

Soil Measurements and Modelling

Kazunori Takahashi
Mato Pavlovic
Mate Gaal
Christina Müller

BAM, Berlin

1. Introduction

In the demining community the impact of the soil is regarded as the severest factor that reduces the reliability of the mine detection process. The influences of magnetic susceptibility and, to a lesser degree, electric conductivity are considered as key factors that determine the performance of metal detectors. It has been proposed elsewhere that magnetic viscosity of the soil, the dependence of susceptibility on frequency, is the major reason for the soil effects encountered in metal detectors. Measurements of soil susceptibility were made using a Bartington MS2 Magnetometer, in two ways. The first one was measuring in situ with an 18.5 cm diameter circular loop probe operating at 958 Hz (κ_{958}). The second way was obtained from 10 cm³ samples, in a sample chamber operating at 465 Hz and 4650 Hz (κ_{LF} and κ_{HF} respectively). The difference $\kappa_{FD} = \kappa_{HF} - \kappa_{LF}$ was also investigated, as a measure of magnetic viscosity. Soil samples were also taken from the test lanes and sent for measurements to the 'Leibniz Institute for Applied Geosciences' in Hannover.

A simple empirical measurement of the effect of a soil on detectors can be made by setting a detector without soil-compensation to a definite sensitivity and measuring the minimum distance to the soil surface at which the detector starts giving signals. This distance is called the ground reference height. This measurement was made on all the soils using a Schiebel AN19 Mod 7 detector, adjusted in a way that it could just detect a calibration pin at 10cm distance from the baseline mark. Equivalent calibration procedure is using a 10mm diameter chromium steel ball, material 100Cr6, at 14cm distance. The results of soil measurements are given in table presenting the mean values and the corresponding standard deviation of the mean. 12 measurements were performed in each lane, which means 24 measurements in each soil.

Table 1 - *Soils in Benkovac 2005 trials. Ground reference height and susceptibility measurements. The sensor of the circular loop probe operating at 958Hz is calibrated to read 0.5 κ on rough soils and will give about 0.75 κ on smooth surfaces*

Soil Types in Benkovac Trials	Ground Reference Height (cm)	Susceptibility at 958 Hz (10^{-5} SI)	Susceptibility at 465 Hz (10^{-5} SI)	Susceptibility at 4650 Hz (10^{-5} SI)	Susceptibility difference between 465 and 4650 Hz (10^{-5} SI)
Lanes 1, 2 (uncooperative) Bauxite – Obrovac soil	14,8 ± 0,2	151,8 ± 1,5	187,1 ± 4,4	167,7 ± 4,0	19,3 ± 0,5
Lanes 3, 4 (neutral) Clay – Sisak soil	1,0 ± 0,2*	12,5 ± 0,3	15,63 ± 0,5	14,8 ± 0,4	0,8 ± 0,2

* mean value and standard deviation are calculated for the measurements where the Schiebel AN19 Mod 7 metal detector produced audio signal; there were spots on the lanes where detector produced no signal at all

As seen from the table, one soil used in Benkovac was highly uncooperative, with ground reference height close to 15 cm, while the other one was neutral.

2. Measurements by the 'Leibniz Institute for Applied Geosciences' from Hannover

a. Magnetic susceptibility

Frequency dependence of magnetic susceptibility of the soil samples was measured. Before 10 ml plastic pots were filled, the soil was first dried and homogenized. For the measurement of the real and imaginary part of the susceptibility value with 12 different frequencies (50 Hz – 10 kHz) Magnon apparatus was used. Field strength was $H=161$ A/m.

