APPLICATION OF MULTI-CHANNEL ELECTRICAL METHOD IN INVESTIGATION OF HYDRAULIC CHANNELS IN QIU JIA WAN MAIN DIKE OF THE YANGTZE RIVER, CHINA

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Abstract

Qiu Jia Wan, the main dike of the Yangtze River in Jia Yu County, Hubei Province, China, is a section scheduled for reconstruction due to underground water leakage. Prior to the reconstruction, the paths of water movement (sand layers or local bodies) and their covering material must clearly be investigated. The traditional methods, e.g. borehole drilling, are expensive and may re-damage the dike, so the noninvasive multi-channel electrical method was chosen to perform the investigation. One surveying profile parallel to and other three profiles perpendicular to the main dike were carried out in the Qiu Jia Wan section. Acquired data were inverted by a two-dimensional inversion method. Our interpretation was able to relate anomalies in resistivity cross sections to water leakage through a sand and gravel layer from the Yangtze River to the back of the dike. The results were consistent with hydro-geological analysis and therefore supplied basic data for the reconstruction task.

Introduction

Qiu Jia Wan, the main dike of the Yangtze River, is within a jurisdictional area of the San He embankment station in Jia Yu County. As a place of strategic importance, San He embankment was first set up over one thousand years ago in the Three-country Period of the Han Dynasty according to the Hubei chronicle of irrigation works (Hubei Irrigation Works, 1990). In the period of 1573 to 1619, many isolated protective embankments in lakeside areas were built around the Qiu Jia Wan area and joined together gradually in the late Ming Dynasty. An ancient river, the Lu River, paralleled the Yangtze River. In 1854, the Rebel Army opened the dike to resist the government army of the Qing Dynasty. The Lu River then changed its path, flowing into the Yangtze River through here, and its dike joined with main dike of the Yangtze River. Many irrigation works were supported by the government along the Yangtze River in the last half of the 20th century. Qiu Jia Wan main dike was progressively increased in width and height. Today a semitruck can freely pass through on its top surface. Because of different components formed in different dynasties, the Qiu Jia Wan main dike consisted of earth materials with different properties. These features strongly affected the safety of the dike.

According to the embankment chronicle of Jia Yu County (Office of Jia Yu Embankment, 1999), in the flood season of 1983, when the water level of the Yangtze River reached 29 meters (m), channel upwelling took place in residence’s pools located 150 m from Qiu Jia Wan dock (corresponding to the route mark K315+900 in Fig. 1); when the water level reached 31 m, channel upwelling and bubbling expanded from 9 m² to 100 m², interrupting traffic. In the flood season of 1998, the water level reached 32.21 m, the highest level in history recorded by the hydrometric station of Jia Yu County. In the period of the maximum water level, the flood
surged in many areas and poured out at K315+200. This event affected the lives of about fifty thousand people. Therefore, Qiu Jia Wan main dike was selected as a key place to reconstruct by Hubei Province.

Prior to the engineering reconstruction, hydraulic channels between the river and underground water and the thickness of covered layers must be investigated. Geophysical techniques are economic and efficient tools in near-surface investigations. After testing in the working site with ground-penetrating radar (GPR), the investigation depths of GPR data were hardly deeper than 10 m due to the loose cover layer. Because the requirements of irrigation works prohibit any explosive sources and seismic signal energy generated by a sledgehammer is so weak, the multi-channel electrical method was chosen to investigate the site.

**Geological Background and Electric Conditions**

The working area was located at the middle Yangtze terrain. Bedrocks in the vicinity of Qiu Jia Wan town were dominantly composed of sandstone and shaly sandstone and fragmentarily exposed. Heterogeneous overburden was composed of soil, mud, gravel, and sand. Additional rocks and soil were brought in from other places for infill where water upwelled in the great flood period of 1998, and these materials were isolated on the surface of the working site.

Electrical property of the surface materials was measured in situ using a small Schlumberger array and compared with electric logging data. The resistivity range of materials was listed in Table 1 for interpretation of inverted data.

<table>
<thead>
<tr>
<th>Geological Group</th>
<th>Material</th>
<th>Range of Resistivity (Ohm-meter)</th>
<th>Representative Value (Ohm-meter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_h$</td>
<td>Soil and clay</td>
<td>5--20</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>Sand and gravel</td>
<td>20-60</td>
<td>32</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>Alluvium made up of mud, sand and gravel</td>
<td>Moisture: 10-40</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dry: &gt;200</td>
<td></td>
</tr>
<tr>
<td>$J_2$</td>
<td>Shale and mudstone</td>
<td>50-150</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>Quartz sandstone</td>
<td>300-1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fine sandstone</td>
<td>100-500</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Shale sandstone</td>
<td>80-250</td>
<td></td>
</tr>
</tbody>
</table>

Layers or local bodies consisting of sand and gravel were well channels between the river water and groundwater. Therefore they were the main objects of the investigation. From column Representative Value in Table 1, saturated sand and gravel can be seen to possess resistivity about 10 ohm-meter higher than other alluvial sediments. These electrical conditions make distinguishing saturated sand and gravel from other alluvium sediments challenging.
Survey Layout and Field Procedures

A second-generation instrument with a multichannel-signal-controlling box made by the China University of Geosciences (CUG), Wuhan, was employed in our investigation. Readings based on Wenner α, β and Schlumberger arrays were used for a preliminary evaluation of efficiency. As a result, Wenner α was determined to be the most sensitive to thinner but widely spread sand and gravel layers among these arrays.

