Dielectric relaxation behaviour of moist soil

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In particular, knowledge of the spatial and temporal variability of water saturation in soils is important to obtain improved estimates of water flow through structures of flood protecting and subsurface disposal as well as the vadose zone ([6],[12], [24]).

High frequency electromagnetic determination of moisture in porous media, e.g. soil, is based on the strong relationship between volumetric water content and relative dielectric permittivity. However, various factors affect this relationship such as measurement frequency, temperature, mineralogical composition, structure, texture, bulk density and chemical composition of the pore fluid ([3], [7], [14], [18], [20]).

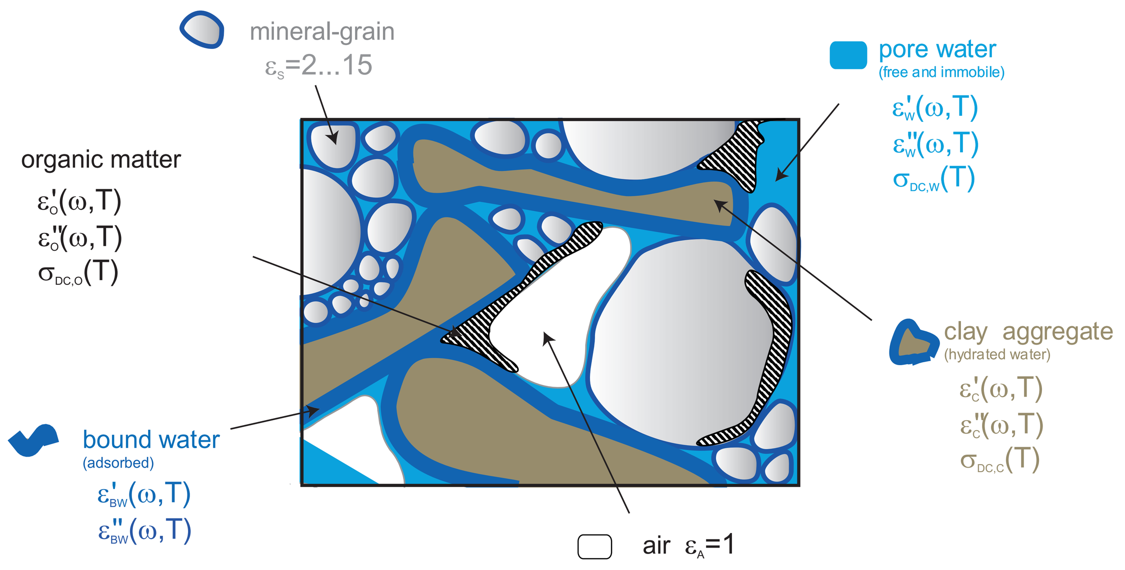


Figure 1: Simplified schematic illustration of unsaturated soil structure with the contribution to the dielectric properties due to several relaxation processes (c.f. [23]).

The objective of numerous experimental, numerical and theoretical investigations is the development of general calibration rules for a broad class of soil textures and structures ([9], [17], [20]).

Mostly these models are based on the assumption of a constant dielectric permittivity in a narrow frequency range around 1GHz as a function of volumetric water content ([2], [15], [19]).

However, the strong frequency dependence in the dielectric relaxation behaviour below 1 GHz due to a certain amount of clay minerals in nearly each real soil is considered only insufficiently ([6], [12], [14], [16], [21], [22]).

Measurement technique - Dike soil - Relaxation model

The complex dielectric permittivity of the soil was examined in the frequency range 1 MHz to 20 GHz at room temperature and under atmospheric pressure with a Rohde & Schwarz ZVR (1 MHz - 4 GHz), PNA E8363B (10 MHz - 40 GHz) and HP8720D (50 MHz to 20 GHz) network analyser. This was performed using a combination of open-ended coaxial-line (HP85070B) and coaxial transmission line technique (sample holder (7x16x100)mm3) ([22], [24], Figure 2). In addition, selected soil samples were examined in the frequency range 1 Hz - 1 MHz with a Solartron Si 1260 - impedance analyser ([4], [23], Fig. 2).

