Resistivity monitoring for the detection of leakage zones in earth fill dams

IN-KY CHO[1], IK-SOO HA[2], KI-SEOG KIM[3], HEE-YOON AHN[3], SEUNGHEE LEE[4] and HYE-JIN KANG[1]

[1] Department of Geophysics, Kangwon National University, Chuncheon, Korea.
[2] Department of Civil Engineering, Kyungnam University, Changwon, Korea.
[3] Heesong Geotech , Daejeon, Korea.
[4] Geoems, Anyang, Gyenggido, Korea.

choik@kangwon.ac.kr

Abstract

We applied the resistivity monitoring at an embankment dam to effectively identify the leakage zones or their expansion with time. We first analyzed the three-dimensional (3D) effects caused by 3D dam structure through 3D finite element modeling. Through numerical tests, we demonstrated the effectiveness of time-lapse inversion for the detection of leakage zone at embankment dams. Applying the resistivity monitoring system devised for dam surveillance to a test dam site, resistivity monitoring data were acquired. Noise characteristics of collected resistivity data were analyzed and a processing procedure was proposed to establish a proper reference model for the time-lapse inversion of future monitoring data.

Introduction

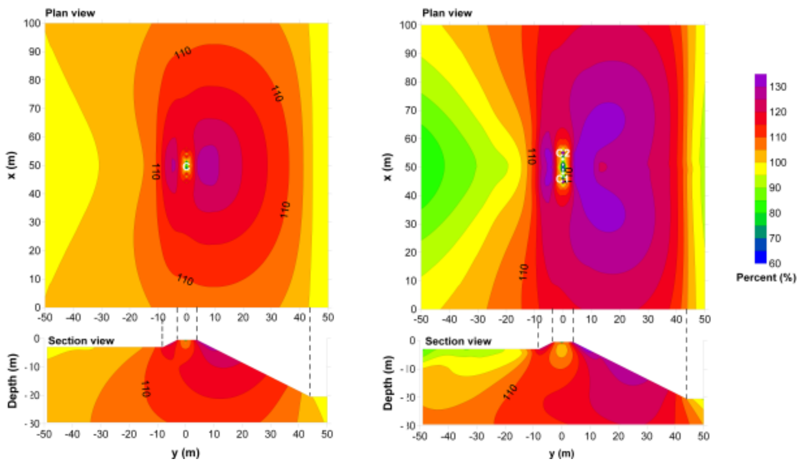
More than 16 percent of 18,000 reservoir dams in Korea are reported to have leakage problems and need to be repaired. Recently, resistivity monitoring has been applied to wide range of engineering and environmental problems with the help of automatic/rapid data acquisition, data communication and effective interpretation software. Resistivity survey and long term monitoring at an embankment dam can provide helpful information about leakage zones.

Resistivity monitoring is based on the fact that a change in the porosity leads to the changes in water content and fine particles, which alter the electrical resistivity. At every embankment dam, internal erosion always occurs as time passes. The internal erosion generally develops into piping over a long time by backward erosion and concentrated leak, and finally leads to dam failure. Thus internal erosion and piping are major cause of embankment dam failure. Internal erosion initially results in an increased porosity due to loss of fine particles in the core. Resistivity is known to be very sensitive to the changes in porosity in embankment dams. Thus resistivity monitoring is a reasonable method to find out the leakage zone. However, resistivity is strongly influenced by seasonal variation of temperature, TDS of reservoir water and water level (SJÖDAHL et al., 2008). Also, various noises prevent accurate measurement of resistivity. These make it very hard to accurately interpret resistivity monitoring data.

In the resistivity monitoring, significant challenges still remain in data acquisition system, noise suppression and time-lapse inversion for more detailed and quantitative interpretation. Here, we will present various problems occurring in the resistivity monitoring for the detection of leakage zones at embankment dams.

3D effect

Generally, 2D data acquisition and interpretation is widely used in the survey of embankment dams because of convenient field work and fast inversion. In the 2D survey, constant physical property and topography are assumed along the strike direction. Also, survey line has to be perpendicular to geological strike direction. But 2D resistivity survey along the dam crest violates this 2D assumption. Topography also does not fulfill the 2D condition and 3D effects caused by the 3D dam structure distort apparent resistivity data (SJÖDAHL et al., 2006; CHO and YEOM, 2007). Consequently, inverted 2D resistivity section does not represent the true resistivity distribution of the embankment dam. This is another problem of 2D resistivity survey at embankment dams. However, 2D survey is still one of the most widely used methods since it provides very useful information about leakage zones.



