Inverse analysis of seepage Safety for earth dams based on monitoring data

Jinhui Lang[1*] and Cheng Fang[2a]

[1] Chuzhou Water Conservancy Bureau, Chuzhou, China
[2] Nanjing Hydraulic Research Institute, Nanjing, China

*334126015@qq.com
aFangcheng9804@foxmail.com

Abstract. After several years of operation, there is a discrepancy between the measured data from the piezometric pipes and the initial design infiltration line of the dam. A mathematical model can be established to infer the permeability characteristics of the rock and soil materials in the earth dam based on actual boundary conditions such as upstream and downstream during the operation. This allows for a re-evaluation of the seepage safety of the dam. Taking a dam in Anhui Province, China as an example, the infiltration coefficient of the downstream dam material of the reservoir dam was found to have an increasing trend based on the inferred data from field measurements after several years of operation. It is recommended to continue strengthening monitoring and analysis of this dam.

Keywords: small reservoir; seepage monitoring; inversion calculation; dam safety.

1 Introduction

The purpose of the seepage safety analysis of dams is to verify whether the originally designed seepage control measures and the current actual seepage conditions can ensure the safe operation of the dam according to the design conditions [1-2]. Seepage is a critical consideration during the operation of dams particularly for earth and rockfill dams as seepage-induced failures have caused numerous dam breaches. Seepage can lead to soil saturation, decreased shear strength, and instability of the dam structure. Moreover, China has a large number of reservoir dams, most of which were constructed between the 1950s and 1970s [3]. During the construction process, the performance parameters of the earth and rockfill materials for the dams were often not specified. In order to ensure the safe operation of dams, a comprehensive seepage safety analysis is necessary.

Taking a dam in Anhui Province, China as a case study, this paper collects a large amount of monitoring data from piezometric pipes [4]. A mathematical model is constructed to divide the rock and soil structure within the dam and set reasonable boundary conditions [5-6]. By utilizing the relationship between the water levels of the upstream

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and downstream during operation and the water levels in the piezometric pipes, the permeability coefficients of various layers of the impermeable body are inferred. Based on this, seepage stability calculations are performed under design conditions to verify whether the dam structure remains in a safe condition. The current safety status of the dam is analyzed, guiding future dam operation and management.

2 Project overview

The reservoir calculated in this paper is a nationally key medium-sized reservoir with comprehensive utilization for urban water supply, irrigation, flood control, and aquaculture purposes. It has a total storage capacity of 28.85 million cubic meters. The hydraulic structure consists of a dam, a main spillway, an emergency spillway, an eastern irrigation culvert, and a western irrigation culvert. The dam is a homogeneous earth dam with a maximum height of 16.0 meters, a crest length of 2080.0 meters, a crest width of 5.0 meters, and a crest elevation of 71.00 meters. The wave-resistant wall is located at an elevation of 72.40 meters, and the dam crest is paved with concrete. During the reinforcement in 2004, single-row clay columns were used for seepage control. The clay columns were arranged along the dam axis with a diameter of 1.2 meters and a spacing of 0.85 meters. The bottom of the columns extends 0.5 meters into the foundation. The upstream slope of the dam has a slope ratio of 1: 2.5 with an elevation of 61.50 meters, and a 2.0-meter platform is provided at an elevation of 64.00 meters on the downstream slope.

3 Analysis of monitoring data

By selecting representative cross-sections for the analysis of monitoring data, the variations between the water levels in the monitoring points of the pipes and the reservoir water level are examined [7]. This assessment is used to determine the effectiveness of the seepage control measures and evaluate the seepage safety status of the dam [8].

3.1 Cross-section 0+558

The water level process lines of the piezometric pipes at cross-section 0+558 are shown in Figure 1. From the figure, it can be observed that the measurements of the three piezometric pipes have a certain correlation with the reservoir water level but are significantly affected by rainfall. Pipes I-1 and I-2 are located before and after the clay column seepage barrier respectively with a potential difference of approximately 50%. Furthermore, the water level of point I-1 closely follows the variations in the reservoir water level, indicating the significant effectiveness of the clay column seepage barrier at this cross-section.