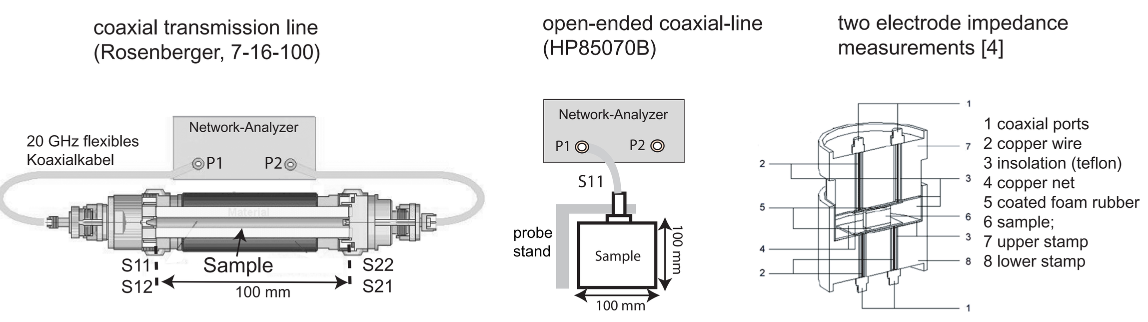


Figure 2: Schematic diagram of the experimental set-up for measuring the dielectric permittivity.

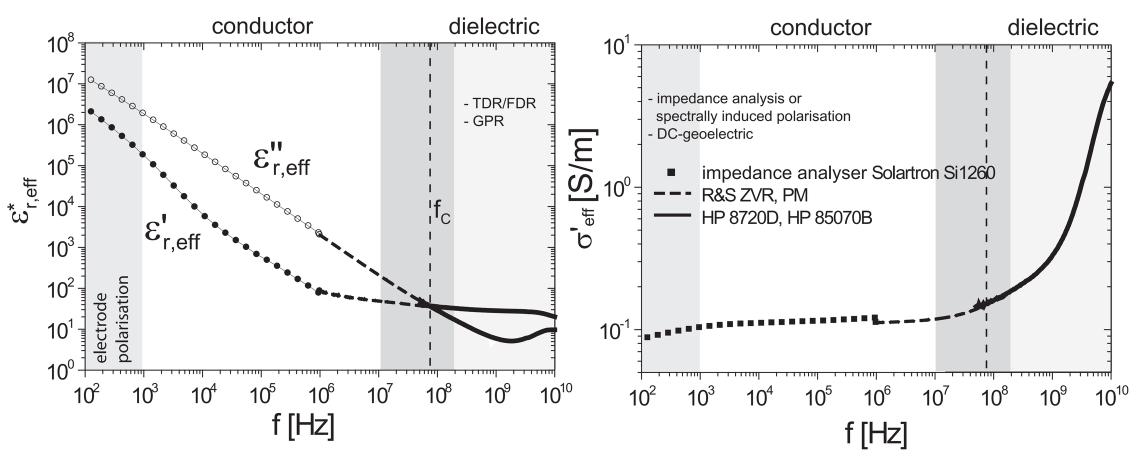


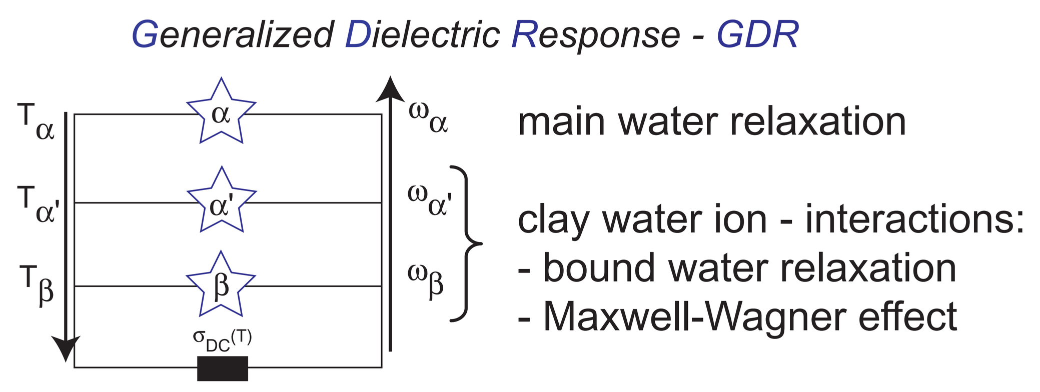
Figure 3: Relative complex dielectric permittivity $\varepsilon^*_{r,eff}$ and real part of the complex electrical conductivity $\sigma'_{eff} = \omega\varepsilon_0\varepsilon''_{r,eff}$ (angular frequency ω, permittivity of free space ε_0) of a soil sample (w = 25 %, ρ = 1.9 g/cm^3) as a function of frequency. Critical frequency $f_c=\omega_c/(2\pi)$ is defined by $\sigma'_{eff}(\omega_c)/(\omega_c\varepsilon_0\varepsilon'_{r,eff}(\omega_c)) = 1$.