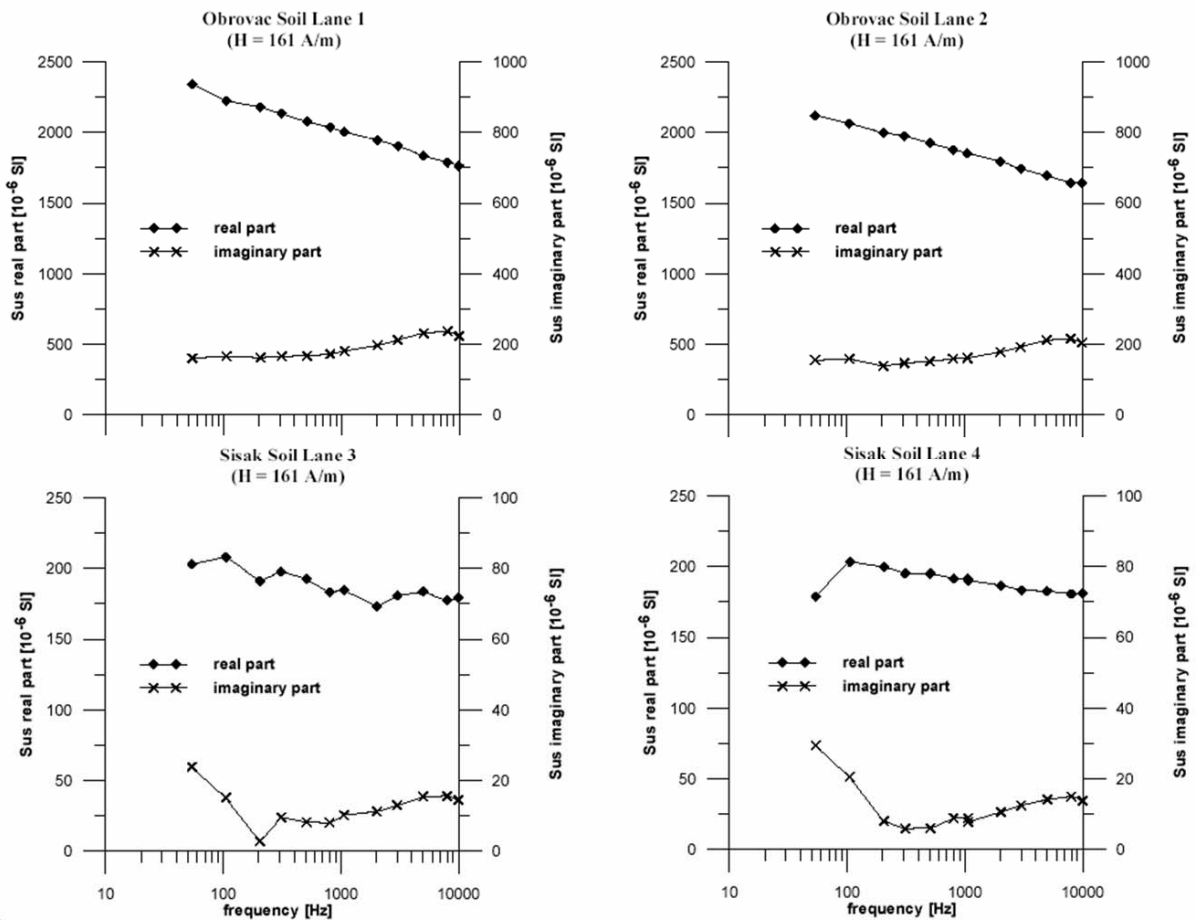


Figure 1. Frequency dependant magnetic susceptibility for Obrovac and Sisak soil

b. Electric Conductivity

Apart from magnetic susceptibility, electric conductivity is considered to be second most important property of the soil that reduces ability of a metal detector to detect a mine that is buried in the soil. Dependence of an electric conductivity to the different water content in the soil, as well as to the frequency was measured.

