Pannonian Basin [7].

The soil samples were collected from the upper cohesive soil horizon of the Banat region, from depths between 0,8 m and 1,5 m and denoted as A, B, C, D, E and F. The natural gravimetric water content of the investigated samples, defined as, $w = M_w / M_S$, where M_w is the mass of water and M_S is the soil mass, was determined according to the Romanian standard [8]. The samples were weighed before and after the procedure and the gravimetric water content was obtained.

The determination of the void ratio of the investigated samples, defined as $e = V_P / V_S$, where V_P is the void space and V_S is the volume of solids, was done according to the Romania standard by using the paraffin method [9].

Considering for the density of water the value $\rho_w = 1$ *g/cm³* and for density of the mineral skeleton, the value $\rho_S = 2.66$ g/ cm^3 [9, 10], and knowing the values of the gravimetric water content *w* and the void ratio *e*, the following expression can be found to link the volumetric water content, defined as $\theta = V_w / V_T$, where V_w is the volume of water and V_T is the total volume, to the values of the gravimetric water content *w*, and the void ratio *e*:

$$\theta = \frac{V_w}{V_T} = \frac{M_w}{(V_P + V_S)\rho_w} = \frac{M_w \rho_S}{M_S(1 + V_P/V_S)\rho_w} = \frac{\rho_S w}{\rho_w}\frac{1}{1+e} = 2.66 \cdot w \cdot \frac{1}{1+e}. \quad (1)$$

All samples were furthermore measured for their decreasing water content (the measurements were made at room temperature at intervals of hours and days, so that only the free water from the macro pores and the micro pores would evaporate). All the results for *w*, θ and *e* are shown in Table 1.

The textural soil classes of the samples were determined based on the particle size distribution using the ternary diagram [11]. Also, the grain size range and composition of each sample is specified. From this, the mean grain diameter range was computed. All the results are shown in Table 2.

Table 1

Natural gravimetric water content *w*, natural volumetric water content θ and the void ratio *e* values, for all the investigated soil mixtures samples

	e	*w* [%]	θ [%]						
			Initial value	After 1 h	After 2 h	After 4 h	After 6 h	After 24 h	After 36 h
A	0.79	23.8	35.6	26.2	5.21	3.5	≈0	-	-
B	0.84	13.96	20.2	15.6	11.19	3.2	0.53	≈0	-
C	0.84	17.30	25	19.2	18.2	7.8	4.5	1.7	≈0
D	0.87	19.62	27.9	23	20.2	9.2	5.7	2.1	≈0
E	0.82	16.85	24.6	20.7	19.1	8.2	1.9	≈0	-
F	0.94	20.64	28.3	26.9	24.2	22.4	9.9	1.5	≈0

Table 2

Textural soil classes, grain size analysis and mean grain diameter range of the samples

Sample	A	B	C	D	E	F
Soil class	siCl	siCl	clSi	siCl	siCl	siCl
Clay [%] $d < 0.002$ (mm)	26%	26%	14%	34%	36%	39%
Silt [%] $0.002 < d < 0.063$ (mm)	61%	66%	79%	61%	61%	61%
Sand [%] $0.063 < d < 0.63$ (mm)	13%	8%	7%	5%	3%	0%

As seen in Table 2, except for sample C classified as clayey silt (clSi) all the other samples are classified as silty-clays (siCl), and are all mixtures of the three basic fractions of silt, clay and sand.

The mean grain diameter range of the samples is also listed in Table 2. The large amount of clay particles in all the samples contributes to their cohesive nature by binding more water on their surface [1].

For the dielectric measurements, each initially extracted soil sample was cut in the shape of a disc of fixed thickness (d=15 mm) with a diameter of 6 cm and then fixed between the plates of the capacitor using an adjustable skrew. The capacitance, C and dissipation factor, $\tan\delta$, of the samples, were measured at room temperature (T=300˚K) in the frequency range 500 Hz to 2 MHz, using an Agilent LCR meter (type A-4980A).