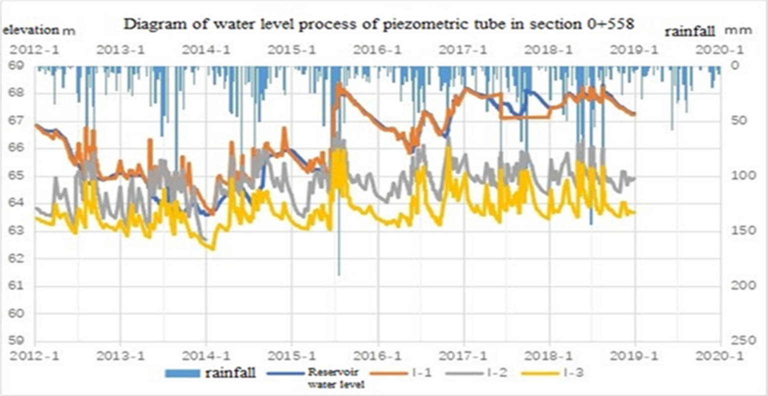

Fig. 1. Water level process lines of piezometric pipes at cross-section 0+558

3.2 Cross-section 0+928·

The water level process lines of the piezometric pipes at cross-section 0+928 can be seen in Figure 2. From the figure, it can be observed that starting from June 2015, the water level in pipe II-1 followed a similar trend as the reservoir water level. The measurements of pipe II-2 are significantly affected by rainfall and show less correlation with the reservoir water level. The water level fluctuates around 67.00 meters and the reliability of the data is poor, so the measurements are only for reference. The measurements of pipe II-3 fluctuate around 60.00 meters, indicating a lower water level, but they are significantly influenced by rainfall.

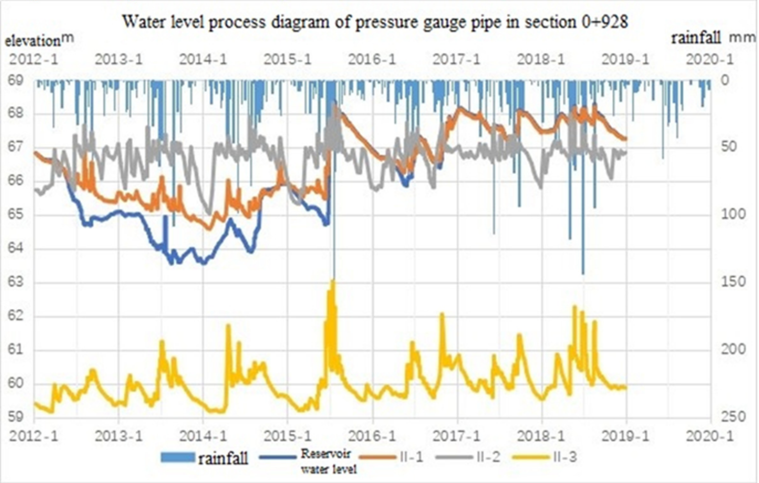

Fig. 2. Water level process lines of piezometric pipes at cross-section 0+928

4 Inverse calculation for seepage safety of earth and rockfill dams

According to the collected monitoring data from the dam pressure pipes on site and the selected analysis processes mentioned above, the inverse analysis calculation is conducted by using the finite element software Autobank [9]. By constructing a computational model based on the zoning of the dam structure and considering the stable reservoir water level during the analysis, the hydraulic performance parameters of different geological zones are continuously adjusted. The aim is to find the computational parameters that couple with the measured water level in the pressure pipes under steady seepage conditions, thereby determining the corresponding parameter values for the dam structure [10-11]. Considering the arrangement of the observation sections and the preliminary geological survey data, the East and West Laoho sections are selected as the calculation sections with station numbers 0+917 and 1+643 respectively. The calculation diagram is shown in Figures 3 and 4. The calculation results are illustrated in Figures 5 and 6.