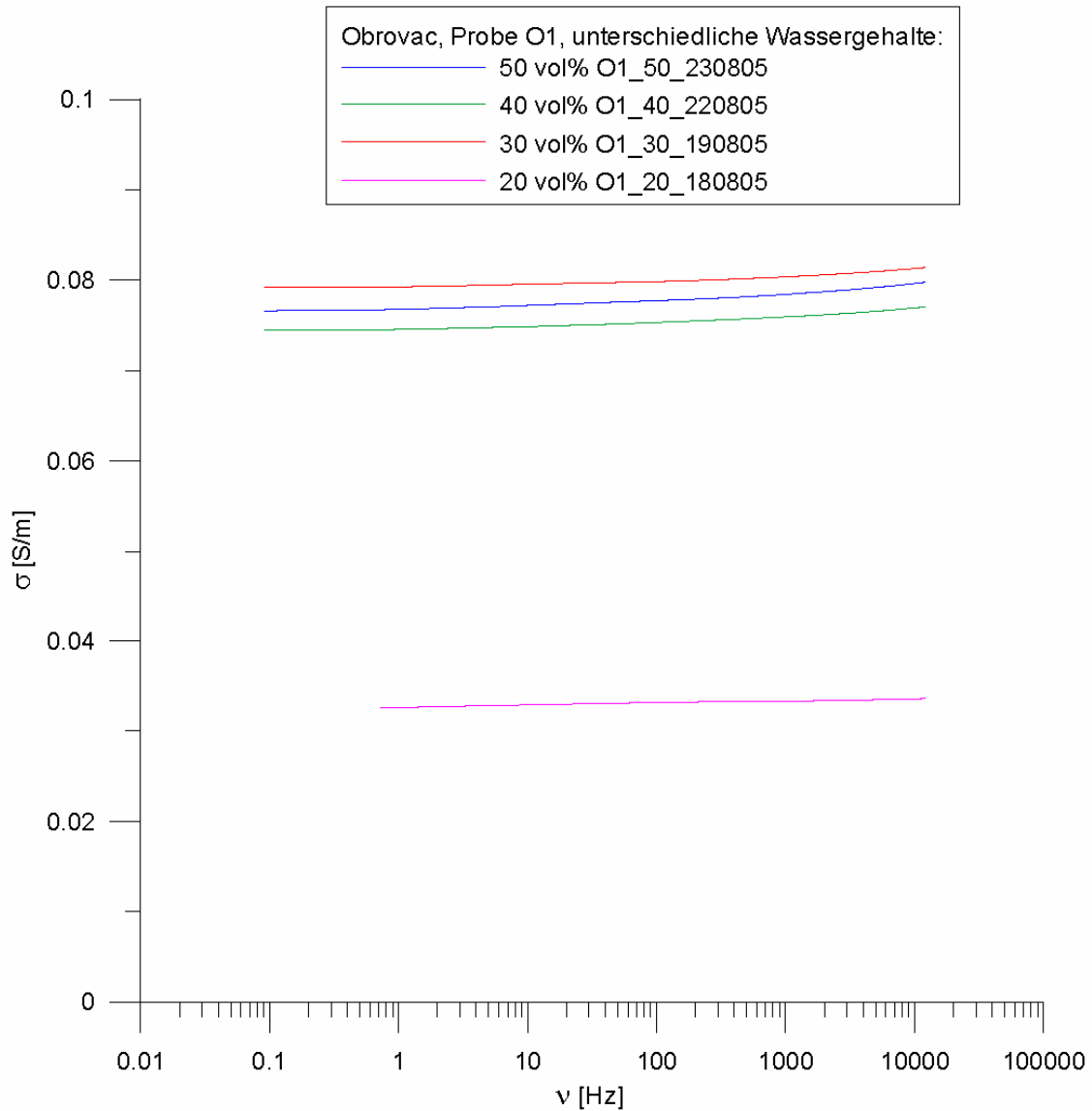


Figure 2. Frequency dependence of electric conductivity, Obrovac soil for different water concentrations

The results show small dependence of conductivity on frequency of about 0.5% for every decade. Significant increase of the conductivity can be seen when comparing the soil with 20vol% of water with 30vol%. With 20vol% the soil still “feels dry”, as by 30vol%, “feels wet”. Further increase of water content to 40vol% and 50vol% also increases the conductivity, but to a lesser degree.

3. Modelling of Ground Reference Height

The ground reference height is a response to a metal detector from a soil. The magnetic susceptibility is the main physical property which measures how much the ground couples electromagnetically with the field produced and detected by the detector coil and the ground reference height is an empirical measurement of the effect of the ground on the detector. By assuming a certain model of frequency dependence for susceptibility the ground reference height can be modelled.

Induced voltage on a one-turn coil of a metal detector due only to the presence of the non-conductive soil can be derived as /1/

$$V(\omega) = j\mu_0\omega\pi a^2 I \int_0^\infty \frac{\chi(\omega)}{2 + \chi(\omega)} J_1(\lambda a)^2 \exp\{-2\lambda h\} d\lambda \quad (1)$$

where

- μ_0 : permeability in free space
- a, b : radius of the transmitting and receiving coils
- λ : integration variable
- J_1 : Bessel function of the first kind and of order of 1
- h : height
- ω : angular frequency

By the Fourier transform and assuming the current Eq. (1) can be transformed to time-domain.

