Integrated Detection Technology: Application in the Investigation of Hidden Seepage Hazards in Dams

Dams, as critical water conservancy infrastructure, play a key role in the flood control system and are closely related to national economic development and the safeguarding of people's lives and property. Due to historical reasons, dams built during different periods generally have safety hazards, posing a serious threat to the safety of people's lives and property as well as the stable development of society. Identifying the spatial locations and distributions of hidden dangers such as see pages in embankments and dams is of significant practical importance, providing a reliable basis for subsequent risk removal and reinforcement projects.

Currently, for the detection of common dam hazards such as seepage, cracks, and looseness, geophysical methods like electrical and electromagnetic methods are widely used. When used alone, these geophysical methods usually have certain limitations. Based on years of practical experience in dam seepage investigations, the author analyzes the strengths and weaknesses of detection techniques like high-density electrical method, natural electrical field method, in-situ tests, and indoor geotechnical tests. A comprehensive and effective method for detecting hidden seepage hazards in dams is summarized, providing a foundation for reinforcement and hazard removal.

1. Basic Principles and Technical Features

1.1 High-Density Electrical Method

The high-density electrical method is a geophysical exploration system developed to meet the actual needs of detailed shallow investigations. The principle of the high-density electrical method involves introducing direct current into the ground via grounding electrodes to establish a stable artificial electric field. By observing the changes in resistivity in both the vertical and horizontal directions at a certain point on the ground, the characteristics of the underground medium can be understood. Figure 1 illustrates the structure of the high-density resistivity exploration system. The high-density electrical method achieves rapid, automatic, and intelligent collection of field measurement data. It provides a large amount of data, high construction efficiency, and relatively ideal detection accuracy, making it a commonly used detection method in dam seepage investigations. At the same time, the application of the high-density electrical method has several constraints. In actual detection practice, one should be aware of factors such as terrain interference, excessive burial depth of the detection body, non-uniqueness of solutions, and side effects.

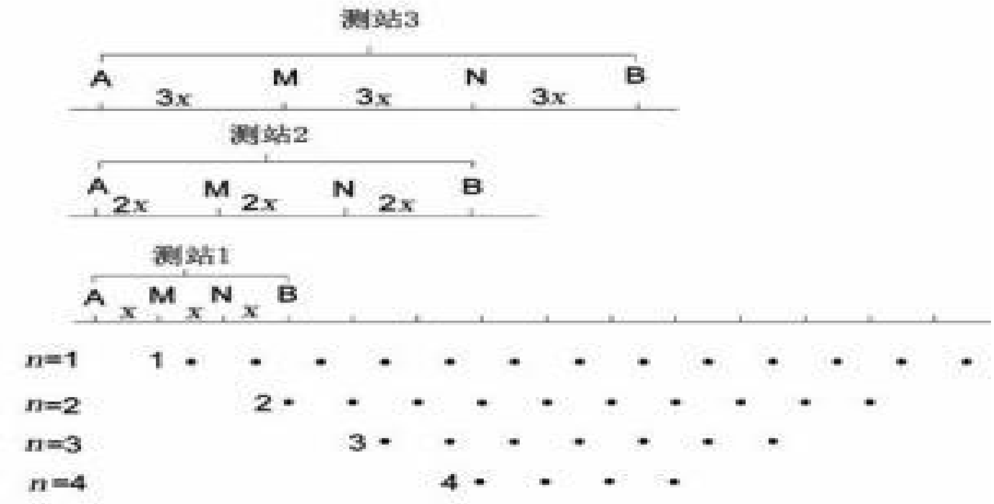


Figure 1: Schematic Diagram of the High-Density Resistivity Exploration System Structure

1.2 Natural Electric Field Method

The formation of natural electric fields mainly has three forms: oxidation-reduction of rock and soil, diffusion-adsorption, and permeation filtration. This investigation primarily utilizes the principle of permeation filtration. That is, the leakage in the dam body has the characteristics of short and narrow channels with a high hydraulic gradient. During the process of water leakage filtration, the water flow carries the positive ions from the solution and aggregates them in the direction of the water flow. In the opposite direction of the water flow, negative ions are retained, thus disrupting the balance of electrical properties, forming a polarization, and producing a filtration electric field. By observing the natural electric potential, the filtration electric field resulting from permeation can be detected. Changes in natural potential can reflect potential leakage's plane position and its channel. As a one-dimensional geophysical exploration method, the natural electric field method cannot interpret the specific location of anomalies.

