

VIBRATION-INDUCED CONDUCTIVITY FLUCTUATION (VICOF) TESTING OF SOILS*

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In this Letter, we propose and experimentally demonstrate a simple method to provide additional information on the electro-mechanical properties of soils by electrical conductivity measurements. The AC electrical conductance of the soil is measured while it is exposed to a periodic vibration. The vibration-induced density fluctuation implies a corresponding conductivity fluctuation that can be seen as combination frequency components, the sum and the difference of the mean AC frequency and the double of vibration frequency, in the current response. The method is demonstrated by measurements on clayey and sandy soils.

Keywords: Soil water content; salinity; soil bulk density; soil connectivity; soil electrical conductivity; conductivity fluctuations.

1. The New Measurement Principle

The bulk electrical conductivity of soils depends on various soil properties, such as water content, salt type and concentration, bulk density (air-filled porosity), clay content and mineralogy, and connectivity structure of soil particles [1]. Therefore, given electrical conductivity measurement data can be the result of many different combinations of soil properties. This interaction of soil properties complicates interpretation of soil electrical conductivity measurements. Soil electrical conductivity sensors, such as capacitance sensors [2–4], electromagnetic induction [5–6], and resistivity tomography [7] are used to quantify soil moisture, salinity, clay content, water flux, and other related soil properties;

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however, the empirical calibrations used for these sensors are very site specific and therefore limited in their application. The goal of this paper is to propose and demonstrate a new technique based on vibration-induced modulation of the electrical conductivity that gives additional and independent information about the *mechano-electrical transport properties* of the soil. With proper models, these electrical transport properties can provide more information about the soil structure, such as soil porosity, and the associated empirical calibrations may be more robust.

The measurement circuitry, which is an expanded version of the standard AC conductivity measurement circuitry, is shown in Figure 1. The AC voltage generator provides a sinusoidal voltage at the main frequency f_1 that drives an AC current through the driving resistor R_1 and the resistor R_s represented by the soil sample. The soil sample is exposed to a *weak* periodic vibration with frequency f_2 . During a vibration period, the absolute value of the acceleration has two maxima that imply the occurrence of *two density maxima due to inertia forces* during the same time. Such an arrangement implies a periodic pressure and density modulation at frequency $2f_2$, inducing a conductance modulation (similarly to a *shaken carbon microphone*) with $2f_2$ first harmonics and that yields voltage components at the combination frequencies $f_1 + 2f_2$ and $f_1 - 2f_2$.

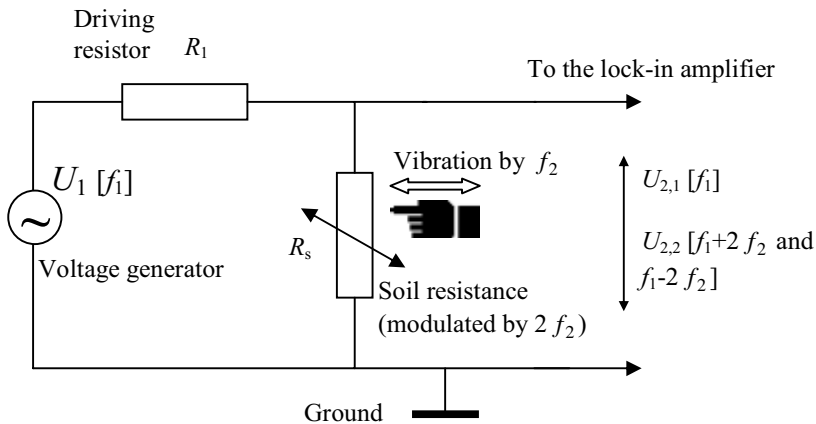


Fig. 1. The measurement circuitry. The soil sample is exposed to a periodic vibration with frequency f_2 . This implies a periodic pressure and density modulation inducing a conductance modulation with $2f_2$ first harmonics and that yields voltage components at the combination frequencies f_1+2f_2 and f_1-2f_2 during the execution of an AC conductivity measurement with sinusoidal voltage of frequency f_1 .

