INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

An Automatic Resistivity Monitoring System for Several Embankment Dams in Korea

Un système de surveillance automatique de la résistivité électrique pour plusieurs barrages de remblai en Corée

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ABSTRACT: The main causes for weak zones in the core zones of embankment dams involve aging effect and seismic movement. Since weak zones tend to have low resistivity due to the higher contents of water in pore spaces, electrical resistivity monitoring has been used for the detection of the weak zones. We have developed a new system that monitors resistivity of dam structure periodically and/or driven by ground motion during earthquake. The system is also equipped with bidirectional communication capabilities and a software that performs time-lapse inversion. The automatic resistivity monitoring systems are tested thoroughly and deployed at nine KRC sites for monitoring structural integrity of dams.

RÉSUMÉ : Les principales causes des zones faibles dans les zones centrales des barrages de remblai impliquent les effets tels le vieillissement et le mouvement sismique. Les zones faibles ont tendance à avoir une faible résistivité électrique en raison des teneurs élevées en eau dans les matériaux de zones centrales. La surveillance de la résistivité électrique a été utilisée pour la détection des zones faibles. Nous avons développé un nouveau système qui surveille non seulementle mouvement du sol pendant le séisme mais aussi la résistivité de la structure du barrage périodiquement. Le système est également équipé d'un logiciel qui effectue les capacités de communication bidirectionnelle et d’inversion de temps passés. Après avoir été testés à fond,le système de surveillance automatique de la résistivité était disposé sur neuf sites de la Société coréenne de la communauté rurale(KRC) pour surveiller l'intégrité structurale des barrages.

KEYWORDS: Resistivity monitoring system, Aging effect, Embankment dams, Weak zone, Seismic events

1 INTRODUCTION

The weak zone in the core zone of embankment dam could be developed by leakage and/or internal erosion due to aging effect and/or earthquake and/or inadequate core zone material. Since water content in weak zone is likely to be higher than that of healthy zone, the value of electrical resistivity of weak zone tends to be lower than that of healthy zone. This is the fundamental basis that the electrical resistivity survey has been used to detect weak zone in embankment dams. Furthermore, because the electrical resistivity survey is almost the only effective, nondestructive, and economical method for determining structural integrity of dams, this survey has been widely used all over the world (Chung et al., 1992; Lee, 2000; Park et al., 2002; Kim et al., 2014).

However, the values of electrical resistivity could be affected not only by water content but also by temperature. Park et al.(1999) and Kim et al.(2013) found that the values of electrical resistivity in dam decrease as temperature increases. Furthermore, water content of core zone in dam is changed not only by leakage but also rainfall and water level in reservoir. Thus, the values of electrical resistivity even for sound embankment dam could be changed due to these seasonal factors. These mean that repeated electrical survey is necessary in order to determine or monitor the structural integrity of dams. This repeated electrical survey could be called ′electrical resistivity monitoring′.

There are total of about 17,000 dams and reservoirs in Korea. K-Water manages 31 dams, Korea Rural Community Corporation (KRC) manages over 3,300 dams and reservoirs and local government manages about 14,000 reservoirs. About 70% of dam and reservoirs in Korea have been built more than 50 years ago. Recently, some reservoirs were collapsed after heavy rainfall and safety of old dam and reservoir has been an important issue in Korea. Since all of dams and reservoirs managed by KRC are the earth embankment dam, KRC has installed electrodes, cables, and distribution boards on the crest at several dams and reservoirs in order to periodically measure electrical resistivity and to evaluate dam safety through observation of resistivity profiles. Conventionally, the measurement has been made twice a year. However, the interpretation of resistivity data is not easy because the resistivity values measured at a dam are affected by various factors, such as seasonal variation of temperature, change in reservoir water level and etc.

In this study, we devised an automatic electrical monitoring system that can measure the resistivity at every pre-set time interval. Using the developed system, we carried out resistivity monitoring and interpreted the resistivity monitoring data by time-lapse inversion to detect the developing leakage zones at a test dam in Korea.