1.3 In-situ Testing

The permeability of the dam's seepage barrier is determined using borehole water injection tests and borehole water pressure tests. The borehole water pressure test is generally used to determine the permeability of seepage barriers in dams, such as concrete seepage walls, which have relatively weak permeability. Borehole water injection tests are mainly suitable for seepage structures in dams that cannot undergo water pressure tests and require lower water isolation standards, such as grout reinforcement. Borehole water injection (pressure) tests can reflect the overall and comprehensive permeability of the dam body, but cannot provide a comprehensive investigation of the dam.

1.4 Indoor Soil Testing

Conventional soil tests are conducted using borehole samples to determine the physical indicators, liquid and plastic limit indices, particle composition, permeability coefficient, and other parameters of the dam's soil body to identify its engineering characteristics. Based on engineering experience, soil test data are often limited by sample representativeness, and the permeability coefficient tends to be underestimated, making it highly restrictive.

High-density electric methods, natural electric field methods, water injection (pressure) tests, and soil tests each have their technical characteristics. Only by understanding the advantages and disadvantages of these methods, and applying them appropriately according to project requirements and field conditions, can engineering problems be effectively addressed. Therefore, to ascertain the spatial distribution and morphological characteristics of dam seepage hazards, the high-density electric method is used to detect the spatial distribution of leakage anomalies. The natural electric field method is employed to determine the existence of leakage channels, and water injection (pressure) tests and soil tests are used to validate these anomalies. The nature of the dam's hazards is then specifically analyzed and determined based on these results.

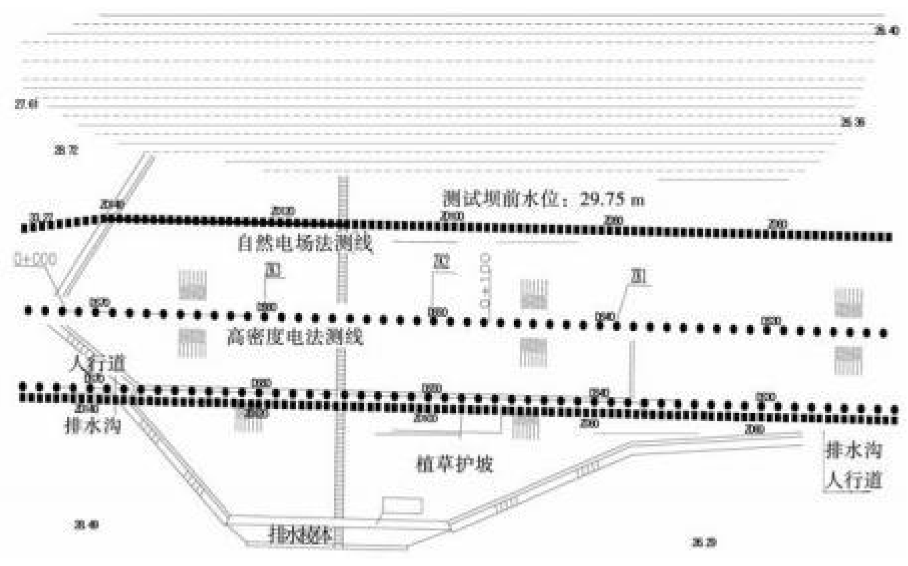
2. Project Example

The survey focused on a small reservoir located in Hainan Province, primarily used for irrigation and supplemented by aquaculture and other comprehensive uses. This small-scale hydraulic project began to exhibit varying degrees of seepage on the downstream slope of the main dam after its completion. To identify the spatial distribution and morphological characteristics of the main dam's seepage risks, onsite geophysical surveys (using high-density electric and natural electric field methods), drilling, in-situ testing (borehole water injection), and indoor soil tests were primarily conducted focusing on the cement mixing pile seepage barrier, dam foundation, and contact zone of the dam body.

