Embankment dam leakage detection by joint use of Magnetic Resonance Sounding and Electrical Resistivity Imaging

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ABSTRACT: Embankment dam leakage may cause devastating consequences and its early detection plays a significant role in the stability of embankment dam. Conventional dam leakage detection methods, such as piezometric tube or osmometer, are restricted by limitations of spatial distribution and high costs of instruments. This paper introduces the method of joint use of Magnetic Resonance Sounding (MRS) and Electrical Resistivity Imaging (ERI) to investigate embankment dam leakage. MRS and ERI are carried out to reveal embankment dam leakage in the same site and the stratigraphy of electrical conductivity obtained by ERI is carefully used for the inversion process of MRS data. And then the amount of groundwater in the subsurface can be directly determined by the technique of MRS. The MRS and ERI results show good consistency with yield data obtained by geological survey. Finally, the detecting capability of joint use of MRS and ERI is verified.

1. Instruction
Rapid detection of embankment dam seepage field and leakage risk is of great significance to prevent dam failure and other security incidents. Traditional methods to explore seepage field are piezometers, exploration well, isotopic tracer, ground penetrating radar, electrical resistivity imaging (ERI), etc. Since the resistivity of geotechnical materials is sensitive to water, non-destructive electrical resistivity imaging method has higher resolution in dam seepage diagnosis. Improved high-density resistivity method holds the advantages as high data capacity, intuitive imaging and portable instrument [1,2], which make it especially suitable for the rapid diagnosis of embankment dams leakage risks. The physical basis of seepage exploration with high-density resistivity method is detecting appearance of low resistivity anomalies when dam leakage occurs. However, geotechnical materials resistivity is influenced by soil properties, degree of weathering and other factors except water [3,4], therefore it’s hard to obtain the determinants of low resistivity anomalies areas only by ERI method. Recently developed magnetic resonance sounding (MRS) method is a new direct way for groundwater exploration. MRS method utilizes the nature of proton relaxation differences between water proton and atomic nucleus of other substances. Rectangular alternating current pulse is emitted underground and signal is collected by the same antenna, then the moisture content, permeability, relaxation time and other parameters of the geotechnical materials could be achieved with proper inversion [5–7]. These characters make it possible to detect dam leakage risk by MRS method.

Based on a detailed site survey, we carry out the application study of joint use of MRS method and electrical resistivity imaging (ERI) method [8,9] to investigate the seepage field and leakage risk of an embankment dam. Taking the aquifer depth obtained by MRS method and combining the data by ERI,
the electrical resistivity value of moisture soil is determined and the leakage channel inside dam is detected. Finally the detecting capability of joint use of MRS and ERI is verified.

2. Brief basic principles

2.1. High-density resistivity method
High-density electrical resistivity method is a kind of array electrical detecting method based on the resistivity variance of different geo-materials. According to the distribution of stratum electricity conduction, the existence of various geological bodies with different resistivity is verified. During the field measurement process, all electrodes are placed on the measuring points firstly, and then programmable electrode switch and engineering electrical measuring instrument are used to collect data rapidly, finally various physical interpretation of geo-electric section could be obtained by data processing. Relative to the conventional electrical resistivity imaging method, high-density resistivity method holds the characteristics of low cost, high efficiency, rich information, easy interpretation and significantly improved exploration capabilities.

2.2. Magnetic resonance sounding method
When applying MRS method, multiple points are selected averagely in the measuring region and the geomagnetic field values of these points are measured by proton magnetometer in order to calculate the Larmor frequency of underground aquifer. Then alternating rectangular current pulse with the frequency are emitted underground by transmitter instrument, and the pulse value increases and affecting area penetrates deeply progressively. Under the alternating excitation which is perpendicular to the earth's magnetic field, the precession direction of the hydrogen protons’ magnetic moment is changed from centering the earth’s magnetic field to the external alternating field.

If the applied alternating excitation is removed in this moment, the hydrogen protons’ magnetic moment will start the restoration of circumferential precession and will cause the magnetic flux changes and induce electromotive force in the receiving antenna. This phenomenon appears as free induction decay signal on the detection equipment. The envelope of the signal decays negative exponentially and its amplitude is related to the number of hydrogen protons in the aquifer [10,11]. Precession motion of the proton’s magnetic moment in the magnetic field is shown in Figure 1(a), and the basic principle of MRS method shown in Figure 1(b). Parameters measured by MRS method and their corresponding hydrogeological meaning by proper inversion method are shown in Table 1. These parameters directly reflect the mode of occurrence and characteristics of underground aquifers [12-14].