2 RESISTITIVTY MONITORING AND INVERSION METOHD

2.1 *Resistivity monitoring method*

The basic concept of resistivity monitoring is that the electrical resistivity survey is repeatedly conducted along the same survey line with identical geometry of electrode arrays over time. By comparing the results of inversion along the identical line, changes in resistivity values can be noted and those changes are further evaluated for the analysis of possible leakage. Logarithmic resistivity change ratio is defined by Eq. 1. The subscript *i* and *j* in Eq. 1 represent the electrical resistivity measured at time phase *i* and *j*, respectively (Kim, 2013).

$$\text{Resistivity ratio} = \log_{10}(\text{phase}_i / \text{phase}_j) \tag{1}$$

In conventional long-term electrical resistivity monitoring technique using Eq. 1, two electrical resistivity data sets at different time shall be separately inverted (thus called 'independent inversion') and changes in resistivity are easily compared by the ratio of pixel-by-pixel values. However, resistivity changes through comparison with independent inversion are not distinct, because the resolving power of resistivity method is not so good to detect the subtle changes in the dam over time. In order to emphasize the small changes of resistivity over time, new inversion technique 'time-lapse inversion' is proven to be more adequate.

2.2 *Time-lapse resistivity inversion*

The time-lapse resistivity inversion employs the initial model of resistivity data as a reference. The method has advantages in detecting dam leakages because most of parameters do not deviate from the initial reference.

The basic assumption for time-lapse inversion is that the overall changes in resistivity over time are small. The methods also assume that smaller weighting is assigned for data that show larger changes with respect to the reference data while larger weighting is assigned for data that show smaller changes (Cho et al., 2013). The weighting function of Kim and Cho (2011) is adopted for our software.

3 AUTOMATIC RESISTITIVTY MONITORING SYSTEM

3.1 *Characteristics of the system*

Figure 1 shows the configuration of the automatic resistivity monitoring system. The main part of the system is ARMS-HS16A. The specifications of ARMS-HS16A are summarized in Table 1. ARMS-HS16A can automatically measure the electrical resistivity at every pre-set time interval. The measured data are transmitted via network such as wireless modem or internet. The inversion including independent inversion and time-lapse inversion for the transmitted data is automatically done in software and report is also automatically generated. These data, results of inversion, and report are stored in the KRC server. The parameters, which are related with electrical resistivity survey i.e. measuring time interval and geometry, can remotely be set via network.

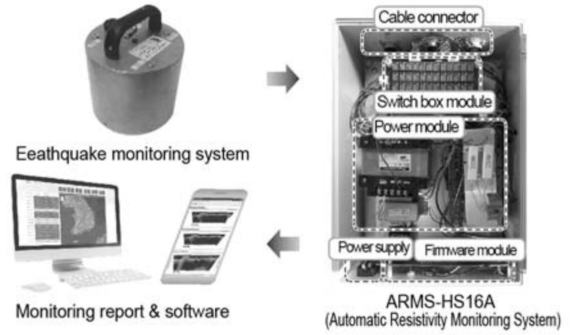

Figure 1. Integrated system of KRC. The system consists of automatic resistivity monitoring system, earthquake monitoring system, and monitoring software for analysis and parameter setting.

Unlike Swedish study (Johansson et al., 2003), our automatic resistivity monitoring system including ARMS-HS16A can be customized for clients managing the dams and reservoirs.

Considering the situation that seismic activities recently increase in Korea, ARMS-HS16A has been developed to interlock with earthquake monitoring system. When significant seismic acceleration stronger than trigger level is measured by earthquake monitoring system at the dam, ARMS-HS16A starts to measure, transmit, conduct inversion, and generate report even though the time is not set to do. Through this interlocking, it is possible to immediately evaluate whether the dam is influenced by the earthquake.

Table 1. Specifications of ARMS-HS16A.

Item	Description
Measurement modes	Apparent resistivity
Measurement range	+/v 10Vp-p (depends on voltage level)
Measuring resolution	Max. 10nV
Transmitter	400W
Output current	1 – 2000mA
Output voltage	400Vp-p
Power supply	AC
Weight	5.0 Kg
Dimensions	W : 250mm, L : 350mm, H : 150mm

3.2 *Outline of dams installed*

The automatic electrical resistivity monitoring systems have been installed at nine embankment dams, managed by KRC, in Korea (see Figure 2). The outline of the dams is summarized in Table 1.

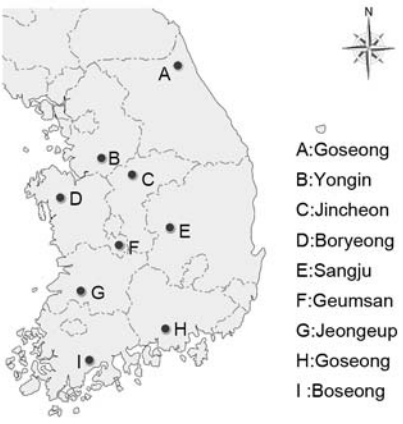

Figure 2. Location of the dams installed with the automatic electrical resistivity monitoring system in Korea.