At small and sinusoidal vibration and corresponding linear response, the voltage on the soil resistance has three frequency components. At the frequency of the voltage generator (main frequency, f_1) there is a classical AC conductance measurement response (voltage divider response):

$$U_{2,1} = U_1 \frac{R_s}{R_1 + R_s}, \tag{1}$$

This allows a determination of the AC resistance of the soil sample from the measurement of $U_{2,1}$ in the classical way:

$$R_s = R_1 \frac{U_{2,1}}{U_1 - U_{2,1}}. \tag{2}$$

Supposing small modulation, we can estimate the sensitivity of the amplitude $U_{2,1}$ against the *root-mean-square (rms)* modulation of the soil resistance dR_s as follows:

$$\frac{dU_{2,1}}{dR_s} = \frac{U_1 R_1}{(R_1 + R_s)^2}. \tag{3}$$

According to the following relation of *amplitude modulation*,

$$\sin(2\pi f_1 t) \sin(4\pi f_2 t) = \frac{1}{2} \cos[2\pi(f_1 + 2f_2)t] + \frac{1}{2} \cos[2\pi(f_1 - 2f_2)t],$$

it can be seen that the modulation yields the following amplitude components at the combination frequencies $f_1 + 2f_2$ and $f_1 - 2f_2$:

$$U_{2,2} = U_{2,2}[f_1 + 2f_2] = U_{2,2}[f_1 - 2f_2] = \frac{1}{2} dU_{2,1} = \frac{1}{2} \frac{U_1 R_1}{(R_1 + R_s)^2} dR_s, \tag{4}$$

where $U_{2,2}$ is the signal above the average background voltage at the combination frequencies. From Eqs. (1), (2) and (4):

$$dR_s = 2 \frac{U_{2,2}}{U_1} \frac{(R_1 + R_s)^2}{R_1} = 2 \frac{U_{2,2}}{U_1 - U_{2,1}} (R_1 + R_s) = 2 \frac{U_{2,2}}{U_1 - U_{2,1}} \left(R_1 + R_1 \frac{U_{2,1}}{U_1 - U_{2,1}} \right), \tag{5}$$

and the *fluctuation amplitude* of the soil resistance can be determined from the known driving resistance R_1 and the measurement of the AC voltage amplitudes:

$$dR_s = 2R_1 \frac{U_{2,2}}{U_1 - U_{2,1}} \left(1 + \frac{U_{2,1}}{U_1 - U_{2,1}} \right). \tag{6}$$

The normalized (relative) resistance fluctuation is especially important because it is probing the strength of modulation of the electrical connectivity properties of the soil. Its value can easily be determined from the above equations:

$$\frac{dR_s}{R_s} = 2R_1 \frac{U_{2,2}}{U_1 - U_{2,1}} \left(1 + \frac{U_{2,1}}{U_1 - U_{2,1}} \right) \left(R_1 \frac{U_{2,1}}{U_1 - U_{2,1}} \right)^{-1}, \tag{7}$$

and even the driving resistance is absent from this final form:

$$\frac{dR_s}{R_s} = 2 \frac{U_{2,2}}{U_{2,1}} \left(1 + \frac{U_{2,1}}{U_1 - U_{2,1}} \right). \tag{8}$$

To evaluate the relative fluctuations of the soil resistance due to vibrations, we only need to know the above voltage components at relevant frequencies and use Eq. (8).

2. Experimental Demonstration

The test experiments were carried out on an antivibration table, (100BM-2 Nano-K vibration isolation platform). An induction coil based vibrator (5W, 60Hz) was fixed to one side of the floating top of the antivibration table so that the vibration was horizontal in a well-defined direction. The soil sample contained in a tin sample holder (9.7 cm diameter and 6.3 cm height) was placed on this floating top. The ground contact was the metal container and the probing contact was provided by a standard cylindrical stainless steel electrode (3 mm diameter and 71 mm length). The electrode was placed 5 cm deep into the soil and 3 cm (d) from the wall of the tin. Figure 2 shows the top view of the arrangement. The lock-in amplifier was Stanford Research Systems Model SR830 DSP.

