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Application of hydrogeological and geophysical methods to delineate leakage pathways in an earth fill dam

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Key Words: leakage, drawdown, hydrogeological approach, geophysical survey, electrical resistivity, self-potential

ABSTRACT

Comprehensive field surveys, including various hydrogeological and geophysical methods, were carried out to appraise the applicability of those methods to a leakage problem at the Sandong earth fill dam in southwestern Korea. The methods applied in the field site were tracer tests, monitoring of drawdown and leakage with discharge of reservoir water, electrical resistivity surveys using the dipole-dipole array, self-potential (SP), and temperature logging methods. The leakage pattern in the reservoir wall was demonstrated by hydrogeological methods and was further clarified by the geophysical surveys. Leakage turned out to be through the right abutment of the reservoir wall. In this study, we confirmed that the electrical resistivity method is effective in detecting the zones favorable to leakage, and SP methods are useful for delineating the leakage pathways themselves, because leaks generate strong streaming-potential anomalies.

INTRODUCTION

Leakage through a reservoir wall that exceeds the design range may create serious problems, threatening the stability of the reservoir. Therefore, it is important to identify the regions where leakage occurs as precisely as possible, to ascertain preferred pathways for leakage, and to determine the rate of leakage.

Leakage patterns in earth fill dams in Korea can be classified into leakage through the abutment, leakage by piping through the dam wall itself, leakage through unstable dam foundations, and leakage due to the composite effects of landslides and distortion of the dam structure. Among these, leakage through abutments of earth fill dams is common, and excessive leakage may cause the breakdown of the structure. Ogilvy et al. (1969) reported that, when leakage velocities reach critical values, erosion may occur, causing subsidence leading to the collapse of the dam. However, if an earth fill dam is properly constructed with filters and an impervious core, and is periodically maintained, it should continue to function satisfactorily.

We have performed hydrogeological tests and geophysical surveys to delineate leakage pathways through the abutment of an earth fill dam located in southwest Korea. The hydrogeological tests included tracer tests, and the monitoring of the relationship between drawdown and leakage and discharge of reservoir water. Geophysical surveys included electrical resistivity and SP surveys, and temperature logging.

STUDY AREA

We studied the Sandong earth fill dam, located in southwest Korea. This earth fill dam showed anomalous leakage through the abutment of the dam, and was selected as a major test site for research into evaluation and repair procedures. The Sandong dam is a water-supply storage, with a stepped dam wall, an overflow spillway, a water intake tower, and a water purification plant. A water supply pipe has been constructed on the left side of the dam wall (Figure 1). This dam is located in a narrow valley, with both abutments rising on a slope of about 1:1.5 to the top of the dam. The upstream slope of the dam is 1:2.5 while the toe drain slope is 1:1.5 (Figure 2). The dam wall is approximately 290 m long and has a maximum height of 47 m. Crest elevation is 397.9 m above sea level, with a maximum storage capacity of 5.3×10^5 m^3. The site is in the Jiri mountain region, which is mainly a Pre-Cambrian gneiss complex. The foundation rocks are Pre-Cambrian gneiss and the abutments of the dam are weathered gneiss. Bedrock talus is found on the right side of the dam wall.

Leakage was detected at three locations near the toe drain (S1, S2, and S3 of Figure 1) of the dam. Eight boreholes were drilled along the crest and the downstream steps of the dam for various hydrogeological tests and temperature logging (Figure 1).

HYDROGEOLOGICAL APPROACH

To provide quantitative information on hydrogeological conditions, a set of boreholes were drilled: six holes completed as piezometers, along both the crest and the second step, and

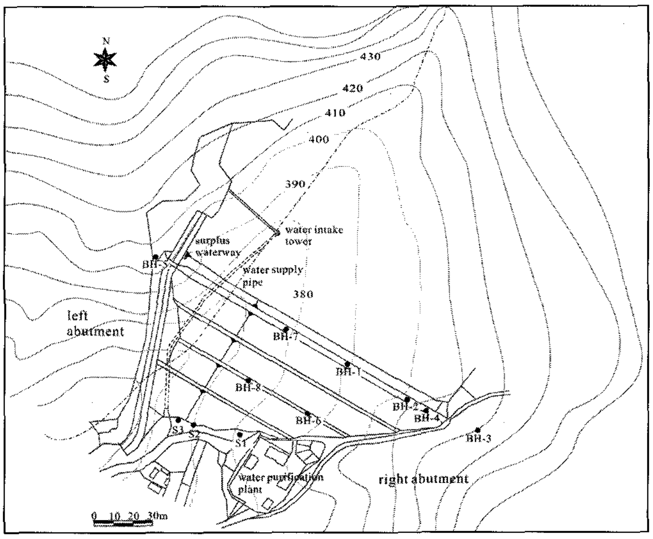

Fig. 1. Plan view of the general setting of the Sandong earth fill dam, with locations of water purification plant, water intake tower, overflow spillway, water supply pipe, three leakage points (S1, S2, and S3), and eight boreholes (BH-1 to BH-8).

