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THREE-DIMENSIONAL INVERSION OF MAGNETIC RESONANCE SOUNDING (MRS) FOR GROUNDWATER DETECTION

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ABSTRACT

For this paper, we consider the resulting 3-D inversion using inversion modeling, which is motivated by developing theory and the recent application of the Magnetic Resonance Sounding (MRS) technique in detecting and mapping of subsurface groundwater. MRS is a non-invasive method which directly detects the groundwater's existence from surface measurements. A pulse current, at a proper frequency, is transmitted into a loop. After hydrogen atoms of water molecules in the subsurface are energized by pulses of alternative currents, the magnetic resonance field is produced by the H protons is measured within the same loop. Generally, MRS has two observable factors: initial amplitude and decay time. The aim of three-dimensional inversion is to extract the information, i.e., the value and distribution of two physical parameters of the subsurface conditions: water content and subsurface properties (pore and grain size). Additionally, we present a general formulation for inverting the initial amplitude and decay time of the MRS data to recover a 3-D distribution of groundwater. The forward problem was solved using an integral equation method in the spatial domain. An improved Levenberg-Marquardt strategy was employed to solve the inverse problem. Two synthetic examples are illustrated to determine the basic functionality of the inversion algorithm. The real data results show applicability and relevance in larger-scale field examples.

Keywords: Decay time; Groundwater; MRS; water content; 3-D inversion

1. INTRODUCTION

Nuclear Magnetic Resonance (NMR) is a phenomenon by which a nucleus of an atom absorbs electromagnetic radiation of a specific frequency in the presence of a strong magnetic field. NMR is a measurement technique that can provide a great amount of information about the pore-scale properties of geological materials. In geophysical applications NMR measurement can be made at the laboratory scale or at the field scale using well logging devices or surface NMR systems. For well logging devices NMR has provided a new dimension to log analysis by permeability indications from logs, and direct identification of fluid type without resistivity. In the petroleum industry NMR technology has been widely used both in logging for oil exploration and in core analysis for petrophysical studies. There is also a relatively new MRS (Magnetic Resonance Sounding) or SNMR (Surface Nuclear Magnetic Resonance) system, designed to sample the top 100–150 m of the earth, for groundwater applications (Schirov et al., 1991). To improve the ability of the SNMR method to determine groundwater parameters in the subsurface, we have carried out a research to study the response of 2-D and 3-D models, i.e. the SNMR relaxation signal for various locations of the antenna loop.

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A 3-D forward modeling code for MRS amplitudes and decay times has been developed; after that an improved 2-D and 3-D inversion algorithm has been investigated consist of model parameterizations regularization schemes (Warsa et al., 2014). Giving a short review of general inversion schemes used in geophysics, the special properties of MRS inversion are evaluated.

2. BACKGROUND THEORY

2.1. Spin Characteristic

Nuclear Magnetic Resonance (NMR) is a phenomenon, occurring when the nuclei of certain atoms are immersed in a static magnetic field and exposed to a second oscillating magnetic field. Some nuclei (such as hydrogen) undergo this phenomenon, and others do not, depend on whether they own a property called ‘spin’. The nucleus of the hydrogen molecule contains a proton. Because of the spin characteristics of the proton, it will assume one of two possible positions within an external magnetic field B_0. It will align at a slight angle in either a parallel or anti-parallel position with the direction of the magnetic field. In the absence of an externally applied magnetic field the magnetic moments have random orientations, whereas by applying an external magnetic field B_0 causes the nuclei to align themselves in one of two orientations with respect to B_0 (denoted parallel and anti-parallel).