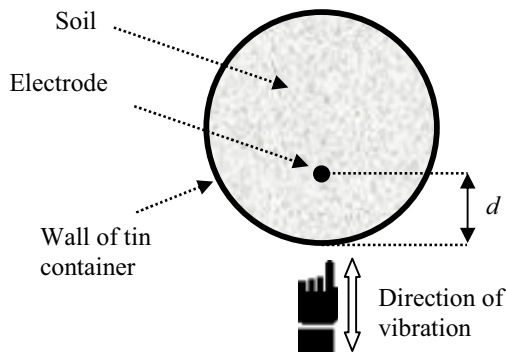


Fig. 2. The arrangement of the electrode, soil sample, and vibration direction used for measurement.

The vibration was very weak, thus it did not cause any observable relaxation of the soil structure (compaction) which was concluded from the stable value of measured conductance. The voltage components at the combination frequency (1.12 kHz) were about 10^5 times smaller than the amplitude at the main frequency ($f_1=1$ kHz).

The two non-saline soil types tested were a clay and a fine sand (Table 1). Soils were wetted by adding water to a pre-determined moisture content based on two matric potentials, -100 and -1000 J kg⁻¹. The two matric potentials were chosen to secure the comparable level of loosely held mobile water content and surface tension in the different soils. The amount of water was determined based on a relationship of gravimetric water content to matric potential as a function of soil texture [8]. To wet the soils, distilled and deionized water was added to air dry soils, mixed thoroughly by shaking in sealed plastic bag, and allowed to equilibrate under constant temperature for 2 months. Three replicates of three compaction levels of each soil texture were measured, 36 samples in all. The soils were uniformly packed in 0.5-1 cm thick layers dropping a 1 kg weight from 2 cm above the soil. The soil surface was loosened between layers to ensure good contact with the next layer. Bulk density varied within 0.8-1.1 g cm⁻³ and 1.1-1.5 g cm⁻³ for clay and sand soils, respectively. After the measurements, soil samples were oven dried at 105 °C to a constant weight and weighed again for moisture determination.

Table 1. Particle size distribution and electrical conductivity of soil samples.

Soil	Particle size distribution (mm)			Texture class	EC _e * dS m ⁻¹
	Sand (2.0-0.05)	Silt (0.05-0.002)	Clay (<0.002)		
	-----%				
1	11.2	36.7	52.1	clay	0.6
2	97.6	0.9	1.5	fine sand	0.3

* EC_e = electrical conductivity of saturated paste extract

Measurements of U_1 [1 kHz], $U_{2,1}$ [1 kHz], $U_{2,2}$ [1.12 kHz] with and without vibration (background) were taken with the electrode placed at three locations in 3 cm from the wall. A minimum of three readings were averaged for each measurement.

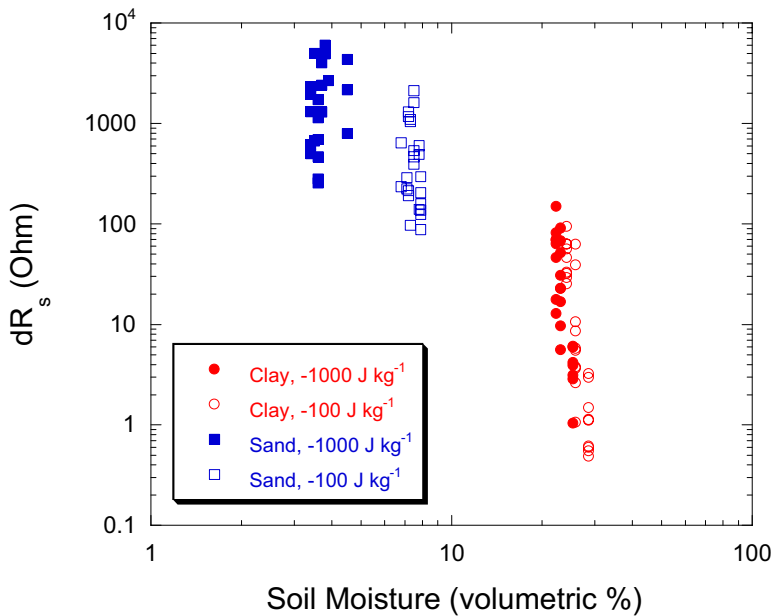


Fig. 3. Dependence of resistance fluctuations on soil moisture.