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two holes (BH-3 and BH-5) completed with screens on the abutments at each end of the dam wall, as shown in Figure 1.

The boreholes were used to carry out two forms of tracer test, and to monitor the variation in drawdown and leakage with discharge of reservoir water.

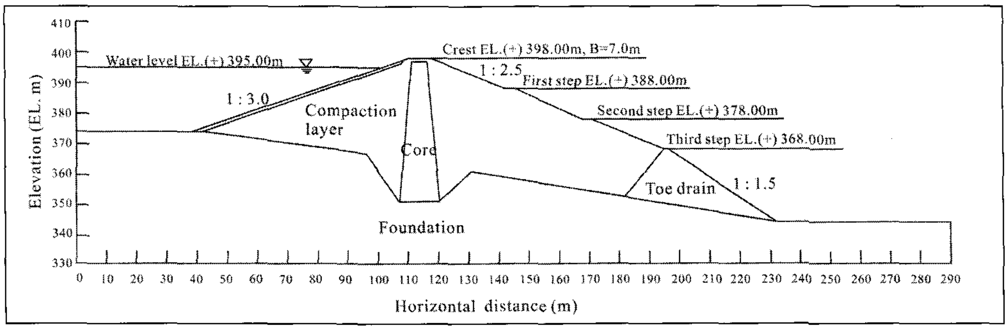

Fig. 2. Vertical cross section of the dam.

Tracer tests

Various tracers, including dyes, non-radioactive additives, and radioactive markers, have been added to reservoir waters in leakage investigations (Drost and Moser, 1983). The tracer chosen in any specific case should not be removed from the flow by adsorption. The U.S. Army Corps of Engineering applied the dye-tracing technique to detect leakage from a canal, and found that the canal, pondages, and the seepage outflow area were hydraulically connected to each other (Sjostrom and Hotchkiss, 1996).

In this study, two tracer tests were performed, using a non-reactive electrolytic solution as tracer. The specific choice was NaCl solution of more than 10 000 ppm concentration, for both tests. Detection of the tracer was by monitoring electrical conductivity at injection and downstream observation holes, and at two leakage points (S1 and S2), with an automatic recording system. Flow was along natural gradients. Test 1 was done by continuous injection at BH-3, and instantaneous injection at BH-7 was attempted in Test 2.

Test 1 was performed by continuous injection of tracer at the rate of 0.56 L/sec for 20 minutes into BH-3. This borehole is located in rock at the right-hand end of the dam wall, and the test was to analyse the effect of aquifers in the abutment and surrounding rocks. The total amount injected was 700 L, and conductivity measurements were made every five minutes for 25 days. The electrical conductivity in BH-3 returned to background values after two days, but neither the conductivity in BH-4, located in the dam wall near the right abutment, nor the conductivities at S1 and S2, changed during the test period (Figure 3).

Test 2 was performed by the instantaneous injection method, with 1000 L of tracer injected at BH-7, located near the centre of the crest, to find leakage through the right abutment. The maximum increases of electrical conductivity at both BH-8 and S1 were observed about 6800 and 11 500 minutes after injection, respectively, but conductivities at S2 and S3 did not change during the test period (Figure 4). This indicates that the tracer was being diluted in the subsurface as it moved to the leakage point. From the results, it is obvious that leakage is through the right abutment; the leakage rate from BH-8 to S1 is calculated to be 12.1 m/day.