$$V(t_0) = \frac{1}{2} \mu_0 a^2 I_0 \int_0^\infty J_1(a\lambda)^2 e^{-2h\lambda} d\lambda \int_{-\infty}^\infty \frac{\chi(\omega)}{2 + \chi(\omega)} e^{j\omega t_0} d\omega \quad (2)$$

Frequency-dependent susceptibility is modelled as

$$\chi(\omega) = \frac{\chi_0}{1 + j\omega\tau} \quad (3)$$

where

$$\tau = \sqrt{\frac{\chi_L - \chi_H}{\chi_H \omega_H^2 - \chi_L \omega_L^2}} \quad (4)$$

$$\chi_0 = \chi_L \left(1 + \omega_L^2 \frac{\chi_L - \chi_H}{\chi_H \omega_H^2 - \chi_L \omega_L^2} \right) \quad (5)$$

χ_L and χ_H are measured susceptibilities at frequencies of ω_L and ω_H , respectively.

By setting a detection threshold for the induced voltage $V(t_0)$ the theoretical ground reference height can be modelled.

The modelling is demonstrated with measured susceptibilities shown in Table 2 /2//3/. Schiebel AN-19/2 metal detector was exploited in the measurements and parameters for the metal detector $a = b = 10.7$ cm, $I_0 = 3$ A, $t_0 = 35 \mu s$ are substituted into Eq. (2) /4/. The measured susceptibilities and their frequency dependencies are shown in Figure 3, and the induced voltages against ground reference heights are calculated as shown in Figure 4. According to the reference /4/ the voltage threshold is set at 91.8 nV. The modelling results are shown in Figure 5. The modelled ground reference heights are in good agreement with the measured ground reference heights.

The ground reference heights are compared to maximum detection distances. The maximum detection distances shown in Table 3 were measured by Schiebel ATMID in the same trail for the ground reference height. In Figure 6 we can observe a tendency that a lower ground reference height gives higher maximum detection distance and vice versa. It is very logical because a soil that has higher ground reference height is “difficult soil” resulting low

maximum detection distance. By also this result it is demonstrated that the modelling of ground reference height works well.

Table 2 - Measured ground reference heights and susceptibilities at frequencies of 465 Hz and 4650 Hz in Mozambique 2005 trials/2//3/. The ground reference heights and the susceptibilities were measured by Schiebel AN19/2 metal detector and Bartington Instruments MS2B dual frequency κ meter, respectively

Lane	Soil	χ at 465 Hz (10^{-5} SI)	χ at 4650 Hz (10^{-5} SI)	$\Delta\chi$ (10^{-5} SI)	Ground reference height (cm)
#2	loamy sand	13.3	13.0	0.3	0.9
#3	sandy loam	111.0	106.0	5	8.3
#4	clay	1124.0	1098.0	26	16.8
#5	clay	1177.0	1147.0	30	18.0
#6	clay	561.0	518.0	43	21.1
#7	sandy loam	2774.0	2728.0	46	21.0

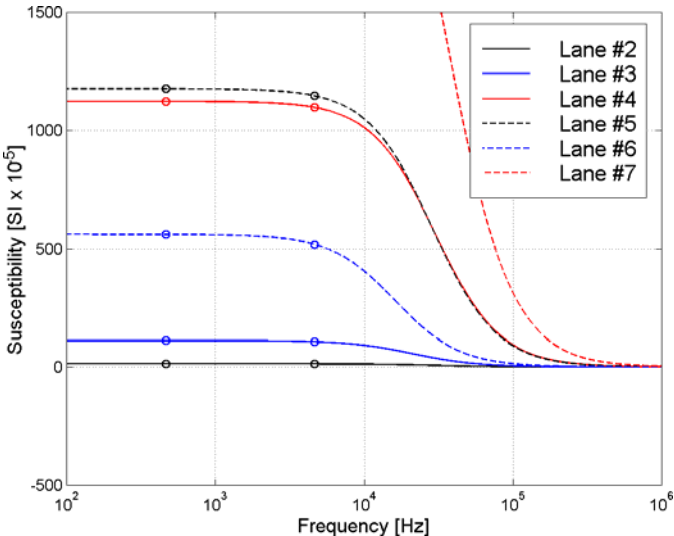


Figure 3. Frequency dependency of real part of susceptibilities calculated from measurements shown in Table 2

