An Approximative Method for Analyzing the Magnetic Field Data to Determine the Location of Preferential Flow Paths in Earthen Dam

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Abstract

The AC magnetic field method allows locating the preferential flow path in the body and foundation of the earthen dam based on the magnetic signals produced by the alternating current flowing in a permeable zone. This paper presents an approximate method for analyzing the magnetic field to determine the location of the flow path in 3D. This method was verified on a hypothetical model built on ANSYS software and 3D physical model and then tested on magnetic field data measured at the study dam. The results show the feasibility of the proposed calculation method with the spatial error between the calculated flow path and the flow paths of the models below 12%. The result of the simulated magnetic field generated by the calculated flow path based on data measured at the dam shows the normalized root-mean-square error between the two sets of measured data and simulated data is about 30%.

Keywords: AC magnetic field, preferential flow paths, earthen dam

1. Introduction

Earthen dams are important artificial constructions because of their economic and social significance. Abnormal seepage occurs in the body and foundation of a dam due to the development of preferential flow paths over time that can cause dam failure. Until now, geophysical methods such as radar, microseismic or electrical resistivity have been known as useful tools in dam investigations due to the advantages of non-destructive investigation methods as well as the possibility of providing visual solutions. Many studies applied conventional geophysical methods such as the self-potential method and the resistivity method in the investigation of seepage in earthen dams had been reported [1, 2, 3]. However, the methods mentioned above are considered to be affected by seasonal fluctuations. Therefore, this is a necessary method for long-term monitoring period to give an accurate interpretation of seepage situation [4].

Recently, the AC magnetic field method introduced by Willowstick LLC. (USA) has overcome the limitations above [5, 6, 7, 8]. For a leaking dam, two electrodes placed in the reservoir and the leak point are connected by circuit wires and an AC generator. The alternating current with an identified frequency following the preferential flow path of the permeable zone inside the body and foundation of the dam creates a time-varying magnetic field on the ground. The magnetic field data collected by a sensor along measuring lines on the ground are then used to determine the location of the preferential flow paths.

This paper presents an approximative method to analyze the magnetic field data to determine the location of the 3D preferential flow paths and the results of the field-scale experiment obtained from the data of the HT dam.

2. Theoretical approach

The relationship between the magnetic field vector **dB** and the current element vector **Idl** is described based on Biot-Savart's law (1980), which is expressed by equation [9]:

$$d\vec{B} = \frac{\mu_0 I}{4\pi} \cdot \frac{d\vec{l} \times \vec{r}}{r^3} \qquad (1)$$

where **r** is the distance from the current element to the measuring point, μ_0 is the permeability of free space.

Consider a straight, infinite wire in the Oxy plane and parallel to Oy ($x = x_0$, $y = 0$, $z = 0$) as shown in Fig.1. At the measuring point ($x = x_P$) on the measuring line parallel to the Oxy plane and perpendicular to the wire, the intensity of horizontal magnetic field B_{xy} obtained from the solution of Equation (1) depends on the distance z_0 between the measuring line and the wire by the expression:

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$$B_{xy} = \frac{\mu_0 I}{2\pi} \cdot \frac{z_0}{(x_P - x_0)^2 + z_0{}^2} \qquad (2)$$

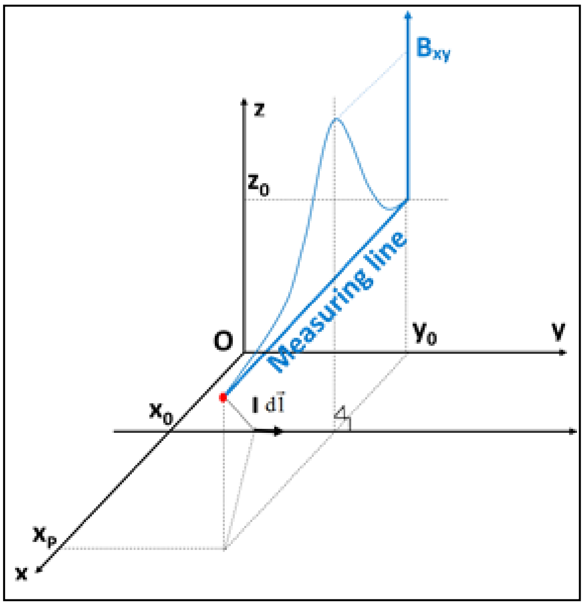

Fig. 1. A straight, infinite wire carrying a current I.

