Research on the application of Magnetic Resonance Sounding in dam leakage detection

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Abstract. Reservoir dams and embankments are important water conservancy facilities, which play an important role in promoting the economy and protecting people's safety. 95% of the reservoir dams in China are made of earth or stone. Among them, the leakage of dam body or dam foundation is common. At present, most of the detection methods of dam leakage are indirect, and the physical parameters such as conductivity, density and temperature used by them have no definite relationship with groundwater. Magnetic Resonance Sounding is a promising geophysical method, by which hydrogeological information such as position, water content, porosity and permeability of aquifer can be obtained directly. This method has a high application prospect in dam leakage detection. In this paper, a theoretical model is established based on the typical dam structure, and the nuclear magnetic resonance response of the dam leakage is studied by numerical simulation. This paper also analyses the influence of the reservoir water on the nuclear magnetic resonance signal. The validity and feasibility of the method are verified by the inversion of the field data in Nanchuan embankment.

1. Introduction

There are more than 260,000 kilometers of flood-control levees and nearly 90,000 reservoir dams in China. Due to the long service life and the limitation of construction techniques, more than 30% of the dams are facing leakage problems. The dam leakage has been one of the most serious dangers that affect the safety of dam, which may lead to the loss of reservoir water and threaten the safety of people's lives and properties [1]. Therefore, the research on the nondestructive detection method of the dam leakage has attracted great attention.

At present, the existing geophysical methods use the physical properties of conductivity, dielectric, density, temperature, magnetic conductivity, electrochemical activity and other parameters to detect the hidden dangers of dams, such as the resistivity method, ground penetrating radar, elastic wave method and transient electromagnetic method. These traditional geophysical methods reveal the abnormal of physical properties of dam leakage from different geophysical parameters [2], but they are all indirect detection methods so that the inversion results are not unique in interpretation.

As we all know, the leakage of dam is closely related to the activities of groundwater. Magnetic Resonance Sounding (MRS) is a promising geophysical method for direct detection and quantification of groundwater. MRS instruments can carry out regional hydrogeological surveys, determine the water prospecting area and the location of aquifers quickly and efficiently [3]. These parameters are closely related to the dam leakage so that MRS can be used for the stability evaluation and hidden danger detection of dams.
In this paper, a theoretical model is established according to the typical dam situation, and the nuclear magnetic resonance (NMR) response of the dam leakage is studied by numerical simulation. In addition, the inversion of the field NMR data in an embankment is processed, which proves the effectiveness of this method.

2. Basic principle of MRS

Figure 1. Schematic diagram of the basic principle of Magnetic Resonance Sounding.

Magnetic resonance sounding makes use of the geomagnetic field and the relaxation properties of H\(^+\) proton in groundwater. In the absence of an external magnetic field, the spin directions of hydrogen nuclei in water are random, thus the macroscopic magnetic moment is zero. However, in the earth’s geomagnetic field, hydrogen nuclei are polarized, resulting in a net magnetic moment. When nuclear magnetic resonance is used to detect groundwater, a pulse of current at the local Larmor frequency flows in the transmitter loop. As a result, the alternating magnetic field excited by the loop diffuses into the ground, and the component of the excitation field perpendicular to Earth’s magnetic field causes magnetic moments to the hydrogen nuclei in the groundwater to tip away from the geomagnetic field orientation [4]. The MRS signals have their origins in the induced electromotive force in the receiving coil, which are caused by the net magnetic moment during the relaxation process [5], as shown in Equation (1)

\[
E(t,q) = e^{-i\omega T_2^*} \int_{V} K(p,q) \cdot w(p) \cdot dV(p)
\]

where \(T_2^*\) is the effective transverse relaxation time, \(p\) is the position, \(q\) defined as the product of the current duration and the current amplitude \(I_0\) in the transmitting coil, is the pulse moment, and \(f(p)\) is the water-content distribution. \(K(p,q)\) is called the kernel or sensitivity function, which represents the contribution of the unit water content at position \(\rho\) to the MRS signal [6], and is given as

\[
K(p,q) = \omega_M \sin(-\gamma \frac{q}{I_0} | \hat{B}_r^e(p) |) \cdot \frac{2}{I_0} | \hat{B}_n^r(p) | \cdot e^{i \zeta_r(p) + \zeta_n(p)} \cdot \hat{b}_r^e(p) \cdot \hat{b}_n^r(p)
\]