In addition to aligning with B_0, the proton precesses at some frequency. The proton precesses in an axis at a precession frequency (Larmor frequency). The frequency of the proton precessing is given by

$$\omega_0 = 2\pi\ f_0 = \gamma\ B_0 \tag{1}$$

where ω_0 is a Larmor frequency and γ is the gyromagnetic/ magneticgyric ratio. For the proton in water molecules, the gyromagnetic ratio γ_p is

$$\gamma_p = 0.26751525.\ 10^9\ \text{Hz/T} = 26752\ \text{G}^{-1}\text{s}^{-1} \tag{2}$$

2.2. Dynamics of the Nuclear Magnetization

In thermal equilibrium the nuclear magnetization $M_0(r)$ due to the Earth’s static magnetic field is the value of magnetization per volume unit in the applied static magnetic field. It is also described by the Curie’s rule (Shushakov, 1996). Generally, the nuclear magnetization $M_0(r)$ is (Abragam, 1983).

$$M_0(r) = n(r)\frac{\gamma^2\hbar^2}{3kT}S(S+1)\cdot B_0 \quad [\frac{N\cdot m}{T\cdot m^3}] \tag{3}$$

where n(r) is the number of nucleon (proton) per volume unit [m^{-3}], S is the nuclear spin (for proton S = ½), $\hbar$ is Planck’s constant $6.626\times10^{-34}/2\pi$ [Nms], k is Boltzmann’s constant [NmK^{1}], T is the temperature [K], B_0 is the external magnetic field [T].

For proton the Equation (3) becomes

$$M_0(r) = n(r)\cdot B_0\,\frac{\gamma^2\hbar^2}{4kT} \quad [\frac{N\cdot m}{T\cdot m^3}] \tag{4}$$

The number of nucleon n(r) is calculated from the water volume. A 1 m^3 water corresponds to about a mass of 998 kg in 1013.25 hPa and 20°C and in 18.0152×10^{-3} kg water (molecular weight) contains 6.022045×10^{23} water molecules (the Avogadro's constant). A 1 m^3 of water contains 3.336×10^{8} H_2O molecules and consequently the double number of proton $n(r)$ is 6.67×10^{28} molecules.

After exciting the water molecules, the magnetization $M_0(r)$ increase directly depending on the number of water molecules in the considered volume element. This process lets the water content $w(r)$, where $0 < w(r) < 100$ %, be described as

$$M'_0(r) = w(r)\cdot n(r)\cdot \frac{\gamma^2\hbar^2}{4kT}B_0 = w(r)\cdot M_0(r) \quad (5)$$

2.3. MRS Signal

The method of MRS is based on the principle of the magnetic resonance of protons of hydrogen atoms in the static Earth's magnetic field. An alternating current pulse through a wire antenna at the surface stimulates an NMR signal as shown in Figure 1. The initial amplitude E_0 of the magnetic resonance signal can be calculated using the existing model (Legchenko & Shushakov, 1998). In a water aquifer the layer cannot be extinguished regularly from distribution of protons. The ratio of induced voltage of stimulated proton must be also sustained. In reality the signal induced in the receiver is equal to the perpendicular component of the magnetic field times the sum of the flux of all the relaxation magnetic dipoles. The fundamental equation (Weichmann et al., 2000) that governs the amplitudes $E_0(q)$ and decay time $T_2^*(q)$ of NMR as a function of the pulse moment q is given by:

$$E_0(q)e^{-t/T_2^*(q)} = \omega_0 M_0 \int_V e^{-t/T_2^*(r)} w(\mathbf{r})\cdot B_\perp(\mathbf{r})\cdot \sin\theta(\mathbf{r})\, dV \quad (6)$$

where M_0 is the nuclear magnetization of the protons, ω_0 is the local Larmor frequency of the hydrogen protons, $w(r)$ is the water content, and $B_\perp(r)$ states the component of the exciting magnetic field perpendicular to the Earth's geomagnetic field. The tilt angle of the protons is given by $\theta(r) = 0.5\gamma B_\perp(r)\, q$ ($q = I_0\tau$, where I_0 and τ are the amplitude and duration time of the current pulse, respectively). The depth of penetration of the method is deeper, when the pulse moment q is increased.