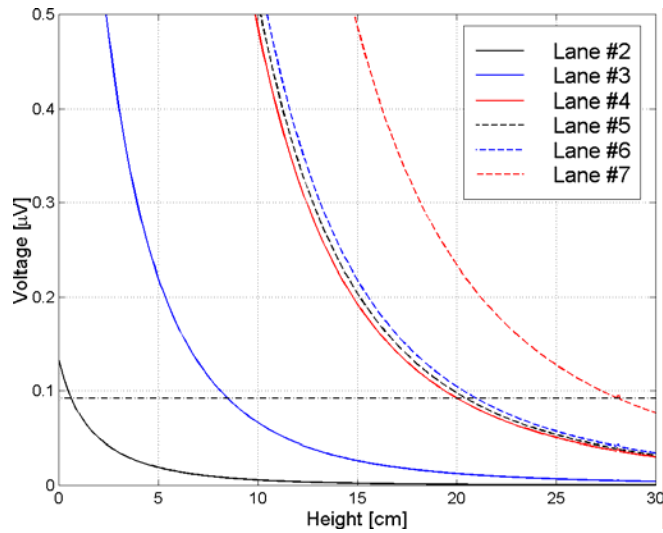


Figure 4. Induced voltage calculated by Eq.(2)

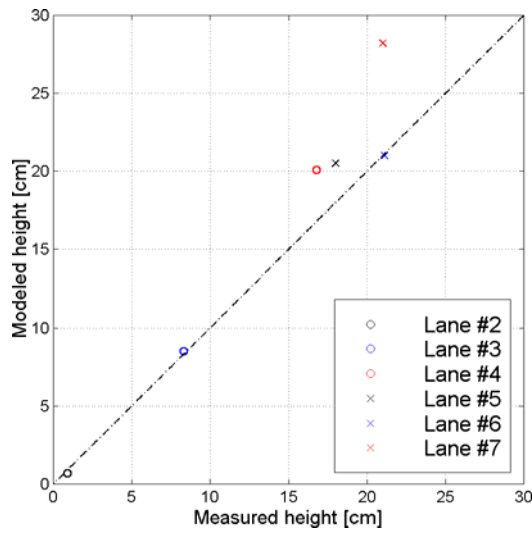


Figure 5. Measured vs modelled ground reference height.

Table 3 - Maximum detection distances for PMN and PMN-2 measured by Schiebel ATMID metal detector /3/.

Lane	Maximum detection distance (cm)	
	PMN	PMN-2
#2	39.13	35.88
#3	49.88	31.98
#4	30.96	23.92
#5	39.99	28.08
#6	37.41	26.26
#7	24.08	26.00

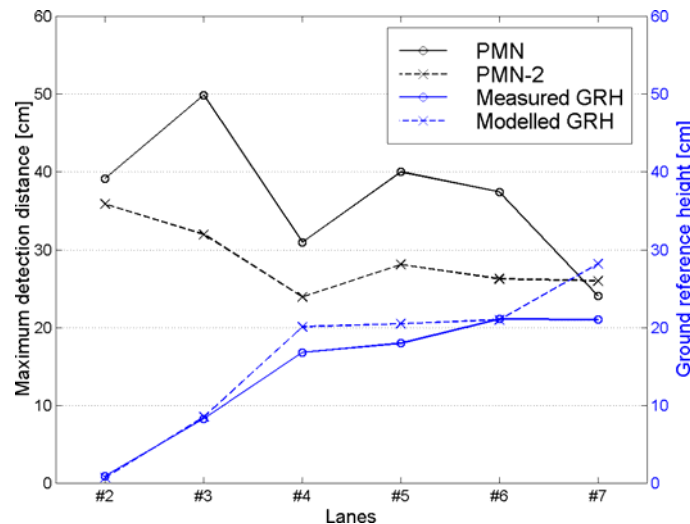


Figure 6. Maximum detection distances and ground reference height for each lane

4. Conclusions

The magnetic susceptibility measurements accomplished by the Bartington device fit well in the frame of the broadband results of GGA Hannover. This linear dependence was already indicated by Billings 2003 /5/, as well as the correlation between the frequency dependence of the magnetic susceptibility connected with soil uncooperativeness and the GRH (ground reference height) confirmed empirically by our measurements.

A modelling method of ground reference height from magnetic susceptibilities measured at two frequencies has been developed. By comparing to the measured ground reference height it is shown that the method gives sufficient results. Moreover the opposite relationships between ground reference height and maximum detection distance is observed.

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