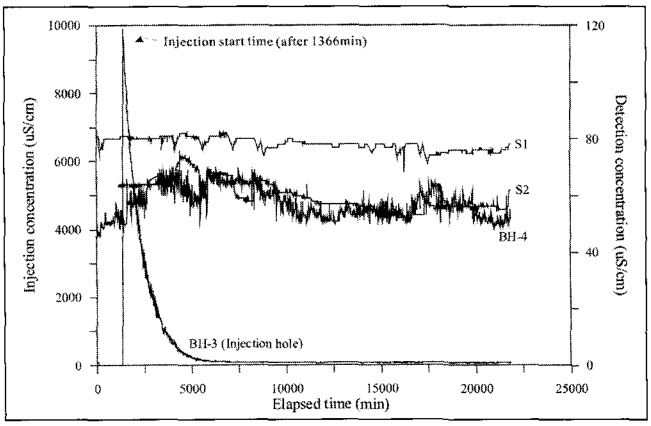

Fig. 3. NaCl concentrations in tracer Test 1. Left-hand axis: concentration in injection borehole BH-3. Right-hand axis: concentration in observation boreholes.

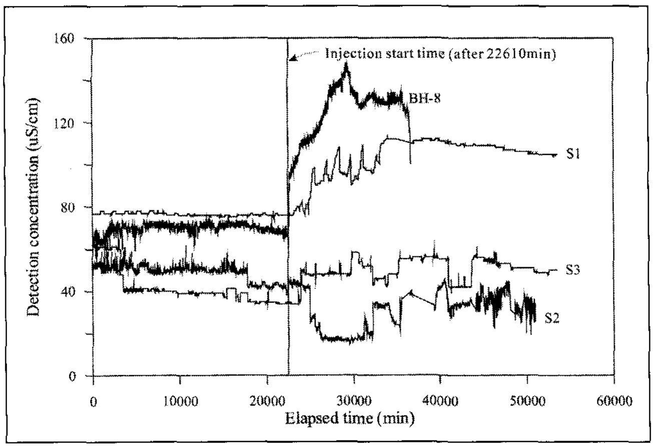

Fig. 4. NaCl concentrations in tracer Test 2.

Monitoring of drawdown and leakage with discharge of reservoir water

When reservoir water is discharged, the piezometric levels at the dam wall generally show nearly linear response to reservoir levels. Piezometric levels, and the quantity of leakage water at S1, S2, and S3, were measured over a period of 10 days as reservoir water was discharged. In order to analyze the effect of stopping discharge, we put a five-day halt between two discharge periods. The drop in reservoir water level was 4.5 m and 6.0 m during each period, respectively (Figure 5).

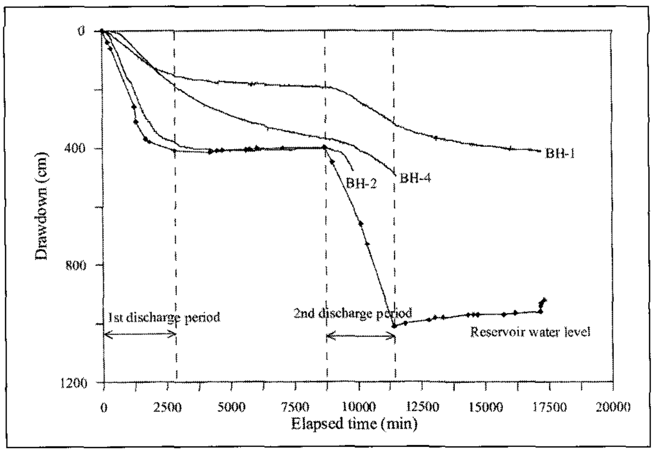

Fig. 5. Drawdown curves for the three piezometers in the dam wall. The drawdown rate in hole BH-2 is the same that of the reservoir water level.

The drawdown curves at BH-1, BH-2, and BH-4 show that the piezometric level at BH-2 varied in a similar way to the reservoir levels, but the level at BH-4 continued to descend even when discharge was halted. The drawdown at BH-1 also followed reservoir water levels, although the changes were smaller than at BH-4 (Figure 5). These results indicate that the major leakage may occur at the bedrock boundary near BH-2 and BH-4.

Leakage rates at leakage points S1, S2, and S3 were also recorded to observe the effect of changing reservoir levels. As shown in Figure 6, the trend of leakage changes at S1 was similar to the trend of the reservoir level, whereas the leakage at S2 occurred only during discharge periods. At S3, leakage was approximately constant until the second discharge period. This indicates that the leakage pattern at S1 was mainly affected by leakage through the right abutment, and also that the leakage pathway in this dam may be through the right abutment close to the bedrock boundary near BH-2 and BH-4.

The two hydrogeological methods were applied to eight observation wells at the dam, and three leakage points at the toe, and the maximum increase of electrical conductivity generated by the tracer material was observed at the well located closest to the right abutment. The drawdown patterns in wells near the right abutment showed a nearly linear response to falls in reservoir levels.