The measurements carried out with the sample, leaded to the values: $(\tan\delta_p, C_p)$ and without the sample, to the values $(\tan\delta_0, C_0)$, respectively. From these measurements, the real and imaginary part of the complex dielectric permittivity of the soil samples were determined [12] using the following equations:

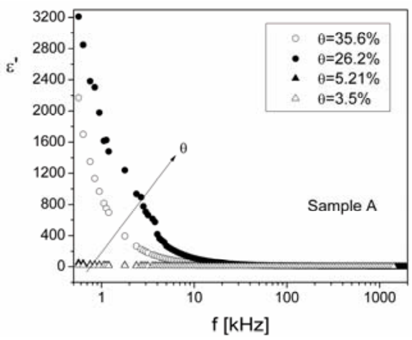
$$\varepsilon' = \frac{C_p}{C_0}, \tag{5}$$

$$\varepsilon''_{eff} = \varepsilon' \tan\delta_P - \varepsilon'^2 \tan\delta_0 . \tag{6}$$

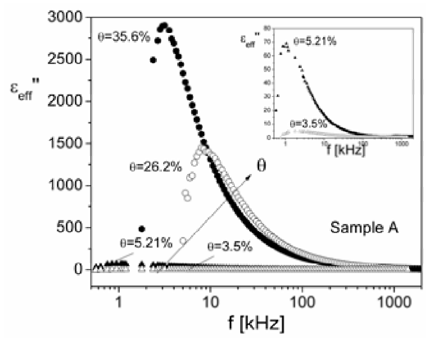
3. RESULTS AND DISCUSSION

3.1. DIELECTRIC PROPERTIES AND BEHAVIOR OF COHESIVE SOILS

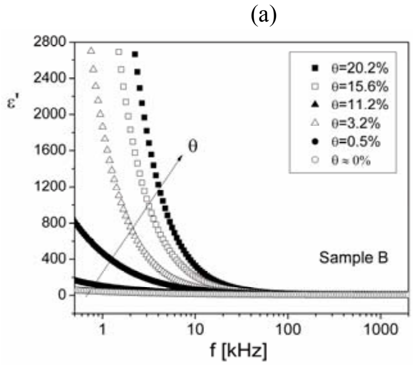
The frequency dependence of the real ε' and imaginary, ε''_{eff} components of the complex dielectric permittivity for all investigated samples is shown in Fig. 1.



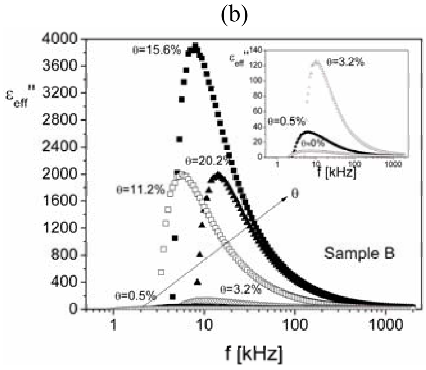
(a)



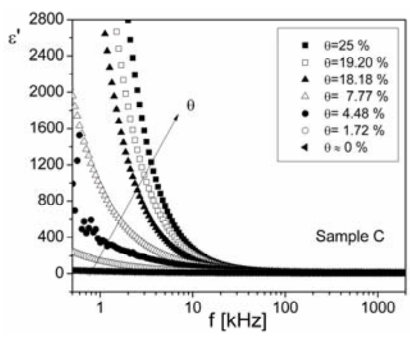
(b)



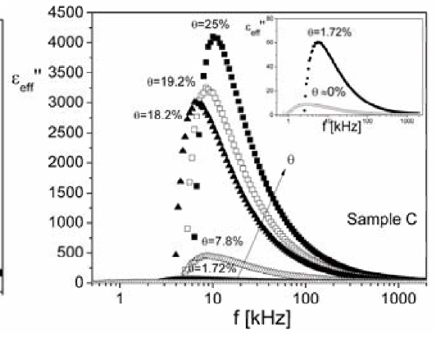
(c)



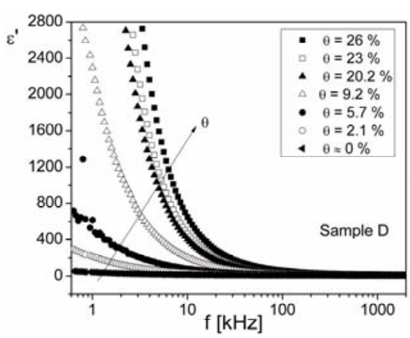
(d)


ε'
θ=25 %
θ=19.20 %
θ=18.18 %
θ= 7.77 %
θ= 4.48 %
θ= 1.72 %
θ ≈ 0 %
θ
Sample C
f [kHz]

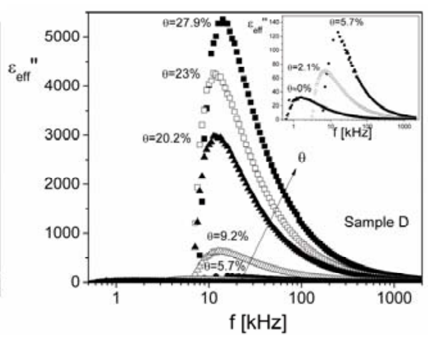
(e)


