Electrical resistivity monitoring of simulated piping and hydraulic fracturing within a dam structure

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Introduction

There are about 20,000 large dams world-wide. In the 20th century, around 200 dam failures have occurred in the world. And the accidents caused a large of property damage and killed about 11,000 people (LIM et al, 2004). In generally, the causes of failures are over flow, seepage and piping of the dam, substructure, slide activity and earthquake. Especially, overflow and piping account for 49.6 % and 47.0 % of the failures, respectively (FORSTER and MACDONALD, 1998). It is difficult to prediction the failures in dam caused by piping.
Piping has been the main cause of fill dam failure and generated by the various causes. The reason why the dam failure was piping by concentrated seepage leakage and backward erosion. Piping by concentrated seepage leakage frequently occur a dam designed with modern technology. Cracks in the dam and locally vulnerable permeable layer formed a seepage flow. But this is not a cause of piping at all times. In addition, the concentrated seepage flow may erode fine soil particles, and carry these fine particles up to the surface. As the erosion process continues, a piping may form through the top stratum. UNSW (Univ. of New South Wales) dam laboratory suggested 4-steps of the progress in piping. Generally, the progress is ①Initiation→②Continuation→③Progression→④Failure (FOSTER et al, 1999). If it is possible to estimated change of resistivity values for a piping, we could prevent the failures of a dam and ensure a safety of a dam.
In this study, we attempted to monitor the changes in electrical resistivity values of earth dam material while a saddle dam is dismantled for the construction of emergency spillways of Dae-chung dam. Two artificial sub-horizontal boreholes were drilled into the embankment structure to simulate piping along the two artificial flow channels. And, after the simulated piping test was finished, we were carried out using injecting with grouting cement fluids on the dam crest. One was to develop a piping detection technique measuring electrical resistivity of earth dam by monitoring, and the other was to estimate reinforcement of dam by grouting, which electrical resistivity lower enough to yield resistivity contrast.
The spatial distribution of the artificial region by leachate was visualized in space using the electrical resistivity change ratio of 2-D resistivity distribution before and after the simulated piping test and hydraulic fracturing.

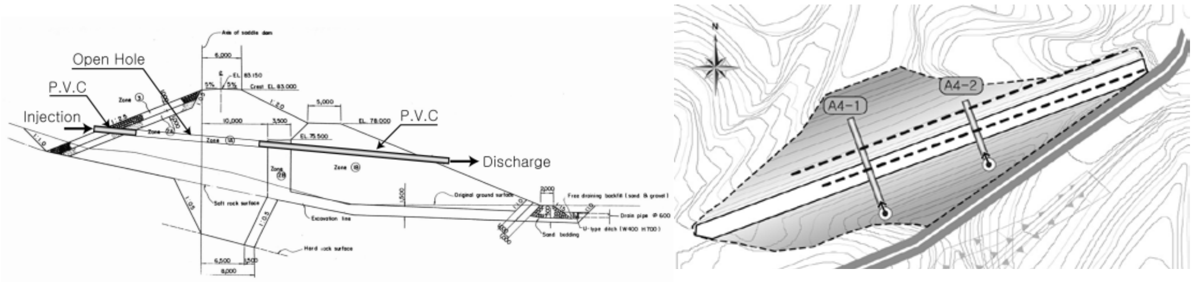
Site Description

Dae-cheong Dam is located at 150 km upstream from the estuary of the Geum River which flows into the Yellow Sea from the middle part of the Korean peninsula. The saddle dam was planned to be dismantled due to reconstruction of emergency spillway. The saddle dam under consideration is an earth dam with central clay core and it has a dimension of 244 m in length and 8m in height. From the geologic investigation performed before the reconstruction of emergency spillway, it was covered with weathered surface soils for mica schist around of saddle dam. Bedrock consists of quartz schist with biotite, amphibole quartz schist, and quartz porphyry.

Simulated Piping Test and Hydraulic fracturing Test

We should try to approach for the various aspects of the situation. First, two artificial sub-horizontal boreholes with diameter of 75.7 mm were drilled into the dam structure to simulate piping along the two artificial flow channels. The boreholes were installed with open-holes, each one at different level (Figure 1(a)). It was tried to identify for resolution of electrical resistivity data. And we had installed the PVC pipe for preventing progressive collapse in the filter zone (Figure 1(b)). The piping test had been conducted for 72 hours, except replacing flow-meters. And it was measured an injection charges, discharge and turbidity during piping test.

Second, four vertical boreholes were drilled at the crest, and hydraulic fracturing carried out. We injected pillar-shaped with cement milk about 10 minutes for hydraulic fracturing. The effect of hydraulic fracturing was visually identified after applying phenolphthalein solution.