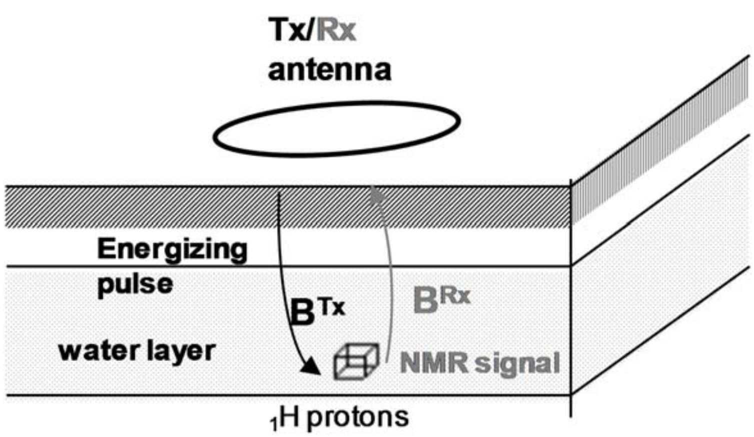

Figure 1 Schematic of MRS (Magnetic Resonance Sounding) field measurements using a coincident transmitter and receiver circular loop

3. 3-D MRS FORWARD MODELING

In this section, a 3-D forward modeling scheme for MRS amplitudes and decay times is presented. The modeling can be used for two and three-dimensional interpretations of MRS surveys. The formulation is reduced to an integral equation matrix problem by considering a finite number of cells with constant spin density (water content and decay time) (Warsa et al., 2002). The equation of initial amplitude E_0 for a 3-D distribution of free-pore-water, which was derived in Section 2, is proved for the numerical calculation from the discrete integral in the sum of a small cell (Figure 2). The cuboids 3-D body model is divided into small cubic cells of the dimension ΔV = Δx Δy Δz.

The fundamental equation that governs the amplitudes of MRS in the subsurface is given discretely by

$$E_0(q) = \sum_z \sum_y \sum_x w(x,y,z) \cdot K_{3D}(x,y,z) \Delta x \Delta y \Delta z \tag{7}$$

Where $K_{3D}(x,y,z) = \omega_0 M_0 \sum_z \sum_y \sum_x B_\perp(x,y,z) \sin\theta(x,y,z) \Delta x \Delta y \Delta z$. Δx, Δy and Δz describe the side-length of the volume element ΔV. The decay times T_2^* as a function of pulse moment can be obtained from

$$E_0(q) e^{-t/T_2^*(q)} = \sum_z \sum_y \sum_x e^{-t/T_2^*(r)} w(r) \cdot K_{3D}(x,y,z)\, \Delta x \Delta y \Delta z \tag{8}$$

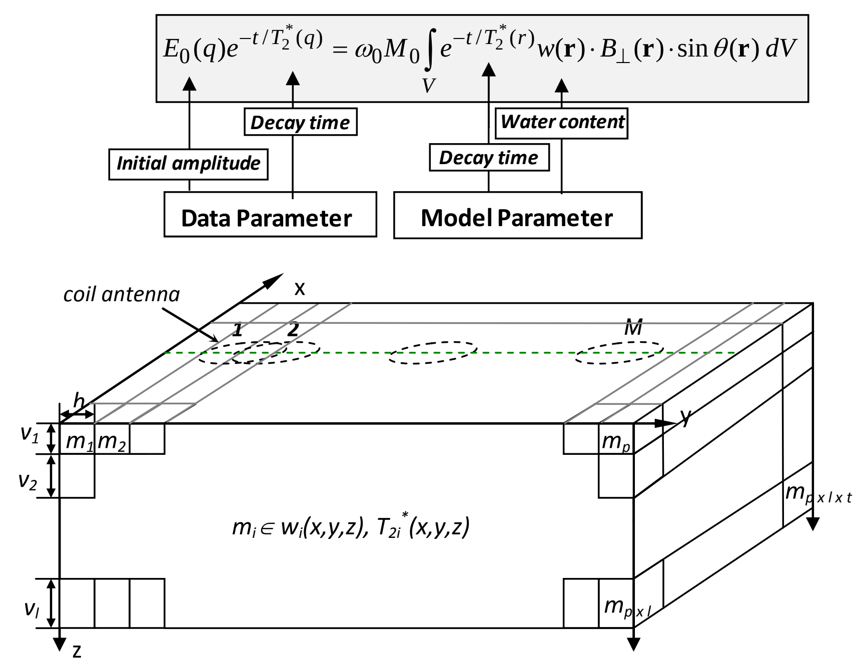

Figure 2 3-D MRS forward modeling for $j = 1,.., M$ sounding points to calculate data parameter **d** which consist of initial amplitude $E_0(q)$ and decay time $T_2^*(q)$ from model parameter **m** for each voxel containing water content w(r) and decay time $T_2^*(r)$