Table 2. Characteristics of the dams

Sites	*Length (m)*	*Height (m)*	*Watershed area(ha)*
A	298	25.9	1,419
B	660	17.5	9,300
C	417	16.5	857
D	306	23.0	7,010
E	277	23.7	2,200
F	174	27.6	322.6
G	433	17.3	480
H	268	21.0	168
I	431	21.2	860

A schematic illustration of the system in the embankment dam with core zone is shown in Figure 2. Generally the electrodes and electrical cables are installed along the center of the crest below which the central clay core is located. The electrodes and the cables for resistivity monitoring are permanently installed because slight changes in positions of electrodes result in pattern changes in the resistivity profiles. This is due to the changes in equipotential surfaces due to changes in geometry of electrodes. Excavation works are done for installation of electrodes. The usual installation depths of electrodes are below the frozen depth, because freezing of water in pore space not only makes resistivity value higher but also makes it difficult for electric current to flow.

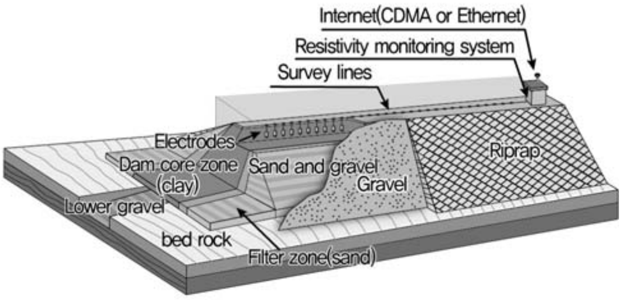

Figure 3. Schematic illustration of the automatic resistivity monitoring system at the embankment dam in Korea.

4 FIELD TEST AND RESULTS

4.1 *Earthquake trigger tests*

As discussed before, the system is designed to start the resistivity measurement whenever earthquake is sensed and/or to perform automatic measurement at a time set by users. Since no earthquake of significant magnitudes occurred after installation, there was no earthquake-triggered measurement. To test the system, we gave the artificial shock to the ground with a sledgehammer and it was found that the system starts the resistivity measurement just after the artificial shock.

The observations to be discussed below are from the results of daily quarterly measurement for fourteen months. During the period of the time, no significant earthquake occurred.

4.2 *Resistivity monitoring*

Figure 4 shows the results of fourteen-month long monitoring for a dam site where the system is installed. Several snapshots among more than 2,000 measurements are selectively shown.

As illustrated in Figure 3, the electrodes are installed at 5 meters apart on the top of the dam core zone. The total length of the installed electrodes is 265 meters.

The ranges of resistivity in all of the time-lapse inversion in Figure 4 are from 30 to 290 ohm・m. The initial variations in Figure 4(a) represent the inhomogeneous nature of the material used for embankment dams. In general, the coarser materials tend to show lower resistivity values. Another factor is the degree of solidification by dehydration after dam construction. It is known that the drier materials tend to show lower resistivity values. Since there are inhomogeneities in the construction materials, this will result in different degree of dehydration and eventually in wide range of resistivity values.

What is far more important in Figure 4 is the fact that the initially inhomogeneous pattern of resistivity distribution does not changes over fourteen months. Minor changes are only not identified above the seepage line (Figure 5). This suggests the little changes in resistivity structures within dam core zone were made for fourteen months.

4.3 *Resistivity changes above seepage line*

In Figure 5, resistivity, temperature, rainfall and water level over time are plotted at a point above the seepage line. Because the resistivity below seepage line does not change significantly over time, we have chosen the ″monitoring″ point above the seepage line. The resistivity value shows higher values during winter and lower values during summer because of seasonal temperature variation. Furthermore, the water content at the shallow point also affects the resistivity value because the water contents low in winter and high in summer season. Even though the resistivity values at the shallow point are not closely related to the changes in reservoir water level, the changes in reservoir water level can distort seriously the resistivity image from the time-lapse inversion (Cho et al., 2014).