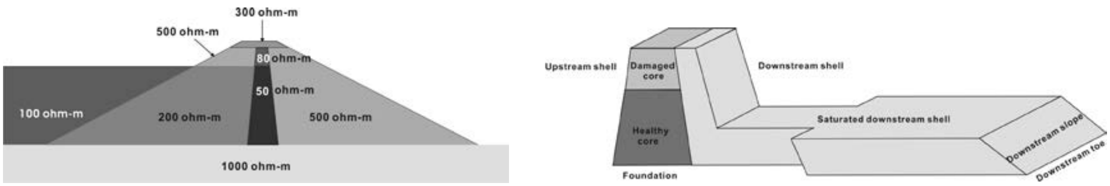
(a) (b)

Fig. 1: Distortion of potential distribution by 3D effect caused by 3D dam structure when a homogeneous dam is excited by a pole (a) and dipole (b) source.

To investigate the 3D effect in the resistivity survey at embankment dams, we carried out 3D numerical modeling. We assumed a homogeneous dam model in which all the component of embankment dam have constant resistivity. Figure 1 shows the distortion of potential at an embankment dam when one ampere current is injected into the ground through a pole and dipole source. From Figure 1, we can see that apparent resistivity is differently influenced according to the location of survey line. If a survey line is located on the crest, measured apparent resistivity is always larger than that of homogeneous half-space model even in the case of dipole-dipole measurement. Not shown here, we calculated dipole-dipole sounding data and plot sounding curve. We set station spacing to 5 m and water level to 10, 13.5 and 17 m. The calculated apparent resistivity is larger than that of homogeneous half-space model by 10 to 30 percent. This means that the apparent resistivity data are distorted by 3D effect caused by 3D dam structure.

Resistivity monitoring

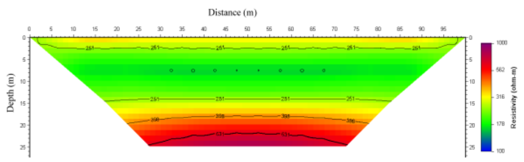
When long term resistivity monitoring is performed, change in resistivity with time can be assessed by simply carrying out independent inversion. To understand how much resistivity change occurs when leakage takes place at an embankment dam, we conducted 3D modeling. Figure 2 shows a leakage model. The physical dimension and resistivity are set empirically. We assumed that damaged core shows increasing resistivity and saturated downstream shell shows decreasing resistivity.

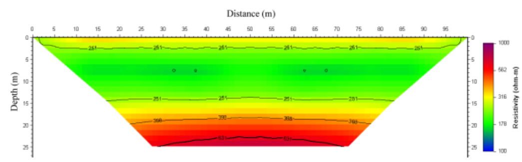


(a) (b)

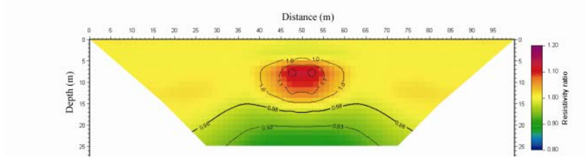
Fig. 2: A healthy (a) and damaged dam model (b).

Figure 3(a) and (b) are comparison of inversion results for a healthy and damaged dam. Two sections are nearly identical. The damaged zone is not defined in the inverted section because changes in apparent resistivity data are too subtle to identify leakage zones. Figure 3(c) is the percent resistivity ratio section. The damaged zone in the core is clearly defined as an increasing resistivity zone in the ratio section. Low resistivity zone at depth is the effect of saturated downstream shell. Monitoring is a reasonable tool to identify the leakage zones in the dam although the section does not exactly represent the saturated downstream shell.





(a) (b)



(c)

Fig. 3: Independent inversion results for a healthy dam (a) and damaged dam (b), and resistivity ratio section (c).

However, the independent inversion does not guarantee that the changes in resistivity are due to actual changes in the subsurface resistivity with time and does not take into account the reference model or prior information. Accordingly, independent inversion is not effective to identify small changes in resistivity (LOKE, 1999). In order to accurately identify changes in resistivity at particular locations and different times, time lapse inversion is required. Time lapse inversion of long term monitoring data is generally based on the conventional least-squares method, but time or cross-model constraint is added in the object function (OLDENBORGER et al., 2007, KIM and CHO, 2011).

Resistivity monitoring system

We devised a resistivity monitoring system. The system is divided into two parts: the field system and office system. Two systems are connected by bidirectional CDMA communication. Office system is composed of three parts; system control unit, data processing unit and data base. The system control unit remotely controls the data acquisition unit and receives acquired data through CDMA communication. Received monitoring data are stored in the data base and processed whenever it is needed.