GEOPHYSICAL APPROACH

Geophysical survey methods, particularly electrical methods, may play an important role in assessing leakage pathways through reservoir dams (Corwin and Butler, 1989). We conducted electrical resistivity surveys along the crest, each step, and each abutment, a self-potential survey, and temperature logging in each borehole, to delineate leakage pathways.

Dipole-dipole array electrical resistivity survey

Electrical resistivity methods investigate the subsurface by measuring the electric potential distribution from known current sources, which reflects geoelectrical structure. Of the specific methods available, the dipole-dipole array method may be a good choice for extended structures like a reservoir dam, because this method gives the highest lateral resolution at the expense of a low signal-to-noise ratio. The objective at this site was to see if it was possible to find leakage pathways in the dam that might lead to stability problems. Seven profiles were made, along the crest extending to 150 m beyond the right-hand end of the dam, the three steps, each abutment, and 20 m from the left abutment. Measured data were inverted to a subsurface resistivity image by a 2.5-dimensional inversion algorithm based on finite element modeling and Active Constraint Balancing (Yi and Kim, 1998).

The electrical resistivity sections show a major low-resistivity anomaly of less than 300 Ω.m from the right side of the dam to the outside of the crest, and this anomaly splits up at the lower step along the right abutment (Figure 7).

SP Survey

In general, fluid flows through a medium generate electrical potentials called streaming potentials through a process known as electrokinesis, and these potentials can be observed as part of the Self-Potential (SP) signal. The magnitude of the electrokinetic SP response depends on the electrical resistivity, dielectric constant, and viscosity of the fluid, and a coupling coefficient between the fluid and the medium. SP anomalies caused by flow through a medium can be measured on the surface above the flow channel (Figure 8). Reynolds (1997) suggested that where groundwater flows through a structure such as a dam, electrokinetic streaming potentials might be generated with sufficient magnitude to be detectable as SP anomalies.

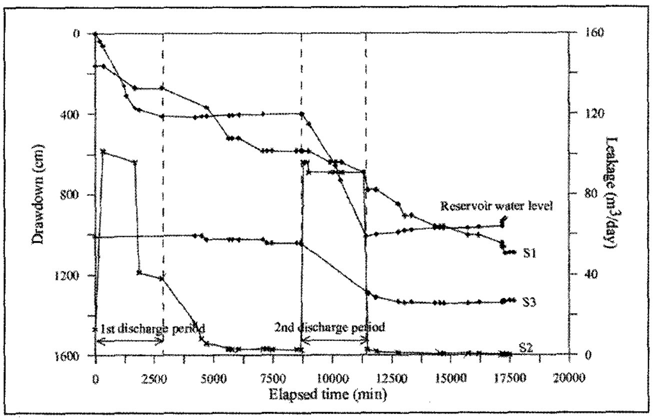

Fig. 6. Leakage curves (m^3/day) at the three leakage points during discharge of water from the reservoir. The leakage pattern at point S1 was similar to the variation in discharge of reservoir water.

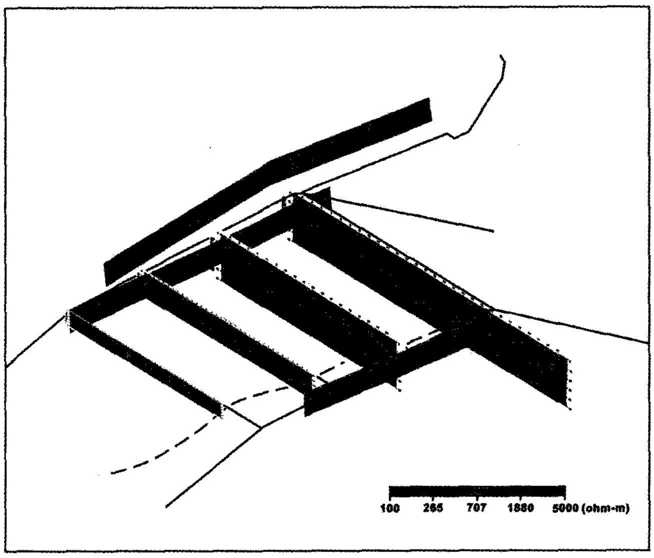

Fig. 7. Results of the dipole-dipole electrical resistivity survey. Inset at upper left indicates location of the lines on the reservoir dam. The dotted line indicates the boundary of the right abutment. A low resistivity region along right abutment elongates at the lower step.