A silty clay loam from a dike at the river Unstrut, Thuringia, Germany was investigated (Table 1). The soil samples were incrementally wetted from air dry up to saturation with natural water and equilibrated 12 - 24 h. From the prepared sample a sub-sample was taken. The presented samples were selected from a data set of up to 130 single measurements (bulk density ρ from 0,7 to 1,8 g/cm^3, gravimetric water content w from 0 to 46 %) representative for the investigated broad frequency range and a narrow porosity range (see Table 2).

Table 1: Physical, chemical and mineralogical properties of the investigated soil.

Texture		Mineralogy		Soil properties	
Gravel	0,5 %	Mica	23 wt.%	Specific surface area	29,95 m^2/g
Sand	19,9 %	Smectite	14 wt.%	Cation exchange capacity	14 mmol(eq)/100g
Silt	49,8 %	Kaoline	2 wt.%	Grain density	2,67 g/cm^3
Clay	29,7 %	Chlorite	6 wt.%	Eluate conductivity	0,12 mS/m
Organic matter	0,6 %	Tectosilicates	37 wt.%		
		Carbonates	17 wt.%		
		Geothite	1 wt.%		

Three relaxation processes are assumed to act in the investigated frequency-temperature-pressure range (c.f. [1], [7], [8], [10], [22]):



A Shuffled Complex Evolution Metropolis (SCEM-UA) algorithm [6] is used to find best fitting parameters (cf. Table 2, Figure 6). The resulting relative error of each parameter is less than 3 %.