The topographic and surveying configurations were illustrated in Fig. 1. A long surveying line I-I’ was laid out on one side of the dike and parallel to the flow of the Yangtze River, from K313+985 to K315+670 and about 70 m away from the central line of the dike. Another three cross profiles called II-II’, III-III’ and IV-IV’ intersected the dike at K316+970, K315+845, and K314+580, respectively.

The electrode interval was set at 5 m for all profiles. In general, 60 electrodes were used to perform the one-fold measurement. One third of the electrodes were moved forward in the next measurement in order to decrease the shadow area. As required by the local government, the work was finished in two weeks, so the shadow area could not be diminished completely.

To insure data quality, some sections were surveyed several times. Readings were acceptable if the total relative error of two readings at different times was within 5%.

Data Inversion and Interpretation

Readings were smoothed using a nine-point movable median filter (Ritz et al., 1999) to suppress near-electrode effects, and then transferred into a XYZ format for inversion. Occam’s inversion method was used to invert smoothed data (deGroot-Hedlin and Constable, 1990; Loke and Barker, 1996). By inspecting the recorded data, we estimated depths to bedrocks and their apparent resistivities, which allowed us to interpolate shadow areas and constrain resistivities of the last three layers by the values listed in Table 1 during inversion. Because of large data sets (the largest one has more than 7,000 readings), the final root-mean-square (rms) errors of fitness were acceptably small (Table 2) although the results were very good by comparison with the known geological information (Figs. 2-5).

Table 2. Iterations and rms errors.

<table>
<thead>
<tr>
<th>Line</th>
<th>I-I’</th>
<th>II-II’</th>
<th>III-III’</th>
<th>IV-IV’</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iterations</td>
<td>7</td>
<td>4</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>rms errors</td>
<td>19.0</td>
<td>9.4</td>
<td>11.2</td>
<td>7.7</td>
</tr>
</tbody>
</table>

Based on Table 1, the inversion results were interpreted. The overburden above the fresh bedrock could be described as a sandwich-like structure (three units). The top layer was predominately composed of soil and clay, mingled with fine-grain sand, pebble pile, and original soil brought in from other places, with thickness changing from several to over 20 meters. The middle layer consisted of sand and gravel and was inhomogenously spread with thickness from several to 25 meters. The bottom layer of the sandwich was a weathered layer mixed with some...
residual alluvium underlying the sand and gravel layer.

The surface of the bedrock was violently undulated and its elevation decreased downstream. Inspection of the three transverse profiles (Figs. 3–5) showed a raised zone of the layer of sand and gravel 60 to 220 m away from the riverside. Based on existing records, most of events of upwelling occurred in this zone. Therefore, the inversion results indicated a stronger relationship between the thickness of the covered aquitar and upwelling of groundwater drainage. This is reasonable because upwelling would easily occur at places with relatively thinner overburden, when the difference between the level of the Yangtze River and the water table of groundwater exceeded a threshold value in flood season. This can be illustrated by the schematic map shown in Fig. 6. Upwelling is troublesome for the safety of a dike because it washes materials out from the subsurface. When upwelling occurs, the stress makes the dike unbalanced and could even make the dike collapse. We delineated three potential upwelling zones within 250 m away from the riverside on the geological interpretation profiles (Figs. 3b–5b) based on inverted results (Figs. 3a–5a). Our suggestion to the reconstruction work was that hydraulic channels consisting of sand and gravel between the Yangtze River and groundwater must be blocked or the overburden thickness of the aquitar must be increased.

Conclusions

The results illustrated that the multi-channel electric method is a useful tool for shallow subsurface applications. Geophysical data obtained from the multi-channel electrical method in the working area revealed that a widely spread hydraulic channel that consisted of a sand and gravel layer existed in the area. Upwelling would occur at places where the thickness of the overburden above the aquifer was thinner. With electrical results and special geological conditions, we concluded that the Qiu Jia Wan main dike of the Yangtze River was in danger and that reconstruction work was critical to the safety of the dike.

Acknowledgments

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Fig. 1. Layout of surveying lines.
Fig. 2. Inverted resistivity profile and geological interpretation of Line I-I'.

(a) an inverted resistivity profile; (b) geological interpretation.
Fig. 3. Inverted resistivity profile and geological interpretation of Line II-II'.

(a) an inverted resistivity profile; (b) geological interpretation.
Fig. 4. Inverted resistivity profile and geological interpretation of Line III-III'.

(a) an inverted resistivity profile; (b) geological interpretation.
Fig. 5. Inverted resistivity profile and geological interpretation of Line IV-IV'.
(a) an inverted resistivity profile; (b) geological interpretation.
Fig. 6. Relationship between river water and groundwater for different water levels and upwelling development during a flood period. (a) groundwater supplies river at a low water level; (b) river water supplies groundwater and imbibition occurs at places of thinner overburden when the river water level is higher than the water table of groundwater; (c) upwelling occurred at place of thinner overburden during a flood period.