Indonesia

Multidimensional SNMR modelling for groundwater exploration

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Abstract

Groundwater is an important economic source of water supply. It serves as an important source for drinking water supply and irrigation for agriculture. In the relation of managing groundwater resources, it is important to forecast of water level, quantity and other changing parameters Furthermore, the groundwater resources are at risk to contaminants from the land surface as well as from intrusions. In many countries the land subsidence occurs when large amounts of groundwater have been withdrawn from certain types of rocks, such as fine-grained sediments.

Surface Nuclear Magnetic Resonance (SNMR) is a relatively new geophysical method that can be used to determine the presence of culturally and economically important substances, such as the subsurface water or hydrocarbon distribution. SNMR is the only geophysical method, which allows to determine water content and pore size distribution directly from the surface In combination with electrical conductivity and permittivity SNMR will be used improve the access to the subsurface. The SNMR method is performed by stimulating an alternating current pulse through an antenna at the surface confirms the existence of water in the sub-surface.

In the future this new method may be applied as an attempt to bring long-term solutions to the water supply problems and also to protect groundwater from the degradation of aquifers. Furthermore, also will be useful as an input to design parameters used to prevent future environment problems [1]. However, in this case of course the use of other geophysical method can provide better answer

Introduction

Groundwater is an important natural resource all around the world. To manage and preserve the groundwater resources quantifying and qualifying of groundwater and hydro-geological parameter of aquifer are provided. Furthermore the availability of groundwater resources and how can be exploited are essential for the sustained socio economic developments of any area, whether urban or rural. It is also critical to forecast the effects of hazard and risk identification concerning the condition of water resources and environment

For this purpose geophysical methods provide a wide range of very useful and powerful tools which, when used correctly and in the right situations, will produce useful information As the range application of geophysical methods has increased, particularly with respect to derelict and contaminated land investigation, the sub-discipline of environmental geophysics has been developed. These measurements can then be used to infer the porosity, permeability, chemical constitution, stratigraphy, geologic structure, and various other properties of a volume material near earth's surface In application of groundwater exploration that can be employed to predict groundwater level, physical parameter of aquifer, sea water intrusion, contaminants from the land surface, land subsidence caused by human activities, mainly from the removal of subsurface water.

One of the geophysical method has been used for monitoring subsidence and decreasing water level is 4D microgravity [2] Monitoring activity using gravity method on a nature phenomenon that relate with physical change of subsurface body can be visualize using its physical parameter (density) of rock if the change give gravity potential field that sufficiently significant to be observed on the surface. Change of groundwater level and sea water intrusion are examples of nature phenomenon that indicate existence of density change in aquifer.

The other geophysical method which may be applied for this purpose is SNMR. The SNMR has been tested on the test site to yield the geometry, water content and hydraulic permeability of the aquifer[3, 4]. Beside allows more detailed and reliable assessment of aquifers the SNMR may also be used to detect the change of water content and hydrogeological parameters caused by subsidence.

To improve the capability of the SNMR method we have carried out a research to study the response of 2D and 3D models, i. e. the SNMR relaxation signal for various locations of the antenna loop. The main aim of this research is to improve the ability of surface NMR method in determination of hydrogeological parameters of the subsurface. Emphasis of the research is the development of a program that allows to determine the initial amplitude and decay time of a SNMR signal for 3D water distribution in dependence of the pulse moment. The amplitudes are directly related to the water content, while the decay times are linked to pore size, grain size, and therefore to hydraulic conductivities At the end we have developed 2D inversion to increase the interpretation of SNMR method

Theoretical Background

The surface nuclear magnetic resonance (SNMR) sounding is a geophysical method that aims at determining hydro-geological parameters from magnetic resonance measurement. This method is based on the principle of the proton magnetic resonance in the Earth's filed of hydrogen 1H atom, which contained in the groundwater molecule H_2O. An NMR signal, stimulated by an alternating current pulse through an antenna at the surface confirms the existence of water in the sub-surface. The amplitudes of NMR signal are directly related to the water content, while the decay times are linked to pore size, grain size and, therefore, to hydraulic conductivities. The phases are related to the electrical conductivity; however this is only used qualitatitively (Table 1).