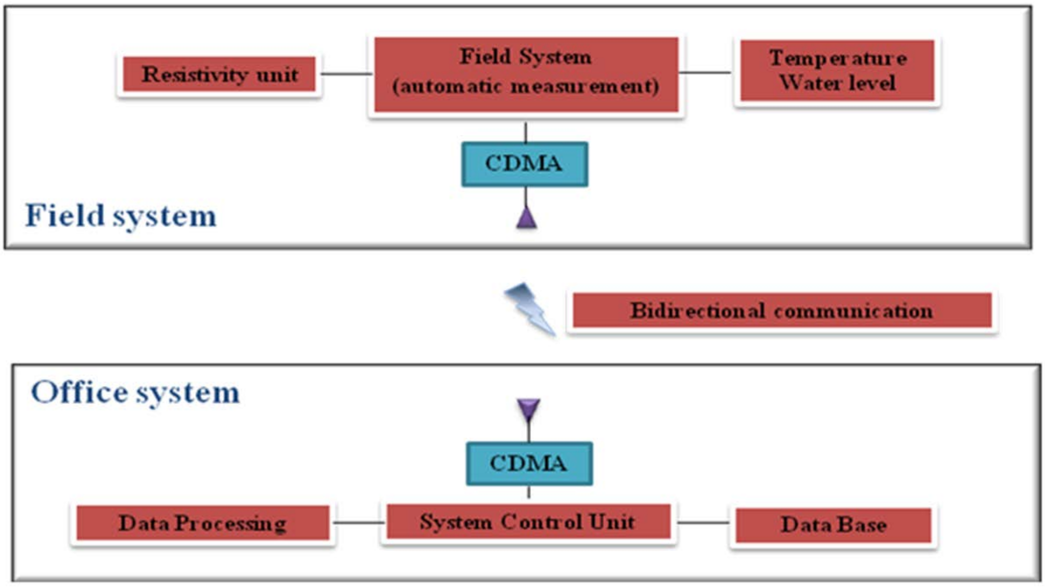


Fig. 4: Resistivity monitoring system devised for the leakage detection in embankment dams.

Resistivity data acquisition system is remotely controlled by system control unit in the office system through CDMA communication. The system is PC based one. Thus the system is composed of embedded main CPU, transmitter, switch box, 24 bit AD converter, 8 Giga bytes memory and modem for CDMA communication. Afterward, we will add other sensors to monitor temperature, water level, etc.

Data processing

We acquired resistivity monitoring data at a test dam site that is located at the southern part of Korean peninsula. The dam is 390 m long and 39.3 m high. We first installed electrodes permanently at the center of the crest. The total length of the survey line was set to 200 m and station spacing to 5 m. Dipole-dipole resistivity data set acquired every 6 hours form Aug. 30, 2011 to Sep. 6, 2011.

Generally, noises are divided into two groups; coherent and random noise. However, in this case appears a mixed type noise repeating non-periodically. Figure 5 represents typical pseudo-sections obtained in the monitoring. As a whole, these 3 sections look to be similar. But there are lots of noises. The red circles seem to be mixed type noise and black circle coherent noise. At this dam, high voltage power line pass over the dam. Also street lights and steel fence are installed along the crest. These are the major noise sources in this dam. Thus data quality is not good and noise contaminated data should be rejected before the inversion.

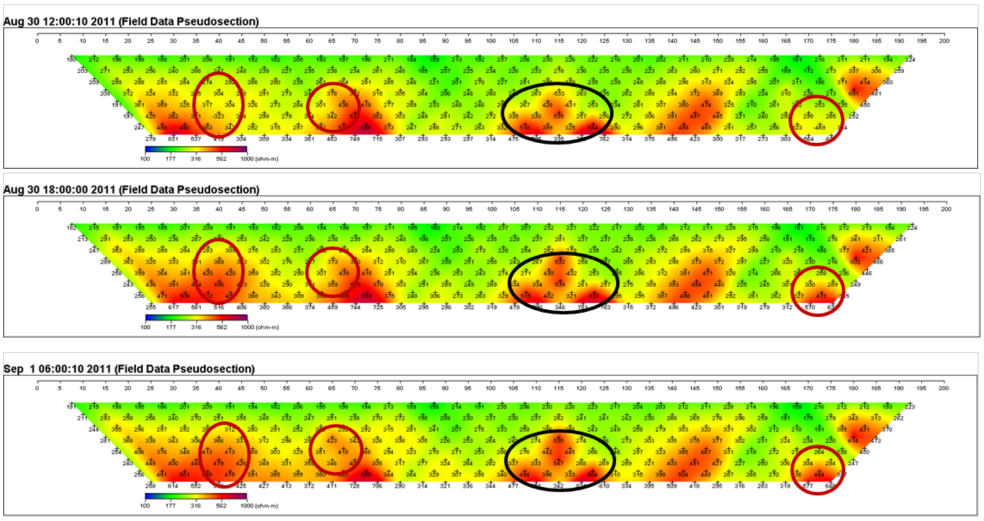


Fig. 5: Typical pseudo-sections obtained in the monitoring. The red circles seem to be mixed type noise and black circle coherent noise.

