Effects of Electromagnetic Stimulation on Soil's Hydraulic Conductivity

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ABSTRACT
A series of bench top tests were performed to investigate the effects of electromagnetic (EM) stimulation on various soil properties. Exploratory tests on EM stimulation's effects on hydraulic conductivity were performed on very fine sand and clay (bentonite) samples with very promising results. It was found that EM waves do indeed affect the hydraulic conductivity of soil. An increasing effect on the hydraulic conductivity proportional to the EM wave's power output was observed for the sandy sample while flow restriction was observed for the clayey sample.

RÉSUMÉ

Une série de tests dessus de banc ont été réalisées pour étudier les effets des champs électromagnétiques (EM) de stimulation sur les propriétés des sols différents. Tests exploratoires sur les effets de stimulation EM sur la conductivité hydraulique ont été réalisés sur un sable très fin et d'argile (bentonite) des échantillons avec des résultats très prometteurs. Il a été constaté que les ondes EM effectivement influer sur la conductivité hydraulique du sol. Un effet croissant sur la conductivité hydraulique proportionnelle à la puissance de la vague d'EM a été observée pour l'échantillon de sable tandis que la restriction de débit a été observé pour l'échantillon argileux.

Keywords: *Hydraulic Conductivity, Dipole Oscillation, Electromagnetic Stimulation*

1 INTRODUCTION

An alternating electric field can make dipole water molecules oscillate. Individual water molecules can be aligned using an electrostatic source and droplets of water can even be levitated by magnetic fields (Ikezoe et al. 1998). It has been shown that when stimulated by an electric field matching the water molecule's resonant frequency, localized vibrations and flow within a water droplet can be induced which can cause an overall deformation through both direct and alternating currents (Yamada et al. 2003).

The research involves the identification of the different effects that EM stimulation has on different soil properties and behaviour such as hydraulic conductivity. Hydraulic conductivity is a measure of the rate at which water moves through a porous material. Hydraulic conductivity is mostly dependent on the viscosity of the fluid, along with the pore and grain size distributions, void ratio, and the level of saturation of the porous medium (Das 2006). The hypothesis is that given an EM wave, individual water molecules can be oscillated and induce a net change in the movement and flow of water through a porous medium without altering the properties of the medium itself.

This work could prove to be of importance in furthering understanding of the effects of EM stimulation on the hydraulic conductivity of soil. A correlation between EM stimulation and hydraulic conductivity could have broad applications for geo-environmental and geotechnical applications such as contaminant remediation in soils, aquifer regeneration, landfill lining, and for various geotechnical applications. EM waves can be used to enhance soil and groundwater remediation in a way that only a minute amount of heat is generated, yet the desired mechanisms in soil are stimulated or slowed down. This will eliminate the harmful pH changing or heat creating effects of direct or alternating currents used to enhance soil remediation.

2 EXPERIMENTAL SETUP

A customizable permeameter to measure the change in hydraulic conductivity given an EM wave emitted from an antenna was developed for this work. The permeameter was built using plastic materials to avoid metallic parts and the resulting uncontrolled interference with regard to EM waves. The permeameter and its contents were stimulated by an EM wave through an antenna with an impedance matched frequency and various power output levels while the hydraulic conductivity was measured incrementally over time.
The EM wave was generated through a coaxial cable via an Agilent E4400B signal generator and amplified using a 100LM8 amplifier manufactured by Amplifier Research. The electrical impedance of the medium within the permeameter, cables, and antennas was first matched to that of the amplifier (50 Ω) using a matching network to minimize the reflection back into the amplifier and maximize the power output into the medium. The measurement of the impedance was performed using an Agilent N9320A network analyzer and a dual directional coupler.

Constant-head permeability tests in accordance with ASTM D2434 were conducted on a saturated fine sand sample using the fabricated permeameter (schematics shown in Fig. 1). Tap water was used as the source for both of these preliminary experiments.