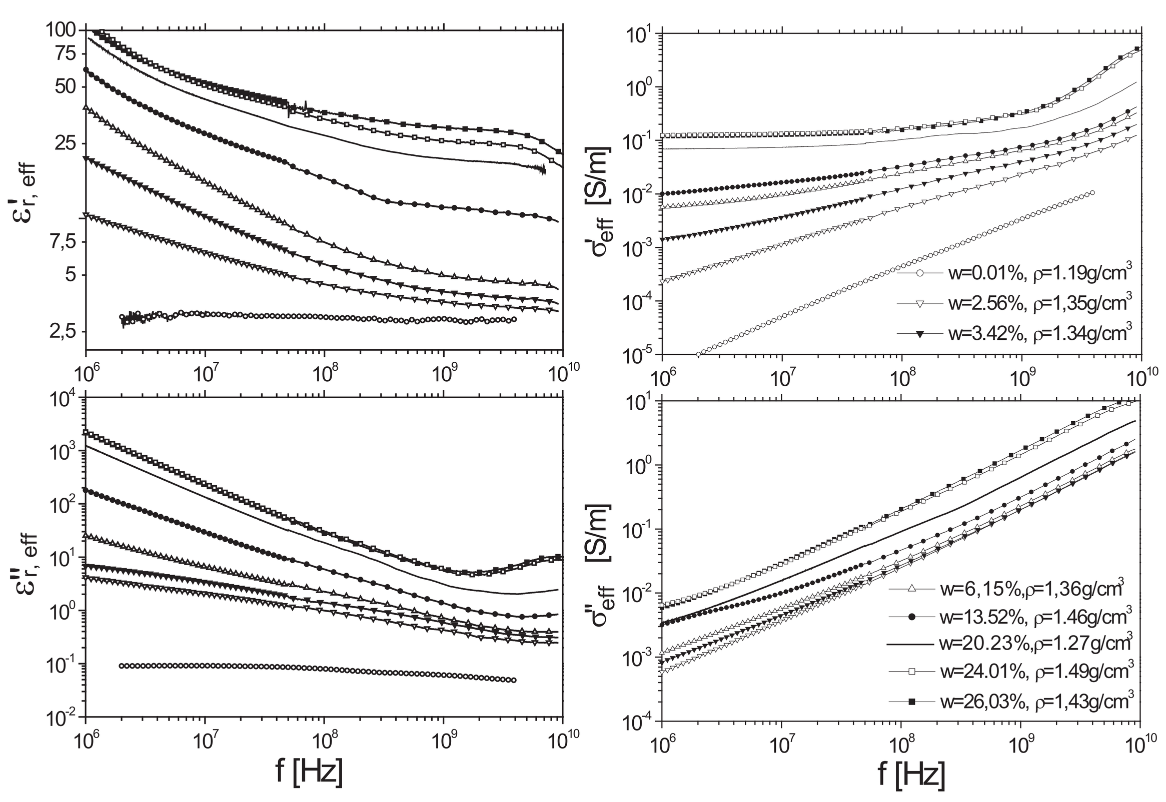


Figure 4: Complex effective relative dielectric permittivity and complex effective electrical conductivity as a function of frequency of the silty clay loam sample for selected gravimetric water contents w and dry bulk densities ρ_d.

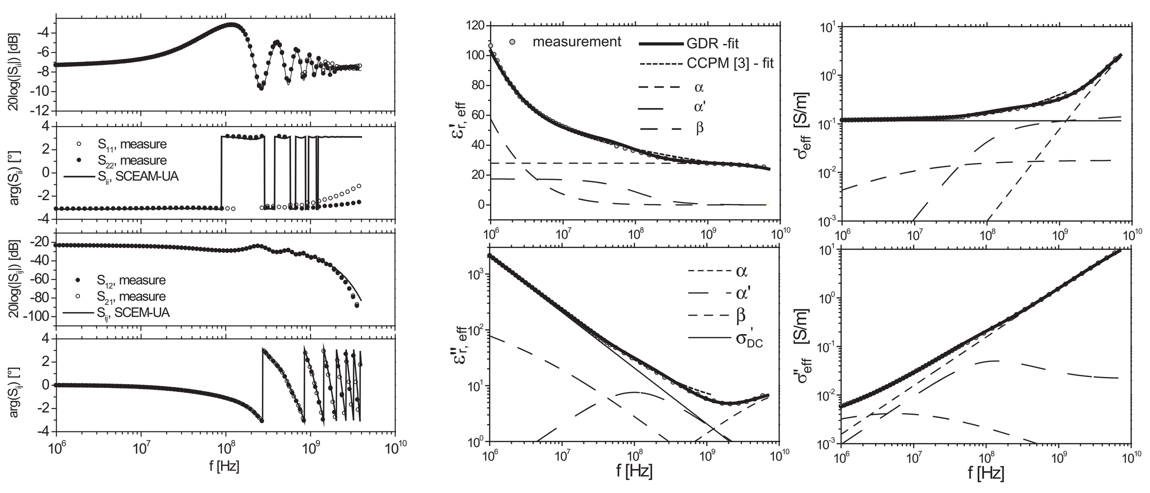


Figure 5: (from left to rigth) S-Parameter S_{ij}, complex effective relative dielectric permittivity $\varepsilon^*_{r,eff}$ and complex effective electrical conductivity $\sigma^*_{eff}=\omega\varepsilon_0\varepsilon^*_{r,eff}$ as a function of frequency of the sample v-10 with the results of the SCEM-UA optimisation (see Table 2).

Characteristics of the dielectric relaxation behaviour

Experimental results

- Relative high frequency permittivity ε_∞ determined in the SCEM-UA optimisation with GDR varies within a small range.
- Relaxation time of main water relaxation τ_α is lower than the expected relaxation time of pure water at 20°C and under atmospheric pressure with 9.3 ps [11]. However, τ_α slightly increases with increasing volumetric water content to τ_α = 5.9 ps.
- Relaxation time $\tau_{\alpha'}$, which is referred to as bound water ([2]), decreases with increasing volumetric water content from 9.9 ns to 2.12 ns.
- Relaxation time τ_β is referred to as relaxation mechanism involving strong clay-water-ion interactions, e.g. the Maxwell-Wagner effect ([1], [7], [8]). In the investigated frequency-temperature-pressure range τ_β shows no systematic dependence on moisture.