2.1 On-site Work Arrangement

The detection of dam seepage adopted a combination of detailed geophysical surveys and in-situ and indoor soil test verifications. Geophysical survey lines were arranged according to relevant standards: on dams with a crest width of no more than 4 meters, a survey line is typically laid along the dam's crest centerline or the upstream shoulder. For dams with a crest width greater than 4 meters, survey lines are arranged along both the upstream and downstream shoulders. Depending on the need to trace the distribution of risks, additional survey lines can be placed on the dam slope, at the foot of the dam, or perpendicular to the dam's axis. For seepage anomalies detected by the aforementioned geophysical methods, boreholes were arranged for water injection (pressure) tests and sampling.

The main structures of this reservoir project consist of the main dam, auxiliary dam, spillway, and water conveyance culvert. The main dam is laid out in a linear fashion. The dam body is a homogeneous earth dam with a crest width of 4.0 meters, a crest length of 271.3 meters, a crest elevation of 33.5 meters, and a maximum dam base width of about 70 meters. Based on the basic conditions of the main dam, two high-density electrical survey lines were laid out along the seepage barrier axis and the trail on the downstream slope, with a point distance of 4 meters, to identify the spatial location of weakly bonded areas (low-resistance seepage zones) of the seepage barrier. Natural electric field survey lines were placed on the upstream waterline and the trail on the downstream slope, with a point distance of 2 meters, to understand the planar location of the seepage areas, as shown in Figure 2.



2.2 Data Analysis

2.2.1 High-Density Electrical Method.

Considering the basic conditions of the main dam and the requirements for seepage detection, the high-density electrical method uses the Wenner configuration. This allows for the simultaneous natural collection of horizontal and vertical two-dimensional exploration data in a single setup. In the high-density electrical method, a single arrangement deploys 60 electrodes, with rolling measurements. High-density profiles are set up along the seepage barrier axis and the trail on the downstream slope, with an electrode distance of 4 meters. The instruments used are the WGMD-9 super high-density electrical system, WDA-1A super digital direct current electrical method instrument, along with electrodes, cables, and other equipment. The power supply source is a 180V direct current power source. When the system is operational, the instrument compensates for polarization, and data collection is automated.

There are two high-density survey lines, arranged parallel to the dam axis. Figure 3 displays the inversion results of the high-density electrical method. For the seepage barrier survey line, at elevations between 15 and 26 meters, the pile numbers are 0+052 to 0+076, 0+092 to 0+112, and 0+136 to 0+164. The resistivity contour lines show low-resistance closed-loop anomalies, suggesting a low-resistance anomaly. For the survey line on the trail of the downstream slope, at elevations between 15 and 24 meters, the pile numbers are 0+052 to 0+072, 0+072 to 0+112, and 0+132 to 0+168. The resistivity contour lines again indicate low-resistance closed-loop anomalies, suggesting a low-resistance anomaly.