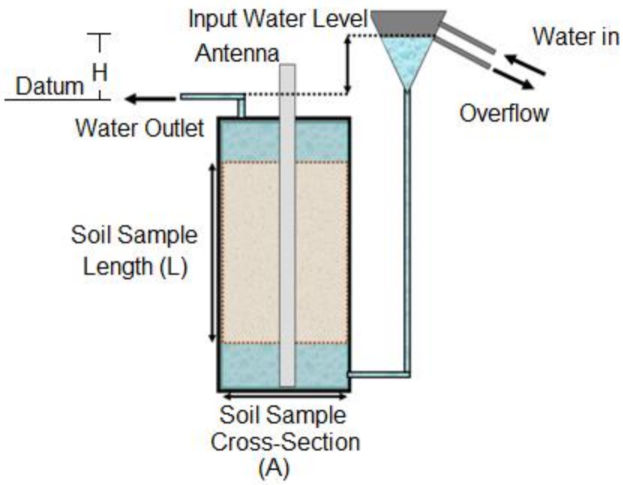

Figure 1. Constant head permeameter schematic

Collection and measurements of outflow over time was conducted to enable the calculation of the hydraulic conductivity of the soil sample with the constant head test. Equation 1 shows the application of Darcy's Law with respect to the calculation of hydraulic conductivity given a constant head permeameter.

$$k = \frac{VL}{AtH} \tag{1}$$

where:

$$V = \frac{\Delta m}{\rho_{H2O}}$$

$$\rho_{H2O} \propto T$$

which results in the following.

$$k = \left(\frac{L}{AH}\right)\left(\frac{\Delta m}{t\rho_{H2O}}\right) \tag{2}$$

where k = Hydraulic conductivity
H = Hydraulic head loss across the soil medium
A =Soil sample cross-sectional area
L = Length of soil sample
T = Water collection duration
V = Volume of water collected
Δm = Change in collection container mass
ρ_{H2O} = Water density at specific temperature
T = Water temperature

Measurements relied on constant values for L, A, and H with incremental measurements taken for Δm_{Water}, and Δt. It was found that it takes 24 hours for the k values to stabilize after they asymptotically decreased. Hence, at least 24 hours were allowed before EM-stimulation occurred.

Falling head permeability tests in accordance with ASTM D2434 were conducted on a bentonite clay sample using the fabricated permeameter schematics shown in Fig. 2.

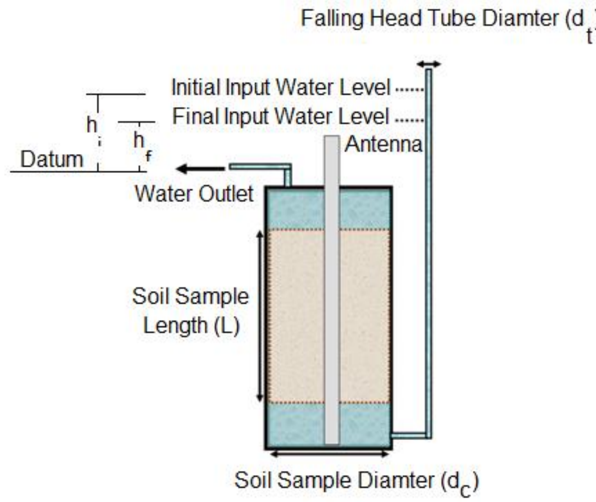

Figure 2. Falling head permeameter schematic

Head differential measurements over time from the initial and final heads given a known datum were conducted for the falling head test. Equation 3 below shows the application of Darcy's Law with respect to the calculation of hydraulic conductivity given a falling head permeameter.

$$k = \left(\frac{d_t^2 L}{d_c^2 t}\right)\ln\left(\frac{h_i}{h_f}\right) \tag{3}$$

where d_t = Falling head tube diameter
d_c = Soil sample diameter
h_i = Initial head loss (difference) across soil sample
h_f = Final head loss (difference) across soil sample

Measurements relied on constant values for L, d_c, and d_t with incremental measurements taken for h_i, h_f, and Δt. Like the constant-head permeameter, it was also found that hydraulic conductivity values asymptotically decreased before they stabilized. Hence, they were also allowed to stabilize to a constant value after at least 24 hours before EM-stimulation started.