Measured quantity (vs. pulse moment)	**Physical parameter (vs. depth)**
Amplitude of the PMR signal E_0 (q)	Water content
Decay time constant of the signal T_2*	Mean Pore size
Phase shift between signal and current φ	Rock layer resistivity

Table 1. Physical parameters determined with SNMR

Methodology

The new geophysical method of SNMR is based on the principle of the magnetic resonance of protons of hydrogen atoms in the Earth's magnetic field. An alternating current pulse through a wire antenna at the surface stimulates a NMR signal. After termination of the exciting pulse the response field due to the relaxation of the precessing hydrogen is measured. The amplitudes of NMR signal are directly related to the water content, while the decay times are linked to pore size, grain size and, therefore, to hydraulic conductivities [4, 5]. The phases are related to the electrical conductivity, however this is only used qualitatively.

The geophysical method of surface nuclear magnetic resonance (SNMR) allows direct determination of hydrogeophysical parameters of the subsurface. The method of SNMR is based on the principle of the magnetic resonance of protons of hydrogen atoms in the Earth's magnetic field. Figure 1a shows spin characteristic of the proton 1H in the absence of an externally applied magnetic field. An external static magnetic field B_0 causes the nuclei to align themselves in one of two orientations with respect to B_0 (Figure 1b). Figure 1c shows the precessing of a proton of hydrogen atom. In SNMR an alternating current pulse through a wire antenna at the surface stimulates the NMR signal. After termination of the exciting pulse the response field due to the relaxation of the precessing hydrogen protons is measured (Figure 1d). The initial amplitude E_0 of the signal corresponds to the water content in the subsurface [5, 6]. The decay time T_2^* (spin-spin relaxation time) of the SNMR signal corresponds to pore sizes. The fundamental integral-equation that governs the amplitudes E_0 (q) of NMR as a function of the pulse moment q is given by

$$E(t,q) = E_0(q)e^{-t/T_2^*(q)} = \omega_0 M_0 \int_V e^{-t/T_2^*(\mathbf{r})} f(\mathbf{r}) \cdot B_\perp(\mathbf{r}) \cdot \sin\theta(\mathbf{r})\, dV, \qquad (1)$$

in which ω_0 is the local Larmor frequency of the hydrogen protons and M_0 is the nuclear magnetization of the protons. The water content and the decay time for a unit volume at the point r in the subsurface are given by f(r) and T_2^*(r) respectively. $\mathbf{B}\perp$(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 $\theta(r) = 0.5\gamma\mathbf{B}\perp(r)q$. Increasing the pulse moment q ($q = \mathbf{I}_0\tau$, where $\mathbf{I}_0$ and t are the amplitude and duration time of the current pulse, respectively) increases the depth of penetration of the method.

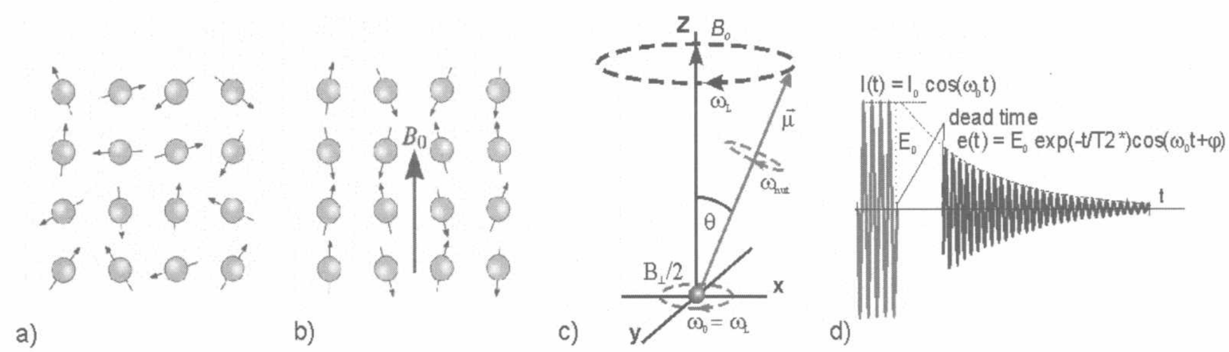

Figure 1: Spin characteristic of the proton. (a) in the absence of an external static magnetic field (b) in an external static magnetic field B_0 (c) the precessing hydrogen proton at the Larmor frequency ω_0 (d) the time diagram of the SNMR signal measurement.