![Figure 1](image-url)

Figure 1 Basic principal of MRS methods (a)Precession motion of the proton’s magnetic moment in the magnetic field (b) The basic principle of MRS method

| Measured parameters       | Interpretive parameters       |
|---------------------------|-------------------------------|
| Initial amplitude $E_0$ (nV) | Water content (%)            |
| Decay time constant $T_2$ (ms) | Mean pore size               |
| Initial phase of the signal $\phi_0$ (°) | Resistivity (ohm·m) |
3. Project overview

3.1. Dam structure

The type of dam in this study is of the type of compacted rockfill dam. The length of the dam axis is 230.0m, crest elevation is 1841.30m, and the maximum height is 35.3m. The typical cross-section of the dam structure is shown in Figure 2. The front part, filling with blended loam and weathered rock breccia, is located on the upstream side of the dam and the permeability coefficient $k = 3.4 \times 10^{-5}$ cm/s. The middle part, filling with loam, is located in the central area and $k = 1.52 \times 10^{-5}$ cm/s. The back part, filling with loam, breccia, pebbly loam and weathered rocks, is close to the middle part and $k=6.2 \times 10^{-5}$ cm/s. Between the stack number 0+050 and 0+170, vertical and horizontal drainage system is set up in the middle and back part of the dam, aiming at reducing the dam phreatic line.

![Figure 2 Typical cross-section of the dam structure](image)

3.2. Dam leakage

During the common operation period of the project, leakage problems emerged on the downstream slope of the dam and the left abutment, location of dam leakage marked as region A is shown in Figure 3(a). Region A is located near the left abutment of the dam foot, the precise leakage scale of the region is below 1822.00m elevation and between stake number 0+025 and 0+057. The present leakage flow of region A is 1.3L/s. The time curves of the leakage flow and reservoir water level, whose relation shows significant positive correlation, are shown in Figure 3(b). Signs of damage such as thaw slumping, longitudinal cracks and surface slide occur in region A at present. Except region A, the phenomena of wetting soil on the downstream slope surface has been found near right abutment.

![Figure 3 Leakage problem of the dam](image)

4. Seepage and leakage detection

4.1. High-density resistivity method detection

In order to detect the dam leakage, five detecting sections were set up parallel to dam axis direction from the dam crest to the downstream slope foot, seeing Figure 3(a). ‘Pole-Pole’ array was adopted to obtain sufficient detecting depth. The number of electrodes is 32 and the electrode spaces are from 2.2m to 7.5m according to the total length of the detecting section. Characteristics of all the detecting sections are summarized in Table 2.
Table 2 Characteristics of all the detecting sections

| No. of detecting section | axle base /m | Elevation/m | Stack Number/m | Electrode array | Number of Electrodes | Electrode space/m |
|--------------------------|--------------|-------------|----------------|-----------------|---------------------|------------------|
| I                        | 0-004.0      | 1841.30     | 0+008          | Pole- Pole      | 32                  | 7.5              |
| II                       | 0+004.0      | 1841.30     | 0+008          | Pole- Pole      | 32                  | 7.5              |
| III                      | 0+021.3      | 1832.65     | 0+014          | Pole- Pole      | 32                  | 6.5              |
| IV                       | 0+040.1      | 1822.00     | 0+024          | Pole- Pole      | 32                  | 5.0              |
| V                        | 0+078.1      | 1803.00     | 0+055          | Pole- Pole      | 32                  | 2.2              |

The gross error detection, data inversion and post-processing are realized in Geotomo Software-Res2dinv 3.54 program. Forward calculation was carried out by Finite difference method. 4-node quadrilateral element was adopted and the mesh was encrypted properly. Least squares optimization algorithm based on smooth inhibition was used to inverse the detecting data. Taking into account the great resistivity difference between dam rockfill and bedrock, the robust inversion method was utilized to reduce the influence of noise and to improve the inversion accuracy as well.

The inversion results of 5 detecting sections are shown in Figure 4. For interpretation convenience, abscissa is stack number with constant coordinate while ordinate is detecting depth with logarithmic coordinate.