4. 3-D MRS INVERSION

4.1. Inversion Scheme

For the inversion of the MRS data, the Tikhonov regularization method was used in order to minimize the number of measurements (Legchenko & Shushakov, 1998; Yaramanci & Petke, 2009) without loss of accuracy. Here, the function to be minimized consisted of two terms, taking both data fit and model smoothness into account.

$$\left\|\mathbf{G}\mathbf{m}^{est} - \mathbf{d}^{obs}\right\|_2^2 + \alpha^2 \left\|\mathbf{L}\mathbf{m}\right\|_2^2 \quad (9)$$

The order of the Tikhonov solution and, therefore, also the degree of smoothness, is defined by matrix **L** that acts as a derivate operator. For **L** = **I** (**I**: unit matrix), the model roughness is taken into account and referred to as the Tikhonov solution of zeroth order. For the MRS standard approach, in most simple cases, **d** and **m** may contain. **d** is the initial amplitude (for different excitation intensities); **m** is water content (of horizontal layers with fixed boundaries). A modified Levenberg-Marquardt algorithm used to find the parameters that minimize the objective function is as follows:

$$\mathbf{m} = (\mathbf{G}^T \mathbf{G} + \alpha\, \mathbf{I})^{-1} \mathbf{G}^T\ \mathbf{d} \quad (10)$$

where α is the damping parameter and I is the identity matrix.

We performed an inversion of the 2-D and 3-D synthetic signals computed for a multi-water lens model. MRS measurements were carried out at the surface. The synthetic MRS data have been calculated using a circular loop (one turn, diameter d = 50 m) in a geomagnetic field of 48000 nT, at an inclination of 60° and declination of 0° in a low conductive half-space.

4.2. 2-D Inversion Modeling

To investigate the imaging capabilities of MRS configuration and in order to conduct an analysis of the 2-D inversion, model geometries representing various hydro-geological or environmental situations were designed. An example of theoretical data is generated by the 3-D forward modeling program. The model simulates a 2-D structure of a multi-water lens with variation in depth, water content and decay time as shown in Figure 3(a). The synthetic data of the initial amplitude and decay time versus pulse moment q are shown in Figure 3(b).

4.3. 3-D Inversion Modeling

A field survey of MRS was carried out at Enschede Oost/Glanerbrug Netherlands. MRS measurements were carried out to investigate and improve the 3-D MRS imaging. In the field measurement magnitude of the Earth's magnetic field, B_0 is 48808 nT which is to be tilted by 22.7° northward away from the vertical (declination 0°, inclination 67.3°), with the Larmor frequency f_L = 2043.7 Hz. The square receiver and transmitter loops are coincident and separated with a radius of 31.75 m in profile direction. The MRS soundings were measured at eleven locations, 25 m apart from each other on the main profile. More details of the field measurement layout and estimated 2-D structure model are shown in Figure 5.