ε_{eff}"
θ=25%
θ=19.2%
θ=18.2%
θ=7.8%
θ=1.72%
θ
Sample C
f [kHz]

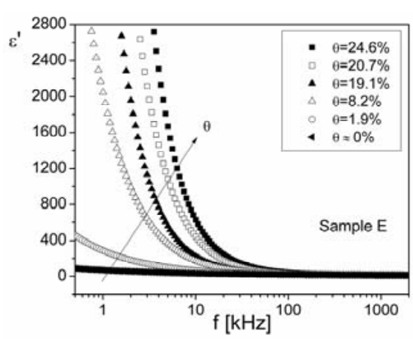
(f)


ε'
θ = 26 %
θ = 23 %
θ = 20.2 %
θ = 9.2 %
θ = 5.7 %
θ = 2.1 %
θ ≈ 0 %
θ
Sample D
f [kHz]

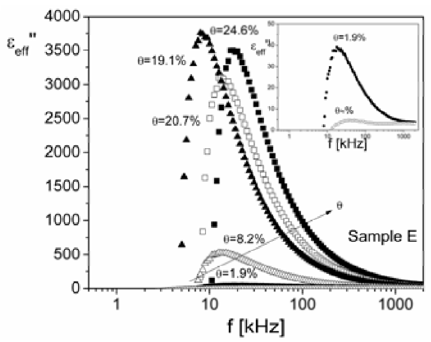
(g)


ε_{eff}"
θ=27.9%
θ=23%
θ=20.2%
θ=9.2%
θ=5.7%
θ
Sample D
f [kHz]

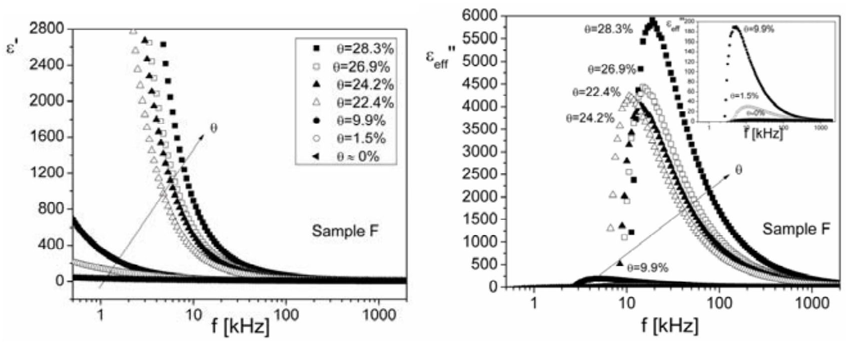
(h)


ε'
θ=24.6%
θ=20.7%
θ=19.1%
θ=8.2%
θ=1.9%
θ ≈ 0%
θ
Sample E
f [kHz]

(i)


ε_{eff}"
θ=24.6%
θ=19.1%
θ=20.7%
θ=8.2%
θ=1.9%
θ
Sample E
f [kHz]

(j)



(k) (l)

Fig. 1 – The frequency dependence of the real and imaginary components of the complex dielectric permittivity for the investigated soil samples, for the different values of the volumetric water content

From Fig. 1, one can observe that the real component of the complex dielectric permittivity ε' drops with the frequency increase for all samples. In addition, the real part also decreases with the volumetric water content decreasing. The large values of ε' in the kHz range, observed for all the samples, can be correlated with both the volumetric water content θ and the weight percentage of clay and silt, more specific to the polarization of the double layer surrounding the charged clay particles [13, 14].

The strong increase of the real component of the dielectric constant at lower frequencies can be partially explained by the Maxwell-Wagner-Sillars effect [15, 16] which occurs due to the charge carriers blocked at the inner dielectric boundary layers. Those boundaries are located at the surface of the soil grains or at the electrode-sample interface. This effect is characteristic to heterogeneous systems where the electric current must pass an interface between two different dielectrics [17].

The imaginary component, ε''_{eff} of the complex dielectric permittivity has an effective value that includes both electrical conductivity and dipolar polarization losses [17, 18]. For low frequencies, the electric field facilitates the propagation of charges. The electrical current that results has a significant contribution to ε''_{eff}, which increases with the increasing conductivity as seen in the dielectric spectra in Fig. 1, where the values of ε''_{eff} for the samples subjected to the drying experiment were much larger for higher volumetric water content values.

The distinctive peak of the complex dielectric permittivity coressponding to the relaxation frequency that was observed for each sample and value of θ is correlated to the dielectric relaxation processes [19, 20]. The frequency range where the difference between the values of ε''_{eff} at each volumetric water content value, θ, is the greatest, corresponds also to the characteristic frequency, where the relaxation occurs. A similar low frequency dielectric relaxation was observed in systems consisting of colloidal particles dispersed in electrolyte solutions [21].