The distribution function representing B_{xy} is in the form of Gaussian with a distribution peak at $x_P = x_0$.

When a current follows the preferential flow path of the permeable zone, the magnetic field intensity at a measuring point is caused by all current elements. The approximative method for estimating the location of flow paths using Equation (2) is proposed with the assumptions:

- The current is straight, infinite
- The magnetic field intensity at a measuring point depends most on the current element which is perpendicular to the measuring line.

For each measuring line y_i, the parameters x_{0i} and z_{0i} describing the position of the preferential flow path can be determined by matching the measured horizontal magnetic field distribution with Equation (2) using the Levenberg-Marquart algorithm. The calculation program was then built on MATLAB to determine the location of the flow path based on the magnetic field data of all measuring lines.

The method was then validated on simulation and experimental magnetic field data.

3. Simulation results

ANSYS software is well-known as a useful engineering software package for simulating fluid dynamics, electromagnetism, and many other physical processes.

A 3D dam model with an assumed preferential flow path was built on ANSYS to verify the method. The hypothetical dam has a length of 50 m, a height of 15 m and the width of the dam bottom of 40 m. The preferential flow path has a diameter of 0.4 m with a conductivity of permeable water of 4 S/m. The magnetic permeability of the soil is approximately 1. Two electrodes locate at the reservoir and the leak point are connected by a circuit wire. The alternating current set at a frequency of 380 Hz and the amperage of 0.1A flows in the preferential flow path and creates a variable magnetic field on the dam face. The magnetic field data were then collected along measuring lines which are 1 m from the dam face.

The magnetic field distribution of the hypothetical model is represented in Fig.2.

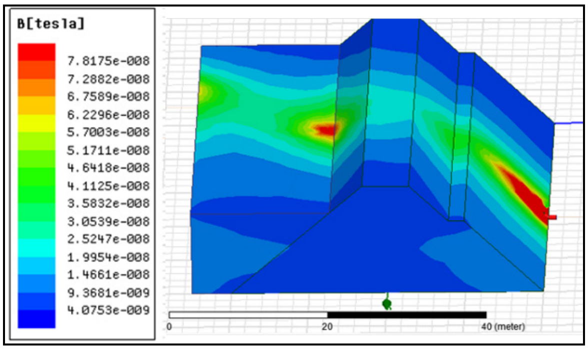

Fig. 2. The magnetic field distribution of hypothetical dam model.

The result of applying the proposed method shows that the location of the calculated flow path is relatively consistent with the model with an average spatial error of $\delta x = \pm$ 2.3% and $\delta z = \pm$ 7.4% as illustrated in Figure 3.

The magnetic field B' generated by the calculated flow path was then built on ANSYS software to compare with the magnetic field B generated by the original hypothetical model. The matching result between B' and B with 4509 observation points shows a normalized root-mean-square error (NRMSE) of less than 20%.

$$NRMSE = \frac{1}{\bar{B}} \sqrt{\frac{\sum_{n=1}^{N} (B - B')^2}{N}} \qquad (3)$$

4. Experimental results

4.1. Laboratory experiment

The 3D physical model consists of two mica trays of sizes 0.8 m x 0.55 m and 1.13 m x 0.46 m, which are placed respectively at 1.01 m and 0.41 m above the ground. Each tray is divided into air zones and a water channel. The water channel is continuously

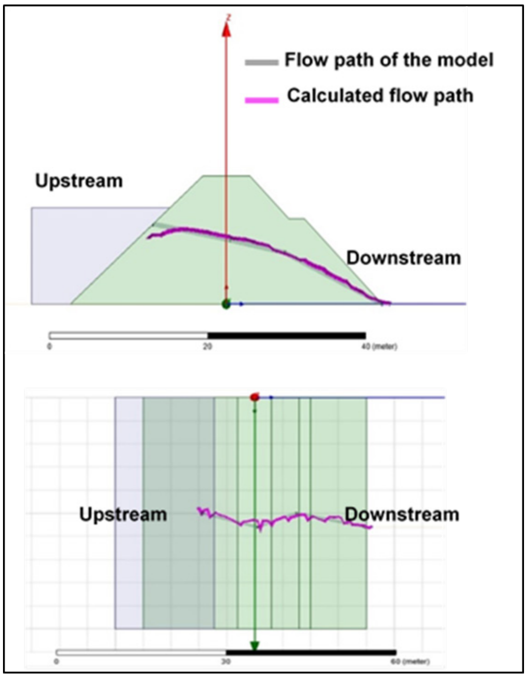

Fig. 3. The calculated preferential flow path of the hypothetical model.