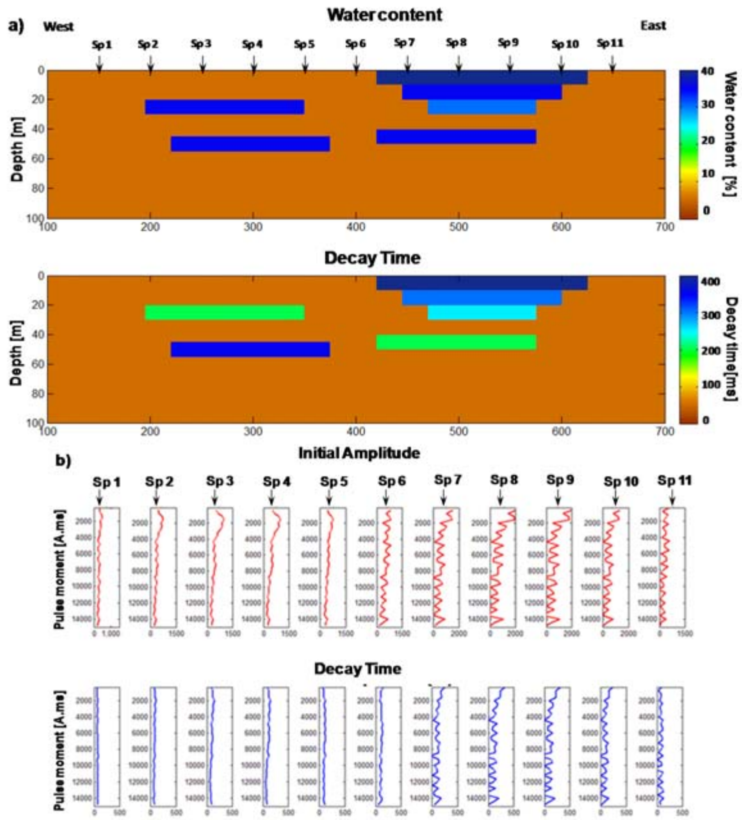

Figure 3 (a) Synthetic multi water lens model for various depths, water contents and decay times; (b) Synthetic MRS data of amplitude (top) and decay time (bottom) generated by forward modeling

The 2-D inversion results of water content and decay time are shown in Figure 4 (top) and (bottom) respectively. The results place the multi-water lens-feature at the correct location as well as the physical properties of water content and decay time.

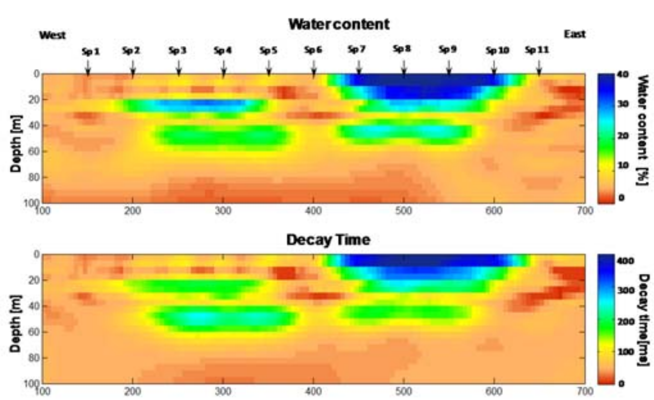

Figure 4 2-D inversion model of water content (top) and decay time (bottom)

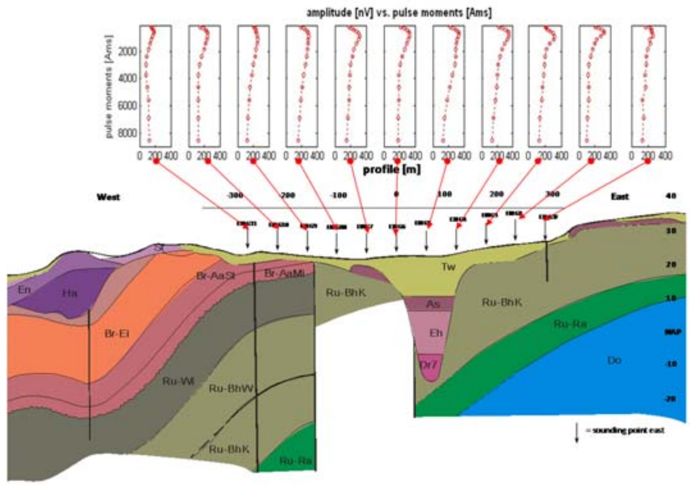

Figure 5 The top section shows the configuration of survey. There are 11 coincident sounding points at the rectangular loop for the profile in the west-east direction. The estimated 2-D model of the subsurface is represented by the bottom section

The 3-D MRS inversion result of water content is shown in Figure 6 (top). The 2-D section in west-east direction of 3-D inversion and water content distribution map is shown in Figure 6 (bottom). The inversion model result of the water content indicates a highly-localized zone of high water content approximately at a depth of 10–30 m between profile -200 m and 200 m.