Corwin and Butler (1989) studied fundamental questions about the SP method through electrode comparisons and long-term stability tests, described data acquisition procedures, and discussed modelling and quantitative interpretation of SP data. They showed that contact potentials caused by interactions between the electrodes and local soil conditions may be larger than the SP generated by streaming potentials related to leakage, and time variations of these contact potentials may also be greater than those related to leakage, so that careful experimental work is necessary.

To eliminate these types of noise, we set up an SP reference point off the dam, and corrected the reference potential at each observation, lest the telluric current related to magnetospheric activity should affect the monitoring results. SP responses were measured at the same stations as the dipole-dipole survey, along the crest and three steps, to compare the two kinds of results, and the measurements were also repeated four or five times every hour.

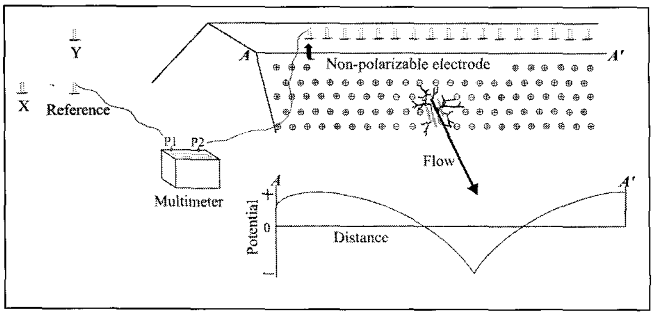

Fig. 8. Schematic diagram for geometry of data acquisition using the SP method at the dam wall (modified from Butler and Llopis, 1990).

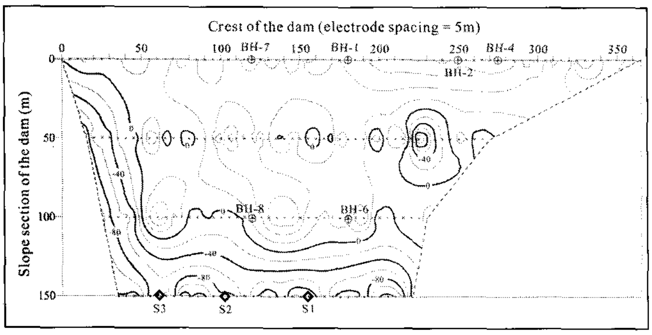

Fig. 9. Interpolated contour map of SP obtained from an array of non-polarizable electrodes on the crest and slope of the reservoir dam. A strong negative SP anomaly can be seen near the right abutment at the first step of the dam wall, spreading towards the downstream toe. The electrode locations are marked by a × symbol along the crest and each step.

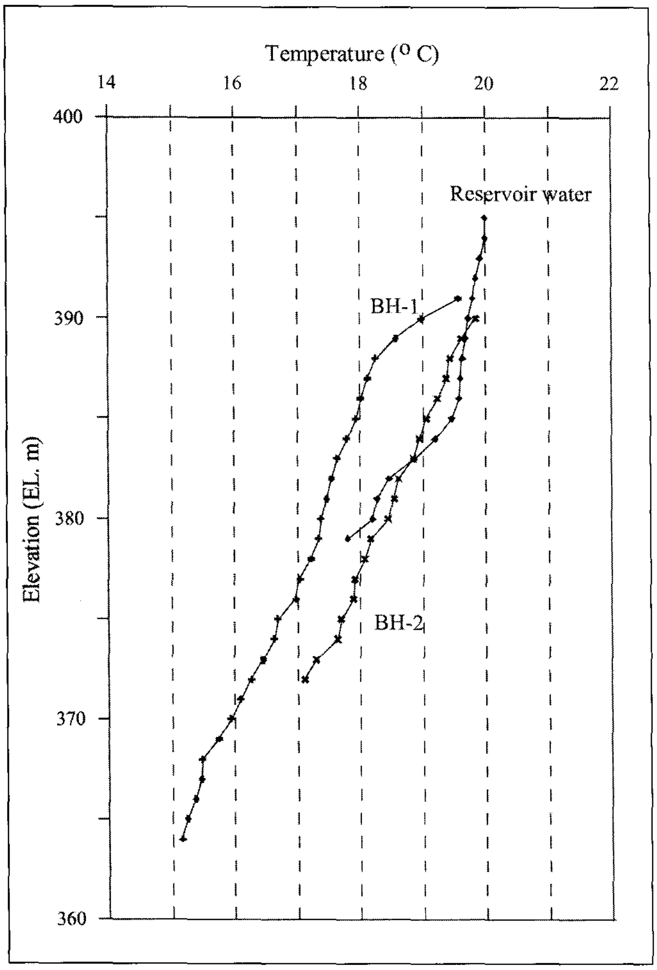

Fig. 10. Comparison of temperature logs at two pilot holes in the dam wall with reservoir water temperatures. Temperature variation of water in BH-2 is similar to that of reservoir water.