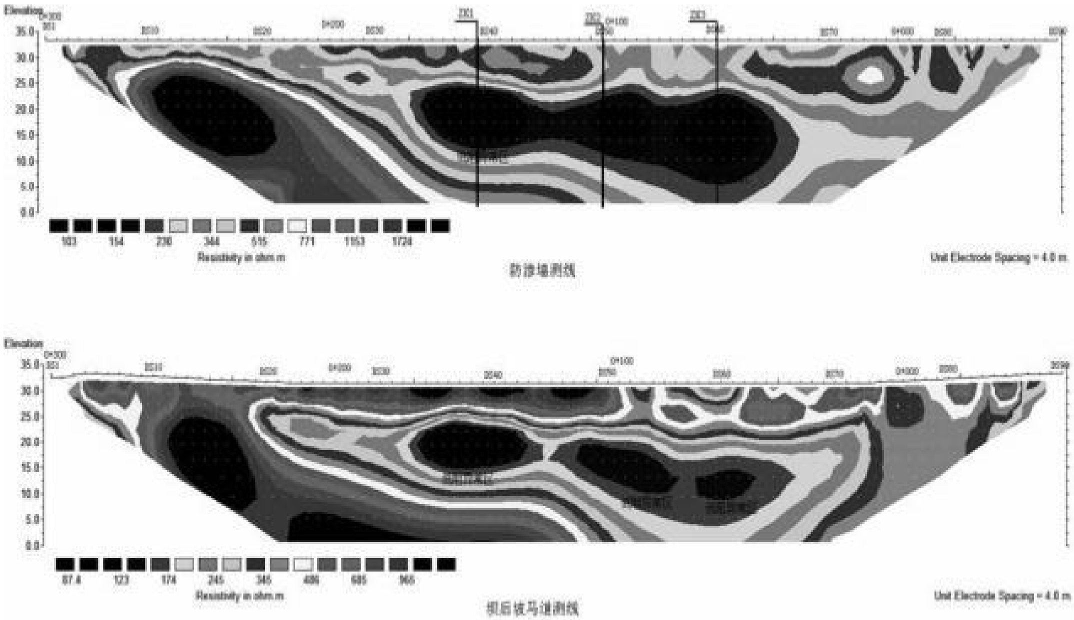


Figure 3: Inversion Results of the High-Density Electrical Method

2.2.2 Natural Electric Field Method

The natural electric field method for detecting seepage relies on what is called a "seepage electric field." As water seeps through underground channels in the dam body, negative ions adhere to the upstream soil and rock, while positive ions cling to the downstream. This creates a natural electric field. By observing these natural potentials, it's possible to determine if there are seepage channels. For this investigation, the WDA-1A super digital DC resistivity meter was used, equipped with non-polarizing electrodes (with a potential difference less than 2 mV). The point spacing was 2.0 m, with a survey line placed parallel to the dam axis on both the upstream water-facing slope and the downstream access road.

Figure 4 shows the results from the natural electric field method. On the upstream water-facing survey line, between stake numbers 0-003 to 0+006 and 0+092 to 0+134, the potential values are relatively low, suggesting seepage segments. On the downstream access road survey line, between stake numbers 0+076 to 0+124, 0+128 to 0+138, and 0+154 to 0+196, the potential values are also low, indicating seepage segments.

Combining the results from the high-density electrical method and the natural electric field method, stake numbers 0+092 to 0+112 at elevations between 15 to 22 m, and 0+136 to 0+164 at elevations between 15 to 26 m show low-resistance closed-loop anomalies, suggesting seepage zones. Between stake numbers 0+052 to 0+076 and elevations of 12 to 20 m, the resistance contour lines also indicate a low-resistance anomaly, suggesting a water-rich zone.