3 RESULTS & DISCUSSION

3.1 Sand Results

Tests performed in this research show a correlation between the fine sand's hydraulic conductivity and the presence of EM stimulation at a frequency of 154 MHz. An increase in the hydraulic conductivity was observed after EM-stimulation was initiated with the magnitude of increase proportional to the power output of the EM wave.

Average increases in the hydraulic conductivity given the EM wave's power output are shown in Table 1. Further testing will be performed using various other soil types while varying values for the EM waves' frequency and power output in order to further determine the nature of the detected correlation. Further testing can enable us to derive a mathematical and/or tabular expression for this relationship.

Table 1. Sand Results

Power (W)	Percent Increase in Hydraulic Conductivity
15	0
28	6
50	14

Fig. 3 shows the sand tests at a 50-W EM-power output carried out within 5 consecutive days after the hydraulic conductivity was allowed to stabilize at roughly 2.25×10^{-4} cm/s; a value typical for the fine sand sample tested (Fetter 2001).

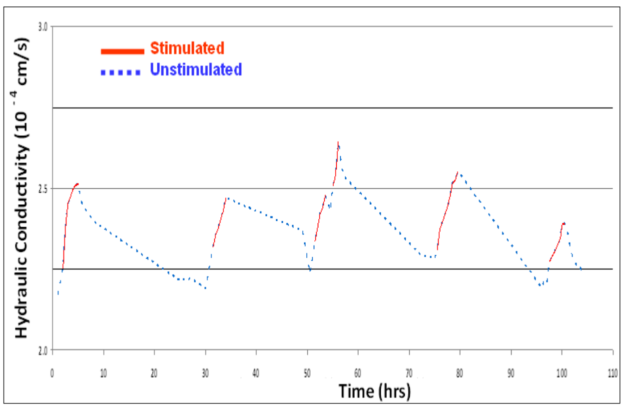

Figure 3. 50-Watt EM power output complete test-data on sand

The majority of the sand tests suggest that the maximum rate of increase in hydraulic conductivity is reached after approximately 3 hours of constant stimulation as shown by the test in Fig. 4. Although some tests show consistent increases in the hydraulic conductivity, it was observed that the rate of increase decreases as a function of time suggesting that there might be a level at which, the effect on the net flow of water in the permeameter due to the EM-stimulation reaches a maximum and then relaxes up to some extent. More investigation is needed to better understand these mechanisms.

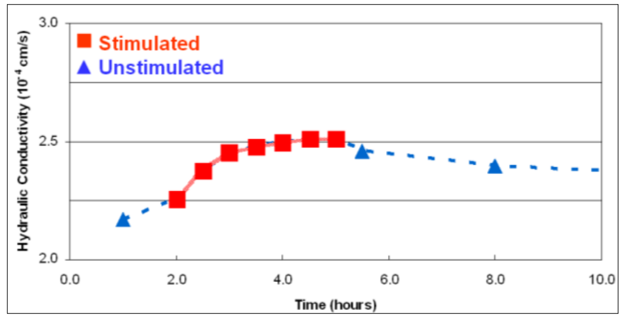

Figure 4. Hydraulic conductivity variation (50-Watt input EM power)