3.2. THEORETICAL MODELS AND THEIR COMPARISON WITH THE EXPERIMENTAL DEPENDENCE $\varepsilon'(\theta)$

There are several empirical and semi-empirical dielectric mixing models that describe the $\varepsilon'(\theta)$ dependence, based only on the volumetric water content, or taking also into account the textural characteristic of the soil.

A very often used empirical model, proposed by Topp *et al.* [5] is based on the equation:

$$\varepsilon' = 3.03 + 9.3 \cdot \theta + 146 \cdot \theta^2 - 76.7 \cdot \theta^3 . \tag{7}$$

This equation was obtained by fitting the average dielectric constant dependence to the volumetric water content, for a large number of soil textures, over a wide frequency domain [5].

Another empirical model that takes into account for the $\varepsilon'(\theta)$ dependence both the frequency and the volumetric water content is the Wensink model [3]. For the theoretical calculations we made, we used the 50 MHz Wensink model [3], which is based on measurements of the complex permittivity in soils from frequencies beginning with 1MHz and which is given by Eq. (8):

$$\varepsilon'(50\text{MHz}) = 1.4 + 87.6\theta - 18.7\theta^2 . \tag{8}$$

Semi-empirical models that are based on a wider range of physical properties have also been developed. An example for such a model is the Wang-Schmugge model, which is largely empirical but it also relies on soil physical characteristics [4]. The Wang-Schmugge dielectric mixing model is a more complex model, that takes into consideration the dielectric permittivies of all the components of the soil sample: bound water, free water, air and soil. The mathematical expression of the Wang and Schmugge model offers two different relationships, one for the case that the volumetric water content is higher than the transition moisture, $\theta > \theta_t$, and one for the case that the volumetric water content is less than or equal to the transition moisture $\theta \le \theta_t$. The two expressions for the dielectric constant are described as:

$$\varepsilon = \theta \cdot \varepsilon_{x1} + (\frac{e}{1+e} - \theta) \cdot \varepsilon_a + (1-n) \cdot \varepsilon_r \quad (\text{for } \theta \le \theta_t), \tag{9}$$

$$\varepsilon = \theta_t \cdot \varepsilon_{x2} + (\theta - \theta_t) \cdot \varepsilon_w + (n-\theta) \cdot \varepsilon_a + (1 - \frac{e}{1+e}) \cdot \varepsilon_r \quad (\text{for } \theta > \theta_t), \tag{10}$$

with

$$\varepsilon_{x1} = \varepsilon_i + (\varepsilon_w - \varepsilon_i)\cdot\frac{\theta}{\theta_t}\cdot\gamma \quad , \qquad \varepsilon_{x2} = \varepsilon_i + (\varepsilon_w - \varepsilon_i)\cdot\gamma\,. \tag{11}$$

In Eqs. (9–11), γ is an empirical parameter, θ_t is the transition moisture, *e* the void ratio, ε_a is the dielectric constant of air, ε_w is the dielectric constant of water, ε_r is the dielectric constant of the rock, ε_i is the dielectric constant of ice, and ε_{x1} and ε_{x2} are the dielectric constants of the initially absorbed water, for both cases. The transition moisture is defined as the moisture content at which the free water phase begins to dominate the soil system. From the expression of the wilting point *WP* (see Eq. 12), which is derived empirically from the size particle distribution the transition moisture can be determined (see Eq.13).

$$\mathrm{WP} = 0.06774 - 0.00064\cdot \mathrm{S} + 0.00478\cdot \mathrm{C}\,, \tag{12}$$

$$\theta_t = 0.49\cdot \mathrm{WP} + 0.165\,, \tag{13}$$

where *S* and *C* are the sand and clay fractions of the soil sample. The empirical parameter γ is also estimated from the expression of the wilting point, and is given by:

$$\gamma = 0.57\cdot \mathrm{WP} + 0.481\,. \tag{14}$$

The soil dielectric constants ε', for all samples and for volumetric water content values θ, from 0 to 0.45 were computed according to the empirical and dielectric mixing model described above. Using the equations (7) and (8), the theoretical dependence $\varepsilon'(\theta)$, corresponding to the Topp and the Wensink model, respectively, were determined. For the Wang-Schmugge model, the values of the void ratio *e*, the sand *S* and clay *C* fractions, given in Table 1 and 2, were used. The theoretical curves for the Wang-Schmugge model for all samples are very similar and overlap each other. A comparison between the Topp, Wensink and Wang-Schmugge models and the experimental dependence $\varepsilon'(\theta)$, determined for frequencies between 100 kHz to 2MHz for all samples, is shown in Fig. 2.