Before the time lapse inversion of long term monitoring data, a proper reference model should be established. We assumed no changes in resistivity since variation of water level and temperature is negligible over this short period. In such a case, the model obtained from independent inversion of data set at a particular time can be used as a reference model. But each data set has its own noise. Thus it is risky to use the independent inversion result as a reference model since the model estimated is not a true one. To estimate an optimal reference model, noise should be effectively suppressed before the inversion. A possible method is the median filtering that effectively suppresses random and mixed type noise. Of course, coherent noise does not be eliminated. Therefore, coherent noise should be rejected by data editing. Mixed type noise produces higher deviation and coherent noise low deviation. This deviation can be used as data weighting in future study of time lapse inversion.

Through median filtering and data editing, we established a filtered data and inverted the filtered data to build a reference model. The reference data was theoretically calculated from the modeling for the reference model. This model is accepted as the representative model at the period from Aug. 30 to Sep. 6, 2011.

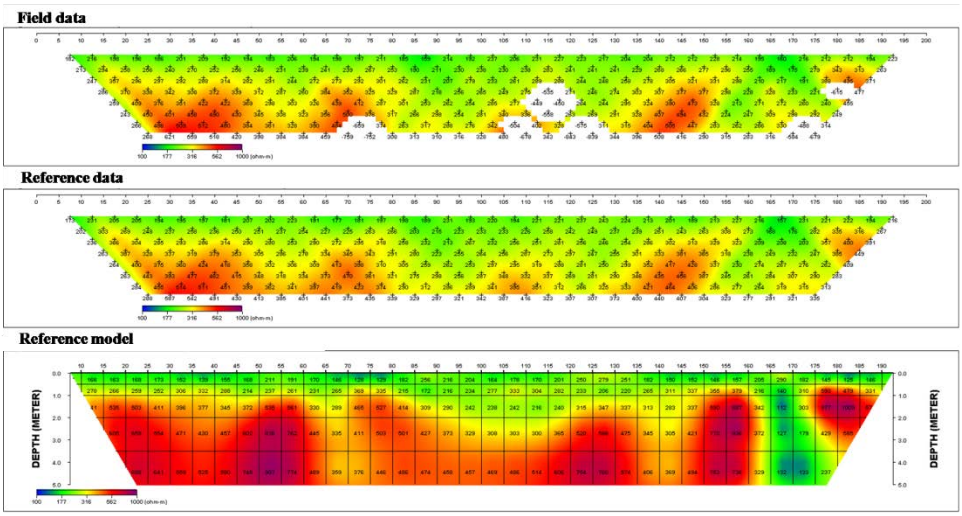


Fig. 6: Filtered data, estimated reference data and model from the inversion of the data set by the median filtering and data editing.

We carried out time lapse inversion using the estimated reference model, for a data set collected at Aug. 30, 18:00. The inversion result has to be the same as the reference model because we assumed no changes in resistivity over a short period. Furthermore many data showing larger deviation than 20% are rejected in the inversion process. However, difference ratio is larger than expected and maximum value reach 10%. Thus, we think that the method to estimate a reference data and model should be more refined in the future.

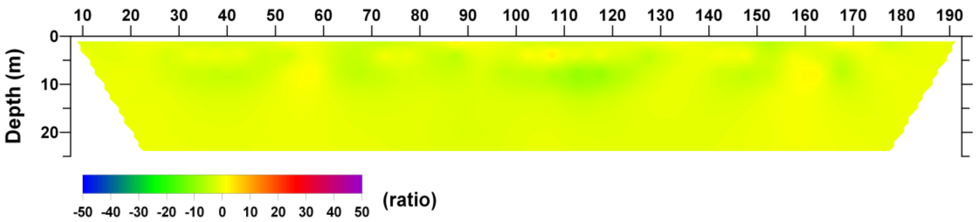


Fig. 7: Resistivity ratio section obtained from the time lapse inversion of a data set acquired at August 30, 18:00.

Discussion

We reviewed the resistivity monitoring at embankment dams and proposed lot of problems in the interpretation of monitoring data; First, more stable and accurate data acquisition system are required to effectively suppress noise. Stable data communication is also necessary. Second, 3D effects caused by 3D dam structure distort the 2D inversion result. This means that the inverted section does not represent the true resistivity section. Data processing, especially to automatically reject the contaminated data, is also the important part of monitoring. Finally, time lapse inversion is a crucial part in the interpretation of long term monitoring data. In the time lapse inversion, optimal choice of model, time and data constraint is also another challenge we have to overcome. We are sure that the resistivity monitoring will be a reliable geophysical tool to find out subsurface changes in time, if we make consistent effort to overcome the problems listed above.

Acknowledgements

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