(a) (b)

Fig. 1: The boreholes were installed for simulated piping test in saddle dam, (a) Plan map, (b) Cross-section of the saddle dam.

Resistivity Monitoring

The electrical resistivity measurements were performed at the dam crest and the downstream slope. The resistivity data were collected with a survey system of SuperStingR8/IP^{TM} by AGI, USA. The length of the survey line was 160m, and the electrodes were spaced 2m. The electrode arrays used were dipole-dipole and modified pole-pole systems. The depth of investigation was extended by increasing the dipole separation to 4m. The resistivity data were collected using both electrode array system form each survey line and both data sets from each survey line were incorporated as one data set for each survey line in order to enhance the quality of the data.

All the electrical resistivity data was first processed and interpreted by DIPRO for Windows, the 2.5-D resistivity interpretation software package. The processing includes bad data elimination, 2.5-D inversion, and drawing 2-D resistivity color images. In the 2.5-D inversion, we adopt the active constraint balancing method (Yi et al., 2003) to enhance the resolving power of the least-squares inversion.

The total number of the electrical resistivity monitoring data was performed 7 times during the simulated piping test. The measurement conditions of the electrical resistivity are listed in Table 1. According to this table, the electrical resistivity measurements were carried out in 11 stages, Phase 1 before the drilled boreholes, and Phase 2 to Phase 9 are during simulated piping test. And we conducted a hydraulic fracturing test in October 18.

To monitor the changes in the dam resistivity before and during simulated piping test, surface survey has been conducted. The result of electrical resistivity survey in dam crest and the downstream slope ranged 100~230 Ωm and 100~180 Ωm, respectively. The electrical resistivity values in dam crest were bigger than these of the downstream slope. It is observed that a low resistivity zone lies in the upper area from the surface to a depth 4m, zone shows a higher resistivity, greater than 150 Ωm. According the boring data at the crest, the upper area of the soil unit consists of mostly silt soil with granule. Therefore we thought that the anomaly in the upper area is attributed to the silt soil and granule with low resistivity.

Monitoring stage	Acquisition date	Description	
Phase 0	16. Sep. 2008	N=12	A preliminary survey
Phase 1	17. Sep. 2008	N=16	
Phase 2	04. Oct. 2008	N=16	Injection of water
Phase 3	04. Oct. 2008	N=16	During piping test
Phase 4	05. Oct. 2008	N=16	
Phase 5	05. Oct. 2008	N=16	
Phase 6	06. Oct. 2008	N=16	
Phase 7	06. Oct. 2008	N=16	
Phase 8	07. Oct. 2008	N=16	
Phase 9	07. Oct. 2008	N=16	Finished piping test
Phase 10	20. Oct. 2008	N=16	2 days before hydraulic fracturing test

Tab. 1: History of simulated tests and electrical resistivity monitoring.

But there were a certain difference the result of Phase 0 and Phase 1 (Figure 2). As a whole, resistivity distribution aspect of profiles for Phase 2 to Phase 9 looks similar results. The ranges of electrical resistivity values were 100-400 Ωm around boreholes, and the RMS error was 4.6-7.5% ranged each phases in the crest. Phase 1 showed the better image than Phase 0 in lower depth zone. The data acquired in Phase 1 unfortunately showed too little electrode separation index to get subsurface image from them. Therefore, one set of monitoring data was assembled using the data from Phase 2 to 10 excluding Phase 1.