Numerical modeling

Interpreting SNMR data consists in determining the water content of each layer, in the hypothesis where the underground is stratified at the scale of the loop dimensions The inversion consists in processing the raw data for the whole set of pulse moments corresponding to the various depths of investigation However, some parameters are well defined such as the product of the thickness of a thin layer by its water content. The development in a 3-D forward modelling of SNMR initial amplitudes and decay times are based on the work of Eikam[7], that can be used for two and three-dimensional interpretation of SNMR surveys. The formulation is reduced to a finite dimensional matrix problem by considering a finite number of cells with constant spin density (water content and decay time). The 3D forward modelling is then calculated by generating synthetic data for several of spin density distribution. This allows to analyse the spatial signal sensitivity of the method and shows the limits and problems of the 1D inversion and interpretation of 2D and 3D structures.

We introduce a 3-D forward modelling of SNMR initial amplitudes and decay times[7, 8, 9]. A prismatic three-dimensional body model is divided into small cubic cells of dimension DV = DxDyDz. The water content f(x,y,z) and the decay times T2*(x,y,z) are assumed to be constant in each cell. Then the integral equation is approximated by the finite summation

$$E(t,q) = \omega_0 M_0 \sum_z \sum_y \sum_x e^{-t/T_2^*(x,y,z)} f(x,y,z) \\ B_\perp(x,y,z)\sin\theta(x,y,z)\Delta x\Delta y\Delta z. \quad (2)$$

From this relation, the complete SNMR signal can be calculated as a function of a three dimensional distribution of the water content f(x,y,z) and decay time T2*(x,y,z) in the subsurface.

Figure 2 represents the 3D model-discretization for which SNMR model have been calculated using one turn circular loop of radius 50m in geomagnetic field of 48000 nT at an inclination of 60° and declination of 00 in a low conductive half-space. The initial amplitude for $t = t_0$, the start of the record, are then given by

$$E_0(q) = \omega_0 M_0 \sum_z \sum_y \sum_x f(x,y,z)\cdot \\ B_\perp(x,y,z)\sin\theta(x,y,z)\Delta x\Delta y\Delta z \quad (3)$$

The inner part of the integral is commonly written as the product of a kernel function and the water content

$$E_0(q) = \omega_0 M_0 \sum_z \sum_y f(y,z)\cdot \\ K_{2D}(q;y,z)\Delta y\Delta z \quad (4)$$

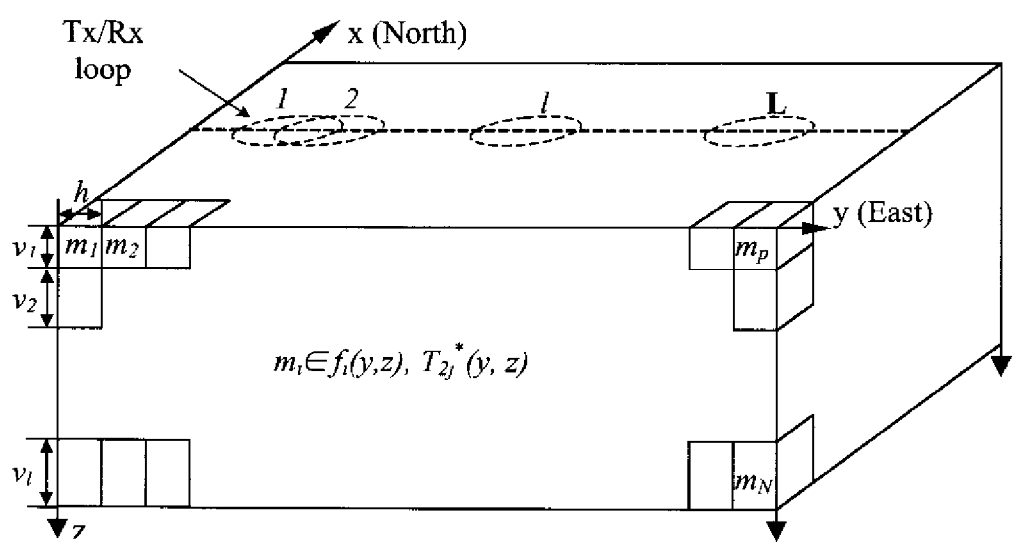

Figure 2: 3-D modeling of surface NMR measurement for *l* = 1,.., L sounding points.

For a study of 2D we assume the water content to be in 2D distributed. We obtain

$$E_0(q) = \omega_0 M_0 \sum_z \sum_y f(y,z) \cdot K_{2D}(q;y,z)\Delta y \Delta z \qquad (5)$$

Sensitivity of SNMR

The slices of a 2D kernel ($K_{2D}(q;y,z)$ in equation 5) in west-east and south-north directions for pulse moment q ranging from 1 to 20 [A.s] are presented in Figure 2-3. The kernels are compiled for a circular loop (D=100 m, 1 turn) in a low conductive media. Increasing the pulse moment q increases the depth of penetration of the method. Whereas sensitivities of west-east sections increase symmetrically, they are focused to the north in south-north sections. This effect is caused by the non-symmetrical contribution of SNMR signal[9, 10].