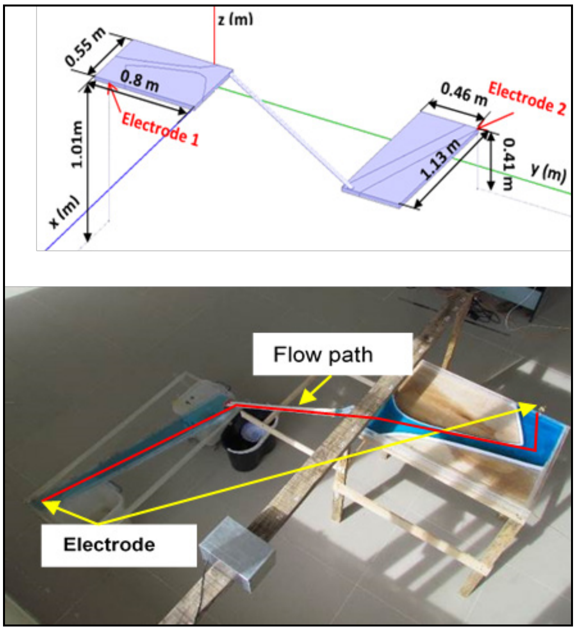

Fig. 4. Illustration of 3D physical models in the laboratory.

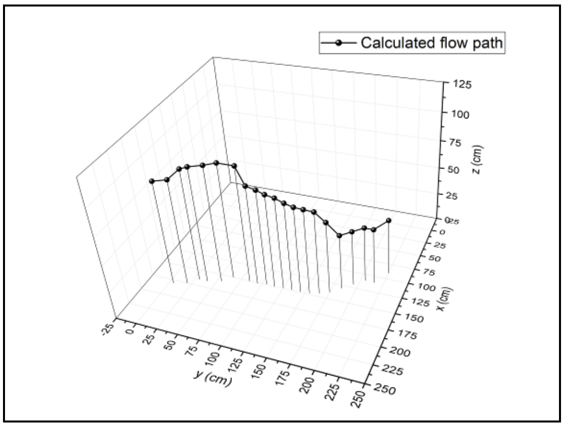

Fig. 5. Result of the calculated flow path from the experiment.

connected between the trays by two small pipes with a diameter of 0.03 m. The location of the electrodes is illustrated in Fig.4. An electric source with a frequency of 380 Hz and an amperage of 0.01 A was used. The conductivity of water of the permeable channel is 4 S/m. The horizontal and vertical magnetic components generated by the current flowing in the water channel were recorded on the measurement plane 0.12 m above the ground with dimensions of 2.1 m x 2.25 m by a self-designed sensor with a sensitivity of about 5 nT. The measurement points form the grid cells of 0.01 m x 0.01 m.

The proposed method was applied to locate the flow path from the experimental data. The result is shown in Fig.5. The average spatial error of the location of the calculated preferential flow path compared to the model is $\delta x = \pm 9.9$ %, $\delta z = \pm 11.5\%$. ANSYS software was then used to build the magnetic field B' generated by the calculated flow path. The normalized root-mean-square error (NRMSE) between the magnetic field generated by the calculated flow path and that of the experiment equals to 26%.

4.2. Field-scale experiment

The field-scale experiment to verify the proposed method was conducted in the small leak point of HT dam. The study dam is a homogeneous earth dam of 36 m in height and a crest length of 215 m. According to the report of the company, the leak area appears at downstream of the dam when the maximum water level reaches 604 - 605 m. The size of the downstream leak zone is about 7 m x 3 m at elevation of 595 m. The maximum flow rate is small, about 0.2 L/min. The magnetic field method was tested to determine the location of the preferential flow path through the dam. Two electrodes located in the reservoir and the leak area were connected by wires. The alternating current flowing in the preferential flow path was set at a frequency of 380 Hz and amperage of 2.0A. The conductivity of the leak water was 0.6 S/m. To increase the conductivity of the leak water for improvement of measurement sensitivity, salt NaCl was dropped into the reservoir along the dam about 2 weeks before measuring. The magnetic field on the dam face was recorded by a self-designed magnetic sensors B_x, B_y and B_z with a sensitivity of about 5 nT. The measuring area has a dimension of 126 m x 36 m with a total of 19 measuring lines parallel to the dam crest. On each measuring line, the distance between the measurement points is 2 m. Due to spatial constraint at the site, the upstream and downstream boundaries of measuring lines is 10 m and 15.5 m away from the electrodes, respectively.