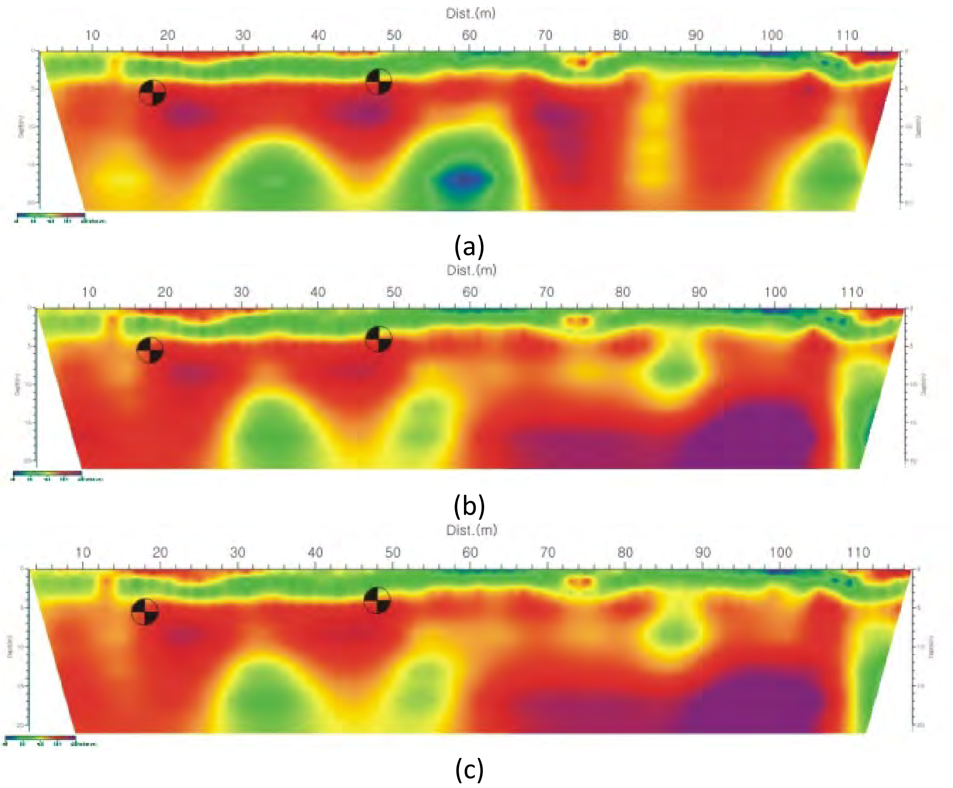


Fig. 2: Time-lapse images of electrical resistivity survey of Phase 0 in the crest (a), and the measurement of Phase 2 (b), and when Phase 9 measurement was completed (c).

In order to image around boreholes, the different images were analyzed for each phases. Figure 3 show the ratio of resistivity changes for Phases 2 to 9 divided by Phase 1. This ratio was calculated simply by dividing every resistivity values for each grid of one profile by that of corresponding grid of the other. If the resistivity change ratio is 1, it is never any change in the phases. And less 1 indicates a decrease in resistivity values, while above 1 indicates an increase. There wasn't changed a ground condition during piping test. Therefore the boreholes area must be imaged as an anomalous zone having the value less than 1 during piping test. We could easily recognize that the electrical resistivity ratio showed many artifacts, while difference images appeared with false anomalies of resistivity increasing. These figures indicate the ratio of resistivity change around the boreholes is very low, less than 5%. So it is really difficult to detect leakages, since the ratio of resistivity change is less than RMS error by inversion.

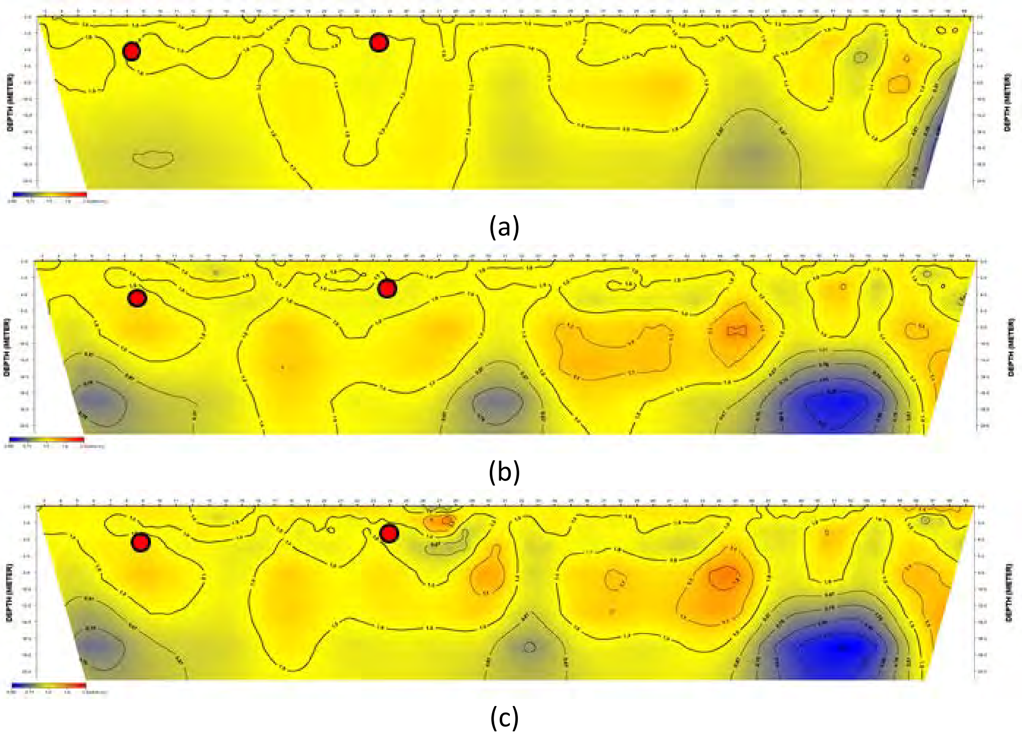


Fig. 3: Resistivity changes of Phase 3 (a), Phase 6 (b), Phase 8(c) expressed in terms of the resistivity ratio between each phase and Phase 1.