![Figure 4 Inversion contours of resistivity](image)

4.2 MRS method detection

MRS method detection of the dam was realized by Numis Poly Multi-channel Magnetic Resonance System and the detecting location is shown in Figure 3(a), which is aimed to get the seepage field...
distribution near dam foot. Geomagnetic field was measured by Numis magnetometer and Larmor frequency was calculated. To reduce the impact of environmental noise, the layout of eight-shaped double loop with 12m side length for antennas was adopted, in addition, the antenna diagonal was set to be parallel to the adjacent powerline direction. Considering the resistivity measured by high-density resistivity method detection, MRS detecting data is inversed by Samovar program supplied by Numis and the results are shown in Figure 5.

![Figure 5 MRS inversion results](image)

5. Detection results interpretation

5.1 MRS results interpretation

From Figure 5, two groups of the MRS inversion results show almost same changing patterns in water content along depth direction. The water content values of the soil layer with the depth of 0~3m are quite lower, that are 5% to 20%, while in the deeper layers with the depth of 5~11m, the water content values are much larger and their maximum values even reached 80% and 60% separately. Through the boring geological survey data that the sorts of detected layers are strongly or weakly weathered marl, and considering the low resistivity anomalies areas near left abutment in the Figure 4(e), inversion results of MRS and ERI match well. Comparing Figure 4(a) and (b), the water contents of aquifer close to left abutment are commonly larger than the aquifer near the middle dam foot with the amplitude of 10% to 20%. The reason of this phenomenon is due to the existence of leakage channel through the dam close to left abutment and consequently large amount of leakage flow.

5.2 High-density resistivity method results interpretation

From the numerical inversion of resistivity contour of five detecting sections, the resistivity distributions of dam, foundation and abutments were revealed well by high-density electrical method. Based on the saturation criterion aforementioned, the ERI results are interpreted in the following part.

The detecting section I in Figure 4(a) is located on the top of dam with elevation 1841.30m near upstream side and its axle base is 0-004m. The detecting scale ranges from stack number 0+008m to 0+240.5m. The section cut off the front and middle part of dam body and is the largest dam section in longitudinal direction. The resistivity of complete marl in central dam foundation is generally greater than 261ohm•m, but in the right and left abutment there are large scales of low resistivity zone, which has been revealed as strongly weathered marl of strong permeability by prior geological survey. The resistivity of unsaturated dam is in the range of 70~100ohm•m and the resistivity of the saturated dam body decreased significantly. Since the section is located in front of the dam vertical and horizontal drainage system, the saturation region is uniform and there are no obvious abnormalities in the section.

The resistivity inversion results of section II are shown in Figure 4(b), whose distribution is similar to section I. There is a wide range of low resistivity zone on the right abutment, which indicates that the strong permeable layer distributes continuously the downstream side. The resistivity of unsaturated dam in section II is in the range of 82~163ohm•m. Comparing to the measuring points with the same elevations in section I, resistivity in this section become higher, which means the dam phreatic line is
decreasing progressively. Meanwhile, a low resistivity anomaly zone with stack number of 0+028-0+053m first appears close to left abutment, which is speculated as the leakage source corresponding to the anomalies in Figure 3(a).

Detecting section III is located on the downstream slope with the elevation of 2/3 maximum dam height, whose resistivity distribution is shown in Figure 4(c). The resistivity of consecutive and complete Marl in dam foundation is generally greater than 343 ohm·m. There is a wide anomaly zone of low resistivity in right abutment with the distribution shape of closed ellipse, which is consistent to the presence of strongly weathered and permeable rock revealed by geological survey. The low resistivity anomaly zone appearing in detecting section II is developing continually in this section, with perforation to the lateral normal saturated soil region. The resistivity inside the anomaly zone is significantly lower than the saturated dam soil, which indicating the deterioration of the leakage channel. New low resistivity anomaly zone appears in dam body close to right abutment with stack number of 0+171-0+177m, which is suspected as the leakage source corresponding to the anomalies in Figure 8.

Detecting section IV in Figure 4(d) is located on the downstream berm and is very close to the leakage area in Figure 3(a). The inversed resistivity in anomaly zones of the section becomes much lower than them in all the sections aforementioned, which indicating confirmation of the export of the leakage channel.

Detecting section IV locating near the dam foot exposed the resistivity distribution of the dam foundation. The section is regarded as a reference and analysis basis for MRS interpretation which has been mentioned in the discussion part of MRS results.