	v-1	v-2	v-3	v-4	v-5	v-6	v-7	v-8	v-9	v-10
w [%]	2.56	3.42	3.71	6.15	8.95	14.00	13.52	20.53	24.01	26.03
ρ_d [g/cm^3]	1.35	1.34	1.33	1.36	1.27	1.11	1.46	1.27	1.49	1.43
ϕ	0.50	0.50	0.50	0.49	0.53	0.57	0.46	0.51	0.45	0.47
ϑ [%]	3.47	4.57	4.95	8.37	11.34	15.61	19.71	26.05	35.74	37.33
f_C [MHz]	<1	<1	1.5	13.59	34.34	46.7	127.3	79.9	83.23	70.0
ε_{1GHz}	3.47	3.70	4.11	4.62	5.69	6.27	10.64	14.86	25.22	30.45
Selected GDR-Parameter										
ε_∞	1.38	0.93	0.82	2.28	2.50	2.60	3.18	3.96	1.92	2.29
$\Delta\varepsilon_\alpha$	1.95	2.09	2.64	2.06	2.29	3.01	6.98	9.83	21.97	24.31
τ_α [ps]	0.31	0.25	0.59	3.11	4.91	5.113	4.91	8.83	5.08	5.90
$\Delta\varepsilon_{\alpha'}$	5.25	7.76	9.74	15.81	14.60	14.39	20.38	25.16	23.70	22.06
$\tau_{\alpha'}$ [ns]	9.89	9.86	9.69	9.97	9.94	9.40	4.52	9.46	2.28	2.12
$\Delta\varepsilon_\beta$	3.61	6.46	10.10	48.33	56.79	44.93	58.94	105.18	164.49	83.90
τ_β [ns]	63.32	49.47	37.38	67.46	28.47	36.79	56.21	92.81	52.95	36.60
$\sigma'_{DC,S}$ [S/m]	5.3e-5	6.3e-5	7.8e-4	3.0e-3	4.0e-3	0.01	0.07	0.048	0.11	0,11

Beside the data obtained in the SCEM-UA optimisation, relative dielectric permittivity at a measurement frequency of 1 GHz, $\varepsilon_{r,1GHz}$ and critical frequency f_c are summarised in Table 2.

f_c increases to a maximum value of 127 MHz at a volumetric water content of ϑ = 19,7% with increasing water content and then decreases to 50 MHz at ϑ = 47,6% (Fig. 6).

Table 2: Selected relaxation parameters of the soil determined in the SCEM-UA optimisation with GDR: ε_∞ high frequency limit of the dielectric permittivity, $\Delta\varepsilon_i$ relaxation strength and τ_i relaxation time of the i-th process, σ'_{DC} apparent direct current electrical conductivity as well as gravimetric water content w, volumetric water content ϑ, dry bulk density ρ_d, porosity ϕ, critical frequency f_c and real part of the relative permittivity ε_{1GHz} at a measurement frequency of 1 GHz.