As we can see in Figure 9, a strong negative anomaly of up to −120 mV is observed at the first step, near the right abutment, and the anomaly splits at the third step. This compares with the low-resistivity regions at the lower step in the dipole-dipole survey result, from which we can delineate the leakage pathway through the right abutment.

Temperature Logging

The main objective of geophysical logging is to obtain more information about the subsurface, and logging results provide continuously recorded observations of in-situ properties under various conditions. Temperature logs of the borehole fluid have a number of important applications in groundwater hydrology, and they are generally essential in the study of the movement of groundwater and contaminants (Keys, 1989). Temperature logging results can also provide very useful information about the vertical variation of water properties in a well, and on the movement of water through a well.

We ran temperature logs in the reservoir water and in boreholes BH-1 and BH-2 in the dam, to identify the leakage pathway through the right abutment (Figure 10). We could verify that there is a leakage pathway through the right side of the abutment, because the variation of temperature with depth in BH-2, located close to the right abutment, is almost the same as that in reservoir water.

DISCUSSION AND CONCLUSIONS

This study area is a reservoir site which has anomalous leakage through one abutment. Two tracer tests indicate that the leakage pattern is through the right abutment, and the leakage rate is calculated to be 12.1 m/day from BH-8 to the discharge point S1 (Figure 1). The results of monitoring of drawdown and leakage variations with discharge of reservoir water indicated that the leakage possibly occurred at the bedrock boundary near BH-2 and BH-4. The trend of leakage at S1 was related to the reservoir level, so we have concluded that the leakage pathway in this reservoir dam is through the right abutment.

Combined images of electrical resistivity distribution showed that a major anomaly from the right side to the outside of the dam crest splits up at the lower step along the right abutment, which supports the previous conclusions about the leakage pathway. From a SP survey we could also demonstrate a leakage pathway through the right abutment. Temperature logging also confirms a leakage pathway through the right abutment.

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사력댐 누수경로 파악을 위한 수리지질과 지구물리 방법의 적용

송성호[1] · 송윤호[2] · 권병두[3]

요 약: 한반도 남서쪽에 위치한 산동저수지에 대하여 저수지 누수문제 파악을 위해 다양한 수리지질학적 방법과 지구물리 방법이 적용되었다. 이 연구에서 적용한 방법은 추적자 시험, 배수에 따른 시추공 수위 변화 및 누수량 변화 측정, 쌍극자배열 전기비저항탐사, 온도 검층 및 자연전위법 등이다. 수리지질학적 방법 적용 결과 누수형태는 댐체 측벽부를 통한 누수로 밝혀졌으며, 지구물리 방법 적용 결과 이러한 누수구간 및 누수유로가 확인되었다. 또한 연구결과로서 지구물리방법 중 전기비저항탐사는 누수구간 규명에 효과적이며, 유동전위를 대상으로 한 자연전위법은 누수 지점 및 누수 유로 확인에 매우 높은 적용성을 확인하였다. 특히 자연번위법 적용 결과 누수가 합쳐져 유출되는 지점 근처에서 측정된 자연전위가 상대적으로 강한 음의 값을 나타냄에 따라 누수량의 증가와 자연전위값의 변화는 상관성이 큰 것으로 나타났다.

水文地質学および物理探査手法によるアースフィルダムの漏水路の検出

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要 旨: 韓国南西部にあるSandongアースフィルダムの漏水問題に対する水文地質学や物理探査的手法などの適用性を調査するために、それら手法を用いた包括的な現地調査が実施された。このサイトで実施された調査は、トレーサー試験、貯留水放出に伴う水量減少および漏水のモニタリング、ダイポール・ダイポール配置による電気探査、温度検層および自然電位(SP)法である。ダム壁の漏水パターンはまず水文地質学方法によって把握され、物理探査によってさらに明確にされた。その結果、漏水箇所はダム壁の右側のせりもち台にあることが判明した。この研究では、電気探査は漏水可能性が大きいゾーンを検知するのに有効であることが確認された。また、漏水によって大きな流動電位異常が形成されるので、SP法が漏水路そのものを検出するのに有効であることがわかった。

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