6. Conclusion
In our work, the possibility of joint application of MRS and ER I methods for dam seepage field detection is verified. The two complementary methods could supply a rapid diagnose way to investigate seepage characters of rockfill dam and the locations of abnormal leakage, which is meaningful to timely determination of leakage cause and the emergency treatment for the dam stability.

The water distribution aquifer obtained by MRS method is in the form of volumetric water content. There is a problem of low resolution when MRS method is independently applied to the seepage detection of dams. Correspondingly, multiple solutions of interpretation induce the difficulty to obtain accurate distribution of groundwater and rock permeability solely using the ERI method. Therefore, joint use of MRS and other ERI methods to investigate embankment dam seepage field is a good way to solve the problem. When detecting the seepage field by joint application of MRS and ERI methods, the mutual relationship is significant. The MRS method can accurately obtain the distribution of groundwater in form of volumetric content, which will be the effective analysis foundation for ERI method. Meanwhile, the successive resistivity distribution gained by ERI method could conquer the low resolution problem of MRS method.

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References
[1] P. Sjödahl, T. Dahlin, S. Johansson, M.H. Loke. (2008): Resistivity monitoring for leakage and internal erosion detection at Hällby embankment dam, Journal of Applied Geophysics, 65, pp.155-164, Elsevier, Stockholm, Sweden.
[2] M.H. Loke, J.E. Chambers, D.F. Rucker, O. Kuras, P.B. Wilkinson. (2013): Recent developments in the direct-current geoelectrical imaging method, Journal of Applied Geophysics, 95, pp.135-156, Elsevier, Stockholm, Sweden.

[3] P. Sjödahl. (2006): Resistivity investigation and monitoring for detection of internal erosion and anomalous seepage in embankment dams, Doctoral Thesis, Lund University, Sweden.

[4] Seokhoon Oh, Chang-Guk Sun. (2008): Combined analysis of electrical resistivity and geotechnical SPT blow counts for the safety assessment of fill dam, Environmental Geology, 54, pp.31-42, Springer, Heidelberg, Germany.

[5] J. F. Girard, A. Legchenko, M. Boucher, J.-M. Baltassat. (2008): Numerical study of the variations of magnetic resonance signals caused by surface slope, Journal of Applied Geophysics, 66, pp.94-103, Elsevier, Stockholm, Sweden.

[6] A. Legchenko, P. Valla. (2002): A review of the basic principles for proton magnetic resonance sounding measurements, Journal of Applied Geophysics, 50(1), pp.3-19, Elsevier, Stockholm, Sweden.

[7] A. Guillen, A. Legchenko. (2002): Application of linear programming techniques to the inversion of proton magnetic resonance measurements for water prospecting from the surface, Journal of Applied Geophysics, 66, pp.104-117, Elsevier, Stockholm, Sweden.

[8] Kamhaeng Wattanasen, Sten-Åke Elming. (2008): Direct and indirect methods for groundwater investigations: A case-study of MRS and VES in the southern part of Sweden, Journal of Applied Geophysics, 50, pp.149-162, Elsevier, Stockholm, Sweden.

[9] J.M. Vouillamoz, B. Chatenoux, F. Mathieu, J.M. Baltassat, A. Legchenko. (2007): Efficiency of joint use of MRS and VES to characterize coastal aquifer in Myanmar, Journal of Applied Geophysics, 61, pp.142–154, Elsevier, Stockholm, Sweden.

[10] M. Hertrich. (2008): Imaging of groundwater with nuclear magnetic resonance, Progress in Nuclear Magnetic Resonance Spectroscopy, 53, pp.227–248, Elsevier, Amsterdam, England.

[11] K. Keating, Rosemary Knight. (2008): A laboratory study of the effect of magnetite on NMR relaxation rates, Journal of Applied Geophysics 66, pp.188-196, Elsevier, Stockholm, Sweden.

[12] LI Pengju. (2010): Study on T2 Spectrum Inversion and Fluid Identification and Evaluation of NMR, Doctoral Thesis, Northeast Petroleum University, Daqing, China.

[13] DAI Miao. (2008): Surface Nuclear Magnetic Resonance Forward and Inversion Research, Master thesis, China University of Geosciences Press, Wuhan, China.

[14] Konstantinos Chalikakis, Mette Ryom Nielsen, Anatoly Legchenko. (2008): MRS applicability for a study of glacial sedimentary aquifers in Central Jutland, Denmark. Journal of Applied Geophysics, 66, pp.176-187, Elsevier, Stockholm, Sweden.