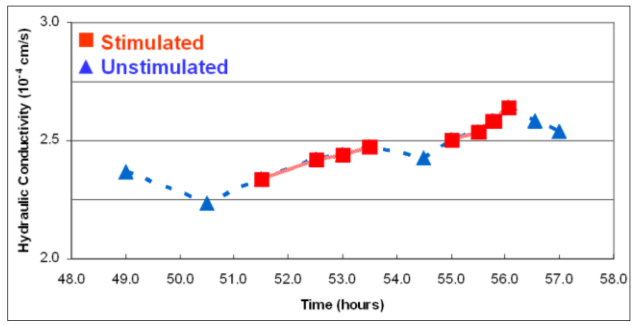

Figure 5. Hydraulic conductivity variation (50-Watt input EM power)

The test, shown in Fig. 5, was used to more concretely validate the effect of EM stimulation on the hydraulic conductivity increase by stopping stimulation midway through the test and restarting it. This resulted in a sudden decrease in the observed hydraulic conductivity while stimulation was halted and a continued upward trend once stimulation was resumed. This clearly shows that the observed increases are primarily due to the EM-stimulation.

The effect of heating due to the EM stimulation was a concern throughout the testing process. An increase in the water's temperature would affect the water's density and therefore the hydraulic conductivity of the soil given equation 1. The effect of temperature was taken into account by sporadically measuring the temperature of the outflow and comparing it to the inflow. Fluctuation in the outflow's temperature was found to be insignificant and closely mirrored the fluctuation in the inflow's temperature which was itself relatively small at ±1°C for both the stimulated and unstimulated cases.

Given a small droplet of water, it would be possible to determine the resonant frequency at which the entire body of water vibrates (Yamada et al. 2003). Since the water in the permeameter is in motion and assumes an amorphous shape in the permeameter, it is all but impossible to pinpoint a resonant frequency at which the agglomeration of molecules vibrates. The difficulties involved with determining the resonant frequency of the dipole oscillations within the agglomerated water in the permeameter prevents from realizing the maximum effects that the EM wave can have on the hydraulic conductivity.

3.2 Clay Results

Fig. 6 shows the clay tests at a 30 Watt power output carried out within 5 consecutive days after the hydraulic conductivity was allowed to stabilize at roughly 7.5010^{-8} cm/s; a value typical for the clay sample tested (Fetter 2001).

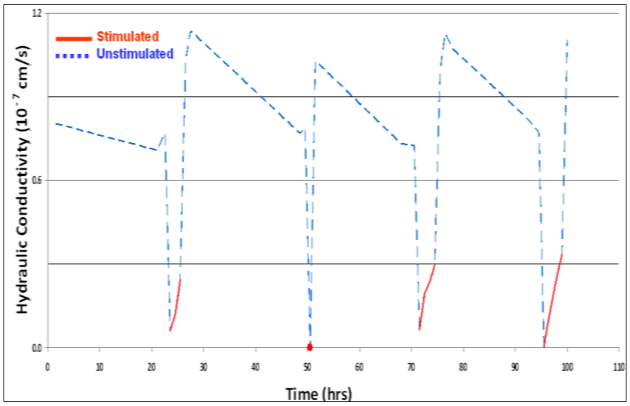

Figure 6. 30-Watt EM power output complete test-data on clay

Test results, from the falling head tests on clay, yielded very different results. As shown in Fig. 6, EM stimulation caused a sharp decrease in the hydraulic conductivity of the clay sample. In most tests, hydraulic conductivity through the clay was effectively reduced close to 100 times for a short amount of time immediately after EM stimulation was initiated. There was some degree of relaxation even before the EM-stimulation was terminated. Thereafter, the EM-stimulation was terminated. The termination of EM-stimulation also caused a sudden spike in the hydraulic conductivity, which surpassed the average pre-stimulation hydraulic conductivity for the clay sample similar to a rebound effect.

Fig. 7 shows some degree of relaxation during stimulation and suggests that the hydraulic conductivity might be regained after a certain amount of time despite the presence of EM stimulation. Limitations of the current equipment prevent running an extended stimulated test beyond 4 hours to determine the behaviour of the hydraulic conductivity and the extent of this relaxation. Further testing is currently being conducted to determine the extent and cause of this phenomenon.