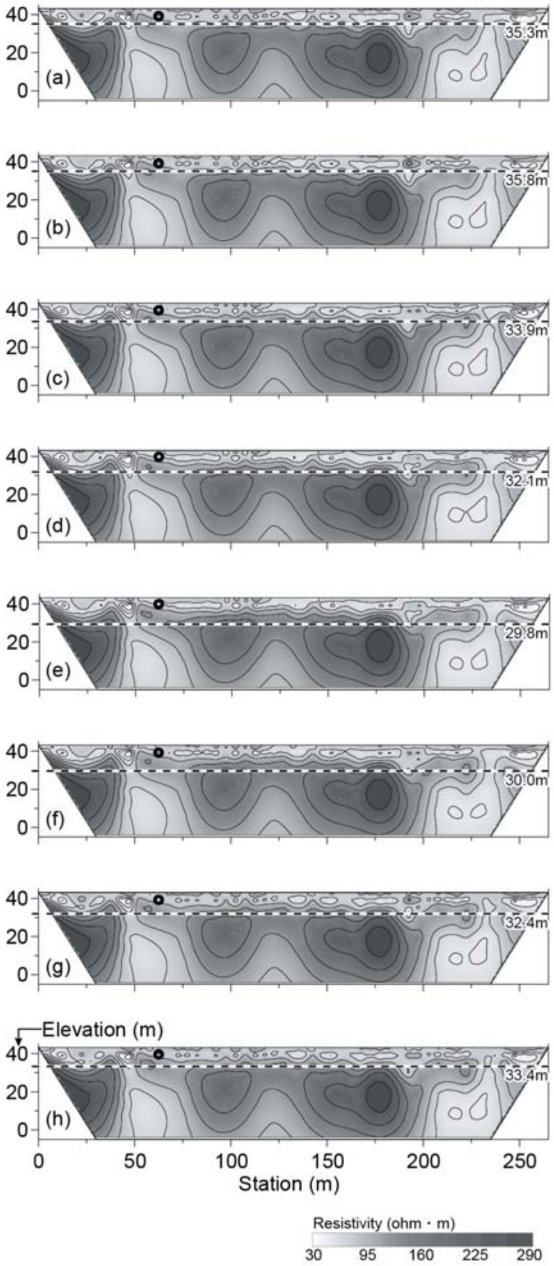

Figure 4. Results of the time-lapse resistivity inversion at a test dam site for fourteen-month. Each inversion snapshot is two months apart and dashed lines indicate the seepage line.

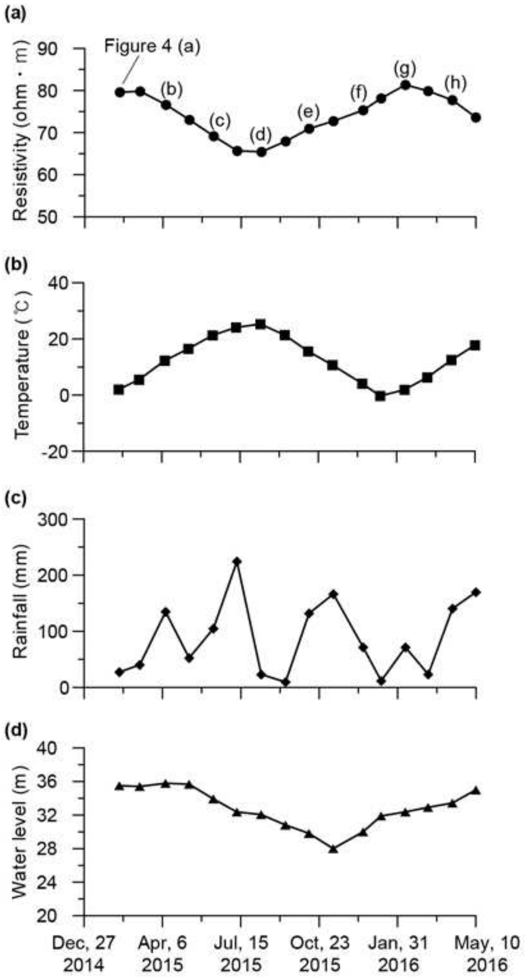

Figure 5. Changes in resistivity over time (a), along with change in temperature (b), rainfall (c), and dam water level (d). The horizontal axes are identical for the four graphs.

5 CONCLUSIONS

For embankment dams, we have developed an earthquake trigger resistivity monitoring system that consists of (1) seismometers (sensors and recorders), (2) resistivity measurement module with bidirectional communication capabilities, and (3) a software module for time-lapse inversion. These systems are applied for nine KRC dams and are also in operation to monitor structural integrity of these dams.

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