In Figure 3, the impact of volumetric soil moisture on soil resistance fluctuation is shown. The scattering of the data is relatively large because of the small diameter of the electrode (3 mm). Thus this technique is sensitive against local inhomogeneities. The scattering of data could be reduced by spatial averaging such as using electrodes with wide and thin blades.

The most important characterization tool of fluctuation of electrical transport properties in disordered materials is the determination of the scaling exponents of the normalized *rms* resistance fluctuations versus the mean resistance or versus the *rms* resistance fluctuations, see [9]. It is because the macroscopic transport properties are usually a power function of the conductivity percolation length, which is the characteristic size of continuous conductor islands in the bulk. Therefore those transport properties can be expected to interrelate by power functions when the macroscopic control parameter (moisture or bulk density) is varied:

$$\frac{dR_s}{R_s} \cong A(dR_s)^z, \tag{9}$$

where A is a prefactor and we call z the VICOF exponent. We expect that z will be characteristic of the different types of soils [9]. To test this hypothesis, we generated the scaling plot in Fig. 4 and indeed the VICOF exponent z is significantly different for the sand (≈ 0.9) and the clay (≈ 0.7) soils.

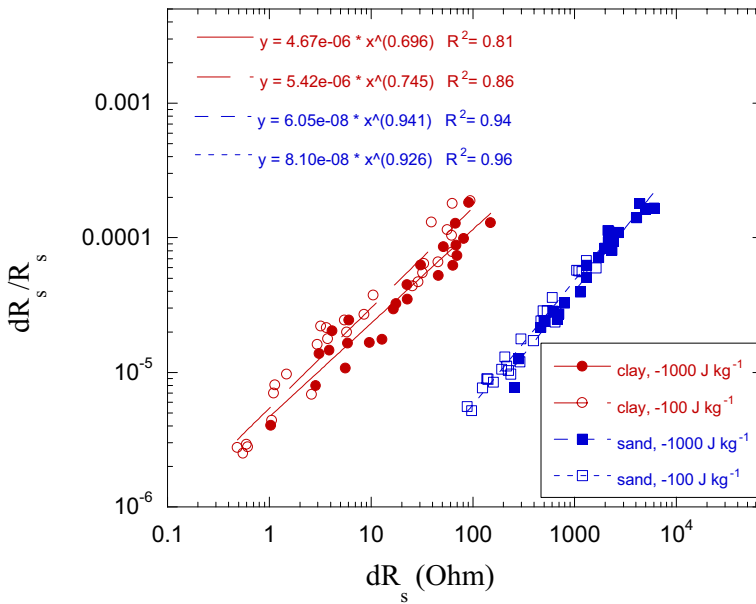


Fig. 4. Scaling plot of different soil samples. Control parameter is the bulk density.

Finally we note that the resistance fluctuation depends upon the soil resistance; however, the normalized resistance fluctuation does not, provided the soil structure is unchanged. This fact can be helpful in measuring soil structure (porosity) independently of soil salinity, provided the variations in salinity are small enough to avoid significant structural variations. This advance provides the opportunity to develop a sensor that may have a more robust empirical calibration.

3. Summary

We have proposed and demonstrated a new method which is testing the mechano-electrical transport properties of soils. The normalized fluctuations show that structural electrical connectivity properties are sensitive to vibration. This information can provide additional information to moisture, texture and salinity status of a given soil measured with traditional bulk electrical conductivity measurements.

The method was briefly demonstrated with cylindrical stainless steel electrodes on clay and fine sand soils.

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