The test shown in Fig. 8 was conducted to determine whether the rebound of the hydraulic conductivity after EM-stimulation was a function of the relaxation observed during the tests. It shows the clear effect that the EM field has on the hydraulic conductivity of the clay sample and also suggests that the rebound effect is independent of the relaxation size and extent.

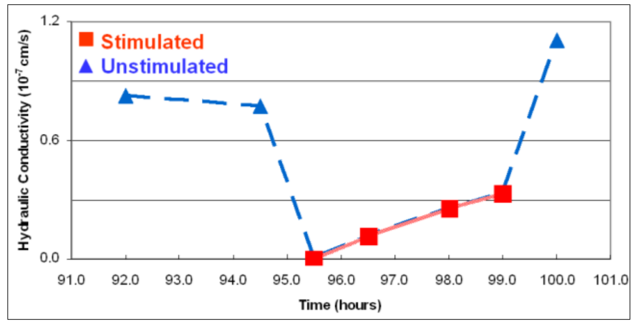

Figure 7. Relaxation of hydraulic conductivity decrease in clay (30-Watt input EM power)

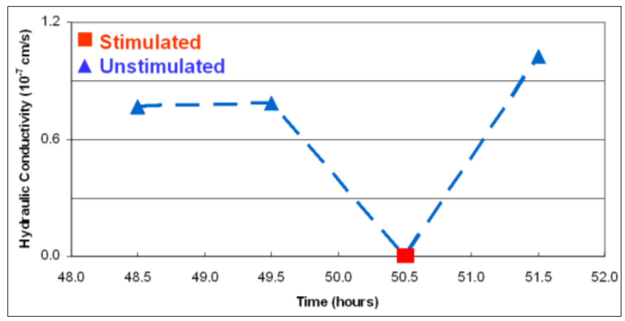

Figure 8. Hydraulic conductivity variation (30-Watt input EM power)

The effect of dielectrophoresis was explored during the conductivity tests in clay. Dielectrophoresis is characterized by an attractive or repulsive force induced by an alternating electric field. Dielectrophoresis has been shown to be effective in manipulating the movement of water molecules through an increase in local water molecule concentrations within medium voltage cables (Patsch et al. 1990). If dielectrophoresis was the source of the change in hydraulic conductivity, then the effect on the flow would reverse when the power-density gradient changed direction. This can be stimulated and tested by maintaining the same field and reversing the flow.

The direction of the flow was reversed in the clay test to examine whether the decrease in hydraulic conductivity is due to dielectrophoresis. The orientation of the antenna was not changed in order to ascertain whether the presence of the electric field had a dielectrophoretic effect on the water molecules. The reverse flow with respect to the electric field radiation pattern has the same decreasing effect on the hydraulic conductivity. This means that dielectrophoresis is not the cause of the decreases in the clay's hydraulic conductivity.

It would stand to reason that the same would be true for sand. Reversing the flow direction would not change the rate of increase in sand's hydraulic conductivity or even cause it to decrease, since dielectrophoresis is not the controlling mechanism for this observed phenomenon.

EM-stimulated tests conducted at the same frequency and power level using the reverse water flow direction yielded similar results. Hydraulic conductivity through the clay sample was effectively reduced by close to 100 percent. The relaxation shown in Fig. 7 was also seen during these tests and the hydraulic conductivity also displayed the observed rebound after stimulation was turned off.

4 CONCLUSION

The experiments outlined in this paper successfully demonstrate the strong effect of EM fields on the hydraulic conductivity of soils. An increase in the hydraulic conductivity of sand proportional to the EM field's power output was observed while a complete momentary flow loss was observed in the bentonite clay sample. Additional tests are currently being conducted to isolate the potential factors affecting the phenomenon to help to draw a conclusion as to the variables that affect this phenomenon.

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