where \(\omega\) is the local Larmor frequency, \(\hat{M}_n\) is the net magnetic moment produced by a unit volume of water, \(\gamma\) is the gyromagnetic ratio for hydrogen protons, \(\hat{B}_r^e(p)\) is the co-rotating part of the transmitting perpendicular field, \(\hat{B}_n^r(p)\) is the counter-rotating part of the receiving perpendicular field, \(\zeta_r(p)\) and \(\zeta_n(p)\) are the phase delays of the transmitting and receiver loops, respectively, and
\( \hat{b}_T(p), \hat{b}_R(p), \) and \( \hat{b}_0 \) are the direction vectors of the transmitting, receiving, and Earth’s magnetic field, respectively. In practical work, we usually consider the amplitude and phase of the MRS signal at \( t = 0 \), and then obtain the water content distribution and other groundwater information. Thus, the key to the forward modelling of MRS is the calculation of the excitation magnetic field’s distribution. In practice, the signal amplitude and kernel function are used to inverse the content and distribution of groundwater. Figure 1 shows the schematic diagram of the basic principle of MRS. After the excitation pulse is cut off, the NMR signal received by the receiving coil shows an obvious exponential decay trend, which is the typical NMR response characteristics of groundwater.

3. Numerical simulation

Due to the water permeability of the earth materials used in the construction of dams, under the effect of high water level, if the filling process is improper, the selected earth materials are not suitable or the compaction is not solid, the water penetrating into the dam body will increase accordingly, which may result in engineering accidents such as landslides or dam leakage. Because of the direct relationship between the dam leakage and the groundwater, MRS method can be used for leakage detection [7]. In this paper, a theoretical dam piping model is set as Figure 2. The direction of the dam body is east-west, the dam height is 20 m, the top width is 4 m, the slope ratio is 1:3, the slope length is 60 m, the height of reservoir water is 10 m, and the height of water behind the dam is 5 m. The phreatic line in the dam body is a continuous falling seepage water surface line, and the results of hydraulic seepage analysis show that the shape of phreatic line is parabola in homogeneous media. In this numerical simulation, it is assumed that the phreatic line in the dam body is a parabola satisfying the Dupuit formula [8]. The water content of the dam body below the phreatic surface is set to 10\%, and the water content above the phreatic surface is 2\%; while the resistivity above and below the phreatic surface is set to 100 \( \Omega \cdot m \) and 50 \( \Omega \cdot m \), respectively. The dam piping model is set as a cylinder with a radius of 2 m, water content of 50\% and axis height of 3 m. Three MRS coils are set up on the dam slope with the radius of 10 m and center height of 10 m. \( \text{Tx/Rx 1} \) is located directly above the leakage model, while \( \text{Tx/Rx 2} \) and \( \text{Tx/Rx 3} \) are located at 10 m and 20 m east of the leakage, respectively. A total of 16 pulse moments are measured in a logarithmic distribution between 0.06 A·s and 10 A·s. The geomagnetic inclination is set to 60\°N, and the Larmor frequency is 2000 Hz.

![Figure 2. Schematic diagram of the dam piping detection based on MRS.](image)

Based on the model above, the calculation of excitation field of coils is carried out using the 3D finite-element software Comsol Multiphysics [9], then the distribution of MRS kernel function in the \( xz \) cross-section under different pulse moment is calculated using equation (2). Figure 3 shows that the amplitude of the kernel function diverges from the loop and attenuates with distance. With an increase in pulse moment, more protons at a greater distance from the coil can be excited, the high kernel-function area also diverges, indicating that there is an increase in investigation depth. It should be
noted that the reservoir water is located far away from the coil, and the magnetic field attenuation is obvious due to the low resistivity, so the kernel function in this area is small, and the reservoir water has little influence on NMR signal.