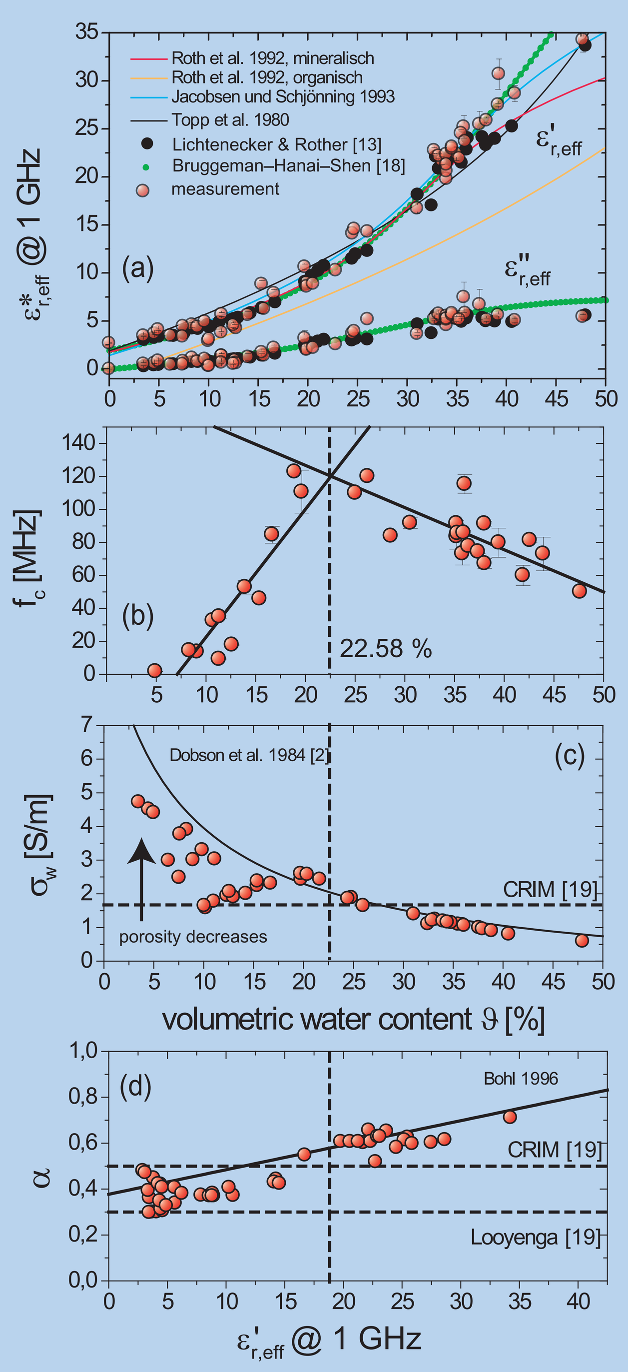


Figure 6: (a) Complex dielectric permittivity at a measurement frequency of 1 GHz (b) critical frequency and (c) apparent conductivity of pore water as a function of volumetric water content ϑ. (d) structure α parameter vs. permittivity.

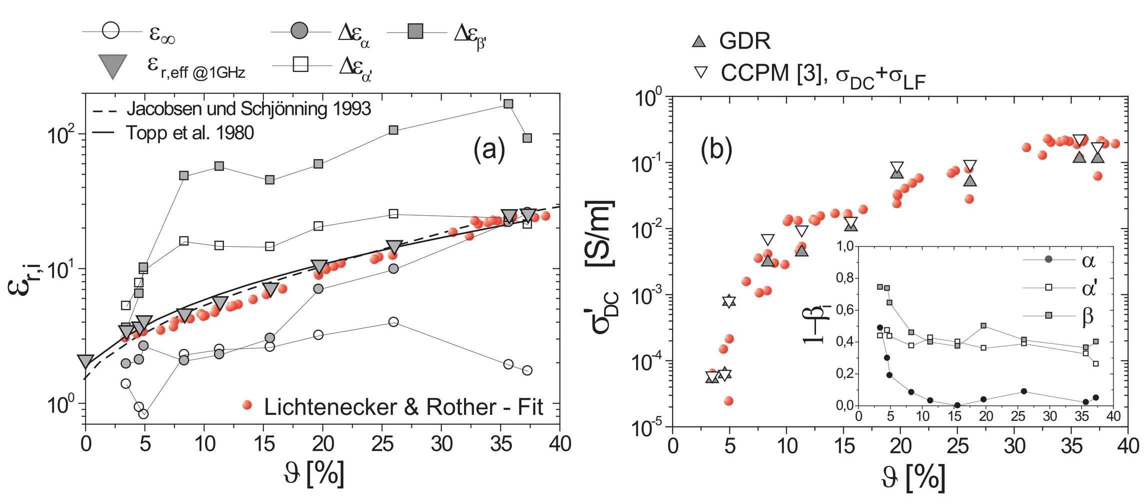


Figure 7: (a) Relaxation strength $\Delta\varepsilon_i$ of the i-th process in comparison to the relative high frequency permittivity ε_∞, (b) apparent direct current electrical conductivity σ'_{DC} and (inset) distribution parameter of the i-th process as a function volumetric water content.

In comparison to the determined relaxation parameters from broadband measurements $\varepsilon_{r,eff}$ @ 1 GHz of all investigated samples was analysed with a simple three phase mixing model according to [13]. The dependence of the so called structure parameter α as well as the direct current conductivity of pore water σ_w on volumetric water content ϑ and porosity Φ was considered (Fig. 6 and 7).

Conclusions

The results show the potential of the chosen approach but a detailed explanation of this complex behaviour is beyond the scope of this study. In general, there is a need of further systematic investigations by broadband dielectric spectroscopy of saturated and unsaturated soils as a function of temperature under controlled hydraulic and mechanical conditions.

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