To study spatial sensitivity for SNMR surveys we modeled 2D sensitivities for three different field layouts. The antenna (1 turn circular loop, radius R = 50 m) is shifted at the surface for intervals of 50 m, 100 m and 150 m between sounding points each for a west-east and south-north profile. The sum of the kernels (magnitudes) of a set of measurements along a profile now gives the 2-D sensitivities to the water distribution. Fig. 2 presents the distribution of sensitivities for pulse moments q = 1, 10, 20 A.s., respectively. To evaluate the lateral resolution of each survey the 2-D kernels are compiled.

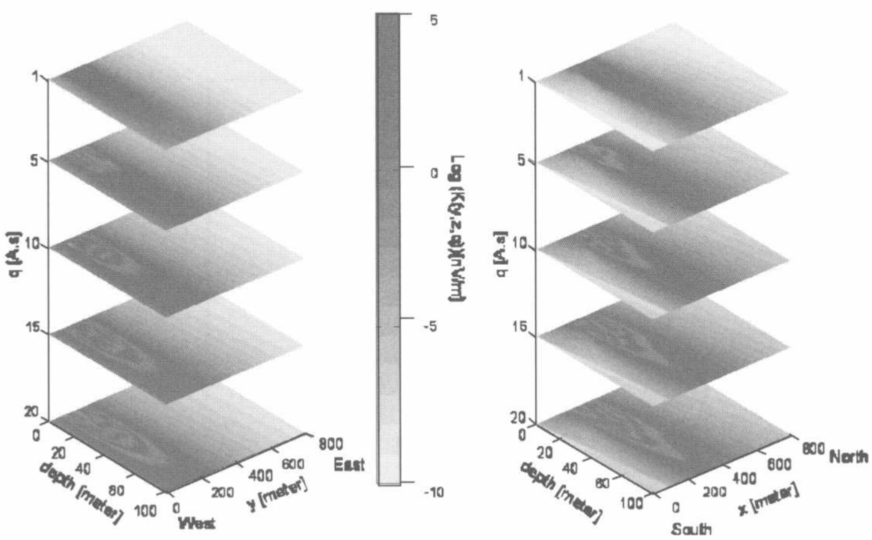

Figure 3: 2-D kernel (magnitudes) for single SNMR sounding at in west-east (left) and south-north (right) direction for pulse moments q = 1, 5, 10, 15, 20 [A.s]; earth magnetic field B_0 = 48000 nT; I = 600; circular loop with 100 m diameter, 1 turn.

Increasing pulse moment q increases the depth of penetration as well as the lateral extension of the sensitive region. A sounding interval of 50 m (1R) with 50 m overlap yields the best lateral coverage. The consistency of lateral coverage rapidly decreases for 100 m (2R) interval for of smaller section than the 1R interval. For 150 m (3R) intervals, which would be the fastest survey progress, the sections display almost no consistent lateral coverage. Therefore only smaller intervals would be favourable for a 2D inversion of field data. However, the lateral resolution can generally not exceed the sounding intervals.

For South to North profile direction a northward shift of sensitivities can be observed. Therefore, regions of low sensitivity occur in the southern part of the profile whereas regions of high sensitivity can be observed beyond the northern profile limits.

2D Inversion

The first task of research is extending the initial amplitude 3D forward modeling code to decay times (T_2*) for SNMR. This scheme can be used for two and three-dimensional interpretation of SNMR surveys. For a better understanding and insight of the capability of the method we calculate the SNMR response of 2D and 3D models, i.e. the SNMR relaxation signal for various locations of the antenna loop.

The 3D forward modelling is then calculated by generating synthetic data for several of spin density distribution. This allows to analyse the spatial signal sensitivity of the method and shows the limits and problems of the 1D inversion and interpretation of 2D and 3D structures [9].

At the end of this research are formulation and implementation of 2D inversion. One of the critical problems in inversion of geophysical data is developing a stable inverse problem solution, which at the same time can resolve complicated geological structures. Traditional geophysical inversion methods are usually based on Tikhonov regularization theory, and they provide a stable solution of the inverse problem. For inversion of SNMR the Tikhonov regularization method was used also to minimize the number of measurements [6] without a loss of the accuracy.