After calculating the distribution of the kernel function in the dam body, the theoretical NMR signal of coil 1–3 can be calculated through equation (1). The MRS signal amplitude versus pulse moment for coil 1–3 are shown as black, green and blue curves in Figure 4, respectively, which are the same as the color of coils in Figure 2. As a comparison, the red curve shows the calculation of the MRS theoretical signal when there is no leakage model. Significant differences are evident for the four conditions. When the Tx/Rx coil is located directly above the leakage, the MRS signal amplitude is the largest; the MRS signal amplitude corresponding to the small pulse moment decreases as the coil deviates from the leakage model; when the Tx/Rx coil deviates from the leakage position by 20 m, the shape of MRS signal curve show significant difference, which is close to the no-leakage condition. The results of numerical simulation above show that due to the sensitivity of MRS to the water content distribution, this method can well identify the existence and location of dam leakage by laying out multiple measuring coils.

Figure 3. Calculation results of the kernel function for the model of dam leakage detection based on MRS.

Figure 4. Signal amplitude of MRS for dam piping model.
4. Field work

Nanchuan Reservoir is a large water conservancy facility for flood control and irrigation in Xianning City, with the functions of power generation, urban water supply and ecological rehydration. The entire dam body is made of clay and uneven gravel stone mixtures. As shown in Figure 5(a), the maximum dam height is 53 m, the top of the dam is 335 m long, the width of dam top is 8 m, the width of dam bottom is 370.5 m, the dam top elevation is 112 m, and the top elevation of wave wall is 113.2 m. The wave wall is of masonry structure with cast-in-place concrete for coping. The reservoir has a water level of 104 m.

Preliminary data show that there are some serious engineering risks and problems in this reservoir, mainly including that the safety factor of anti-slip stability does not meet the specification requirements, the shaft of water conveyance structure is crooked and fractured, and there is a strong permeable zone on the right side of the river bed. Therefore, the purpose of this detection is to find the leakage area of the dam body.

![Figure 5. Profile (a) and plan (b) of the layout of survey lines in study area.](image)

We carry out MRS survey at Nanchuan Reservoir. A total of 11 measuring points are set up as shown in Figure 5 (with 6 measuring points in line L1 and 5 points in L2), and the direction of measuring lines is north-south. According to the geological data of the study area, the purpose layer to be explored is the earth and stone filling inside Nanchuan Dam, the required detection depth is within 50 m. In order to reduce the impact of electromagnetic interference, 8-figure loops were used with the side length of 50 m, and a square reference coil with a side length of 10 m and seven turns is located in the direction west from the primary coil. The distance between adjacent measuring points is 15 m. The geomagnetic inclination is 46°N, and the Larmor frequency is 2090.3 Hz. The MRS instruments (NUMISplus) is used to excite electromagnetic fields and collect NMR signals.

After the NMR signal of each measuring point is obtained, the MRS inversion software Samovar is used to inverse the field data, and the section map of the underground water-content distribution corresponding to L1 and L2 lines is shown in Figure 6. The average signal to noise ratio is 1.89. It shows that the areas with high water content occur at 0–20 m and 40–60 m in horizontal and 3–8 and 15–20 m in depth for line L1; while the high water-content areas of L2 is similar to L1 in horizontal but about 8 m deeper in depth, which corresponds to the elevation difference between the two lines. Therefore, it can be inferred that there are two leakages in the dam body within the range of the measuring line. The correctness of the results from MRS has been confirmed by other geophysical methods and engineering application later.
Moreover, the inversion results of water content in the deep area of L2 line are larger than that of L1 line, the explanation to this phenomenon is that the water level of the reservoir is high, and the L2 line is closer to the reservoir water so that its influence to the signal of MRS is larger. Therefore, small MRS coils should be used in the detection of dam leakage when the water level of reservoir is high.

![Figure 6. 2-D inversion results of MRS in the study area.](image)

5. Conclusions
Based on the actual situation, this paper establishes a dam model and calculates the theoretical NMR response of the leakage, the feasibility of MRS in leakage detection is confirmed by the inversion of the field NMR data in Nanchuan embankment. The work of MRS can provide an effective reference for the existence and location of the leakage. Combined with Magnetic Resonance Sounding and other methods, the problem of multi-solution in dam-leakage inversion and interpretation can be greatly reduced, and more accurate detection results can be obtained. Generally, the influence of reservoir water on MRS signal is negligible. However, when the water level of reservoir is high and a large coil is used for measurement, the NMR signal corresponding to the large pulse moment may be affected, which may cover up the anomaly of deep leakage. Therefore, under the condition of sufficient signal-to-noise ratio, small MRS coils should be used in the detection of dam leakage.

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