As can be observed from Fig. 2, the experimental data for all samples fit reasonably well with the theoretical models, for frequencies in the range of 500 kHz to 2MHz (Fig. 2 b, c, d), but are dispersed at frequencies around and less 100 kHz (Fig. 2 a).

For a volumetric water content up to 10% and frequencies of 500 kHz to 2 MHz the best fit to the experimental data is given by the Wensink model. For volumetric water contents greater than 10% and frequencies around 500 kHz, the best fit is given by the Wang-Schmugge and Topp theoretical models which are very close to each other. At 1 MHz and 2 MHz, the experimental results are just below the Wang-Schmugge and Topp model.

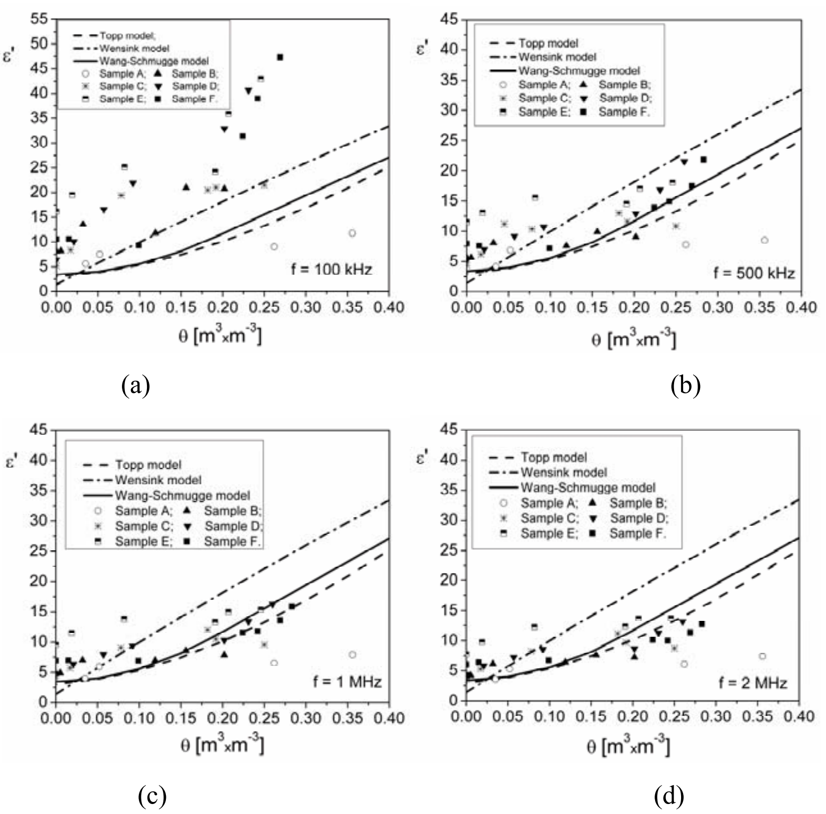


Fig. 2 – A comparison between the theoretical dependence $\varepsilon'(\theta)$, computed using the Topp, Wensink and Wang-Schmugge models and the experiemental dependence $\varepsilon'(\theta)$, for soil samples at frequencies of: a) 100 kHz; b) 500 kHz; c) 1 MHz; d) 2 MHz.

4. CONCLUSIONS

The low frequency dielectric behavior of near surface cohesive soils from the Banat area, Romania, was investigated for the first time.

For this purpose, the frequency (f) and the volumetric water content (θ) dependencies of the real, ε' and the imaginary, ε''_{eff}, components of the complex dielectric permittivity, in the frequency range 0.5 kHz – 2 MHz, were determined.

The experimental results showed large values of $\varepsilon'(\theta)$ and $\varepsilon''_{eff}(\theta)$ for all the investigated samples, due to the conduction and relaxation losses. By drying the samples and decreasing of the volumetric water content, decrease correspondingly ε' and ε''_{eff} values.

The experimental dependence $\varepsilon'(\theta)$ at frequencies between 100 kHz to 2 MHz, were compared with the Topp, Wensink and Wang-Schmugge theoretical models. The results obtained, for all samples, shown that the experimental dependence $\varepsilon'(\theta)$, fits reasonably well with the theoretical models, for frequencies in the range of 500 kHz to 2 MHz, and for volumetric water contents, greater than 10%, but are dispersed at frequencies around and less 100 kHz.

The results obtained are very important for different applications of nondestructive testing on soils, and in evaluating the data obtained from ground-penetrating radar (GPR) investigations.

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