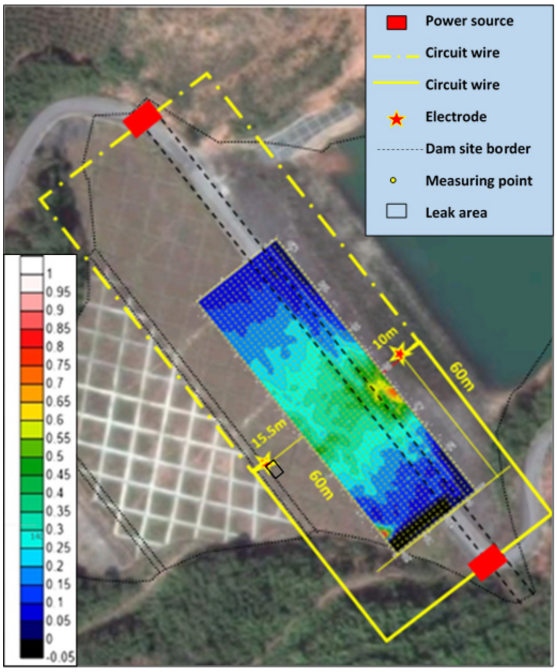

Fig. 6. The horizontal magnetic field of the study dam.

The result of the normalized horizontal magnetic field distribution is shown in Fig.6. The matching result of experimental data with Equation (2) using the calculation program built on MATLAB is illustrated in Fig.7.

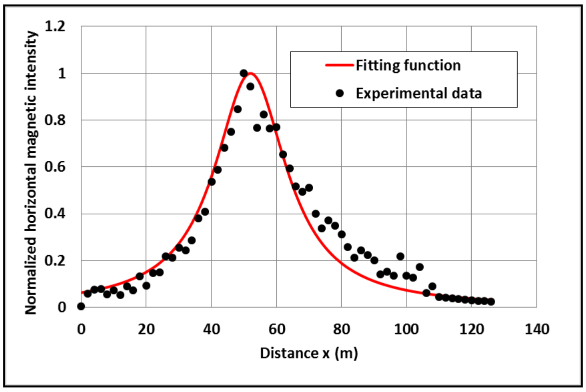

Fig. 7. Illustration of matching result using the calculation program built on MATLAB.

The normalized root-mean-square error (RMSE) of matches are in the range of 0.07 to 0.18. The result of estimating the location of the flow path is shown in Fig.8. ANSYS software was then used to simulate the magnetic field B' generated by the calculated flow path with physical and geometric parameters set corresponding to reality. The magnetic field B' was compared with the magnetic field B from the experiment. The result shows a normalized root-mean-square error (NRMSE) of about 30% with 1216 observation points. This value is higher than the result obtained from the laboratory experiment. The reason may come from the heterogeneity of the flow path in the field-scale.

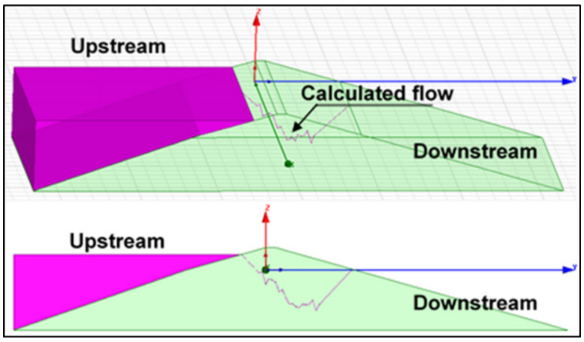

Fig. 8. Result of the location of the preferential flow path of the study dam.

5. Conclusion

The paper presents some results when applying the approximated method based on the analytic solution of the Biot-Savart equation for analysis of magnetic field data to determine the location of the preferential flow path through the earth dam in three dimensions. The method was validated on a hypothetical model built on ANSYS software and 3D physical model. The results show the preferential flow path with the spatial error less than 12%. In the field-scale experiment of HT dam, the method was used to analyze the preferential flow path of leak from the magnetic data. The magnetic field generated by the calculated flow path was then built on ANSYS software to compare with the magnetic field B from the experiment. The result shows that the normalized root-mean-square error between the two sets of measured data and simulated data is about 30%.

The preliminary achievements confirm the feasibility of the method in the analysis of magnetic data for the location of the preferential flow path underground. In the future, factors affecting the errors in the calculation results should be further studied and assessed to improve the methodology for practical applications.

Acknowledgments

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