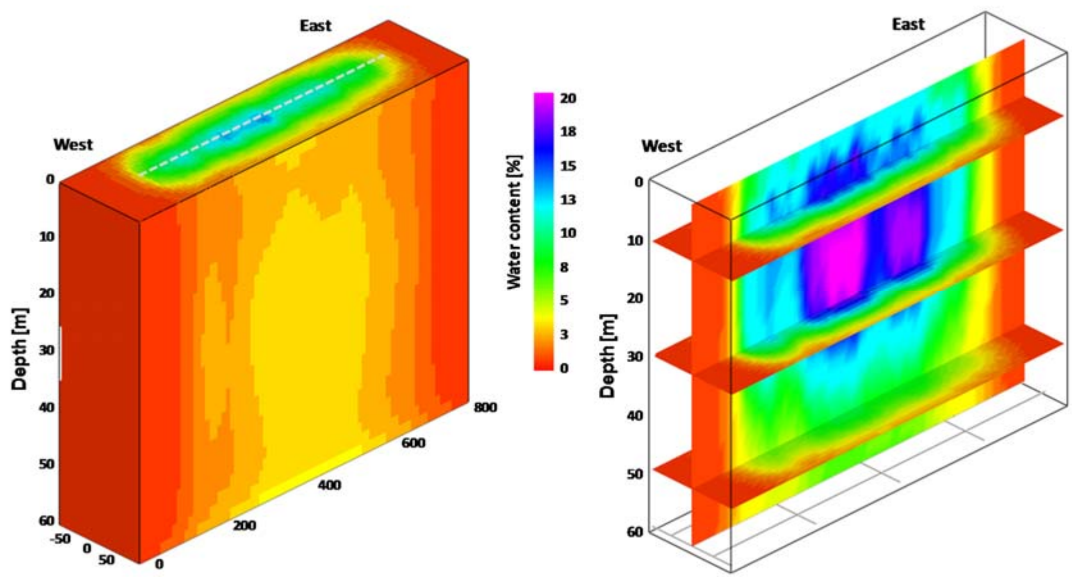

Figure 6 The 3-D inversion result of water content (top) and 2-D west-east section with a map of the water content distribution at the depth of 10, 30 and 50 m (bottom) for the MRS data at Enschede, Netherland

5. CONCLUSION

The research objective is to develop a three-dimensional inverse modeling of MRS (magnetic resonance sounding) methods more realistically. Forward modeling is solved using an integral equation method in the spatial domain which is used to calculate the initial amplitude and decay time responses from a synthetic model of water content and decay time simulating some hydro-geological model in the field. Furthermore, 2-D and 3-D inversion program accommodating Levenberg-Marquardt strategy have been developed to produce the distribution model of water content and decay time. Amplitude and decay time as a function of pulse moment (pulse intensity) are data parameters, whereas water content and decay time are model parameters in the spatial domain. The aim of inversion modeling is to extract the information of water content and decay time correlating with the pore size of rock. 3-D modeling of MRS data is necessary to predict the MRS signal response of aquifers. For optimization of field layouts, the forward modeling method is used for taking appropriate measurements on given 2-D and 3-D situations. 3-D SNMR sensitivities are necessary to evaluate lateral and vertical resolutions. We have developed a reliable technique for 2-D and 3-D inversion modeling of MRS.

The application to synthetic data indicated that the algorithm of forward and inverse modeling have been functioning properly to produce images of water content and decay time of sub-surface as well as the geometric properties. The application of paleochannel investigation has demonstrated the program ability to determine 2-D distribution of water content and to delineate the 3-D model. Similar to most surface geophysical methods, 3-D MRS has limited resolution, but it is effective for investigating water-saturated geological formations larger than several tens of meters (Legchenko et al., 2011).

6. ACKNOWLEDGEMENT

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