The ratio of resistivity change was very low until Phase 6. Therefore, we changed two kind of ground condition for a big change of resistivity. First, Phase 8 was saturated around 24 hours in the boreholes for piping test. Second, we collapsed the right borehole. Figure 4 shows the resistivity change ratio of Phase 8/Phase 6 on the dam crest. White rectangle indicates the zone of borehole was collapsed by water injection, and left borehole isn't collapse. The resistivity change ratio is 1~3 % range around borehole (A4-1), but white rectangle area is decreasing with 28%. The detection of leakage could be difficult to conclude that the resistivity change ratio was decreased. Because the resistivity change ratio was appeared that increasing or decreasing of resistivity value during piping test.

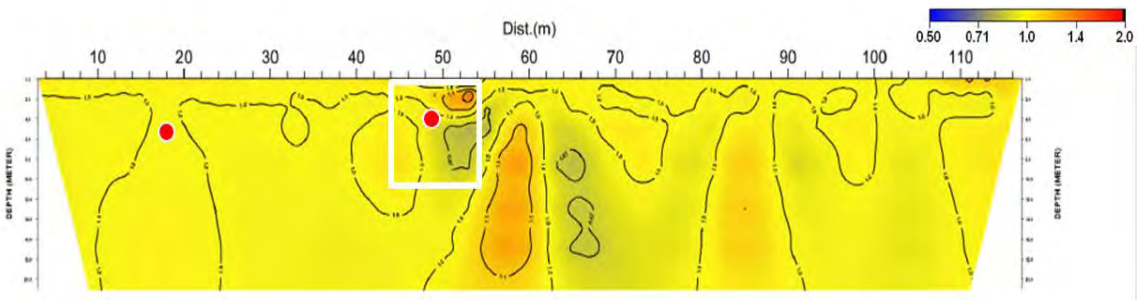


Fig. 4: The resistivity change ratio of the Phase 8/Phase 6 on the dam crest.

After the simulated piping test was finished, we was analysed the resistivity change ratio for the hydraulic fracturing test. Figure 5 shows the resistivity change ratio of Phase 10/Phase 1 on the dam crest after hydraulic fracturing. The most obvious change of ground condition is observed near to the location of 47 m, while little change near 16 m and 112 m. The anomalies of resistivity decrease on and the surface are mainly attributed to the overflow of ground material which was observed in field. The effect of hydraulic fracturing was visually identified after applying phenolphthalein solution since the solution changes its color after reacting with grouting cement. An injected cement of pillar-shaped would be turned magenta by applying phenolphthalein solution. The scale of the grout materials wasn't big, but it was confirmed to spread widely in around injected boreholes during destruction from the saddle dam.

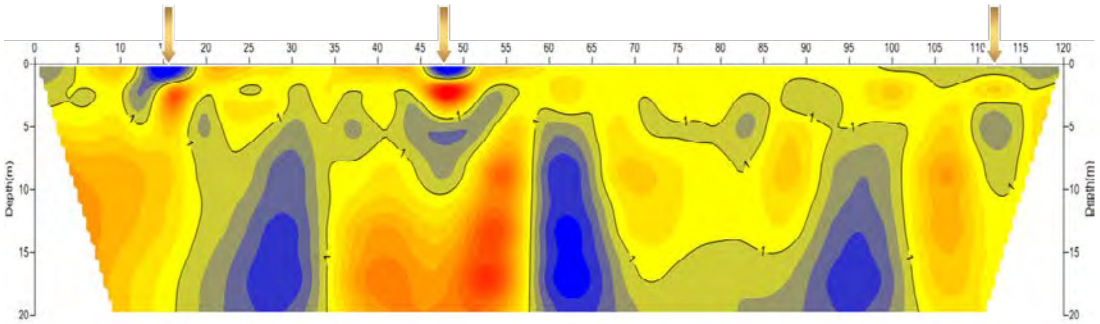


Fig. 5: The resistivity change ratio for Phase 10/Phase 1 on the dam crest after hydraulic fracturing.

Conclusion

The electrical resistivity monitoring of piping in a dismantled saddle dam provided an excellent opportunity to evaluate potential for detecting piping. We were able to obtain high-quality resistivity along-dam profiles of total 8 phases for 4 days during piping. This is demonstrated by low RMS error (2.5~7.5%). However, the decreased resistivity due to injection of water is not apparent. This is probably because the decreased resistivity is within the range of RMS error. Therefore, resistivity monitoring may not be suitable for the detection of piping especially at early stages. We suggest tighter spacing of electrodes for future studies. For artificial hydraulic fracturing experiments; it is found that the extent of propagation of grout material is identified by resistivity monitoring.

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