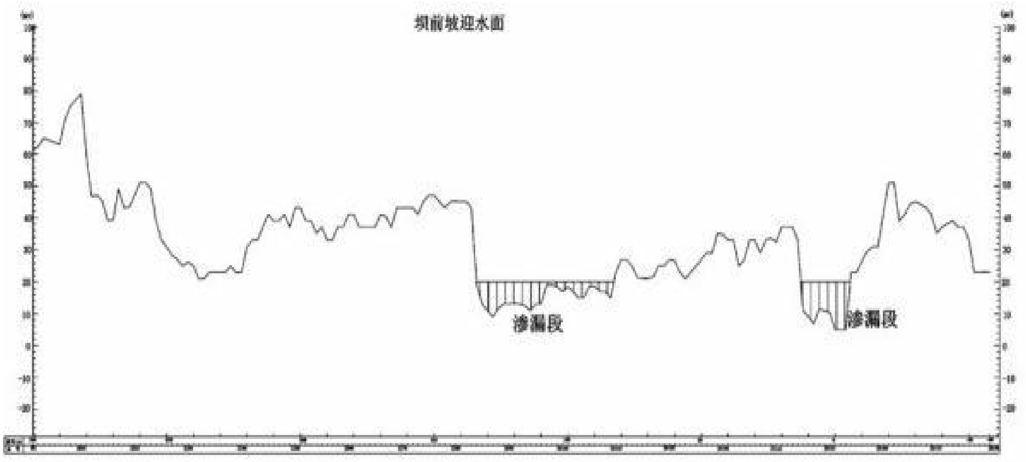
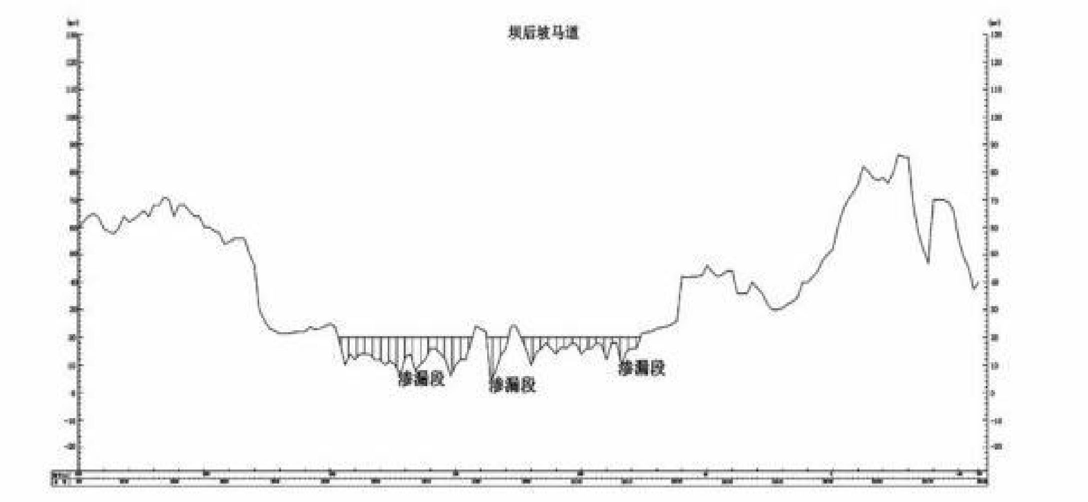


Figure 4: Results from the Natural Electric Field Method Survey Line



Continued Figure 4: Results from the Natural Electric Field Method Survey Line.

2.2.3 Water Injection and Geotechnical Testing

To validate the above-mentioned anomalies, three boreholes (ZK1, ZK2, and ZK3) were drilled on the dam axis, corresponding to stake numbers 0+148, 0+104, and 0+064 respectively. Geotechnical testing of the core samples revealed uneven mixing at the bottom of the cement mixing piles, with generally poor continuity and most samples appearing fragmented. The contact zone cement mixing piles showed poor performance, appearing loose. The base granite weathered soil was primarily full to strong weathered granite soil, ranging from the bottom of the cement mixing pile's anti-seepage wall to the weak weathering limit of the dam base granite. It was hard-plastic in texture, with moderate compressibility and weak permeability, though parts had moderate permeability. The rock core appeared as compact sandy soil, with gravel components accounting for 10.2%, sand grains for 32.7%, and silt and clay particles for 57.1%, similar in composition to the construction fill.

Based on water injection test results, the permeability coefficient of the anti-seepage wall mainly ranged from $2.78 \times 10^{-6} \sim 3.60 \times 10^{-4}$ cm/s, falling within the medium to weak permeability range. The permeability coefficient of the base granite weathered soil mainly ranged from 4. 03 ×10 - 5~ 1. 80 ×10 - 5 cm/s indicating weak permeability.

By integrating the findings from the high-density electrical and natural electric field methods, and validating through borehole water injection tests and geotechnical testing, the primary seepage anomaly areas of the reservoir's main dam were identified, mainly in the cement mixing pile's anti-seepage wall and the dam base contact zone. This provides a foundation for subsequent reinforcement measures.

3 Conclusion

The aforementioned exploratory practices have shown that by utilizing the strong reflection capabilities of the high-density resistivity method towards low-resistance bodies, combined with the high sensitivity of the natural electric field method for detecting underground water seepage, selecting appropriate working parameters and on-site layouts, and integrating the data from borehole water injection tests and indoor geotechnical tests, we can effectively identify seepage hazards in dam bodies. This approach offers significant economic and social benefits.

In summary, the rational combination of the aforementioned methods can effectively address issues related to seepage hazards in dams within hydraulic and hydropower engineering projects, providing a foundation for subsequent interventions.