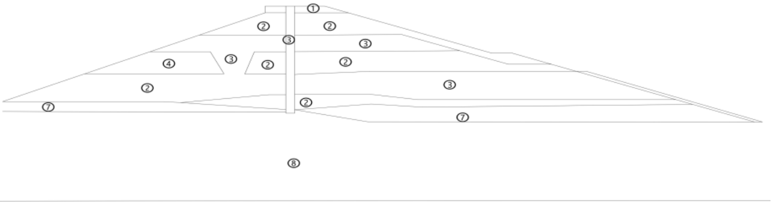

Fig. 3. Calculation diagram of 0+917 section

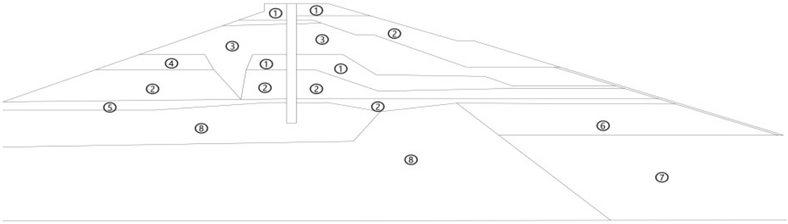

Fig. 4. Calculation diagram of 1+643 section

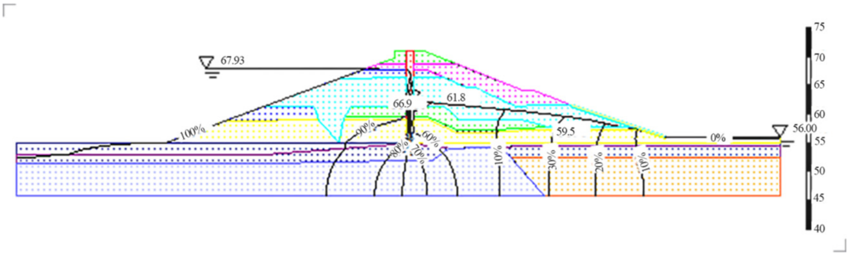

Fig. 5. Inverse Calculation of Permeability Coefficient for Section 0+917

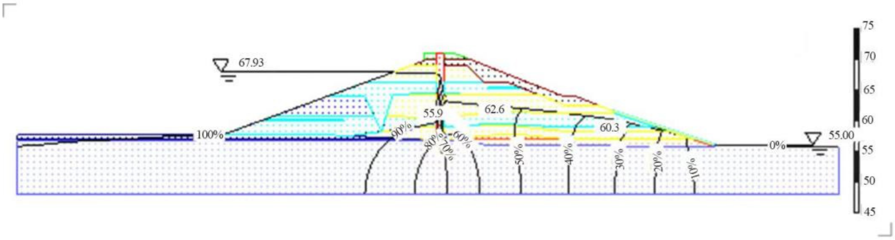

Fig. 6. Inverse Calculation of Permeability Coefficient for Section 1+643

The measured values of the monitoring pipes and the finite element calculation values are shown in the following Table 1.

Table 1. Calculation cross-section piezometric pipe measurement and finite element comparison calculation results

Section number	Pressure pipe number	Measured Value	Finite Element Calculation Value
0+917	II-1	67.89	67.85
	II-2	66.67	66.66
	II-3	60.08	60.03
1+643	V-1	67.84	67.81
	V-2	66.38	66.34
	V-3	58.51	58.50

The values of the permeability parameters for each zone of the dam are shown in the following Table 2.

Table 2. Calculate the value of the permeability coefficient of each section of the section

Location	Number	Soil Name	Design Permeability Coefficient (cm/s)	Inverse Calculation Permeability Coefficient (cm/s)
Dam body	①	Clay	1.05×10-4	1.18×10-4
	②	Heavy silty loam	1.05×10-4	1.05×10-4
	③	Clay	1.05×10-4	1.18×10-4
	④	Clay	1.05×10-4	1.18×10-4
	⑤	Siliceous heavy silty loam	1.05×10-4	1.05×10-4
Dam foundation	⑥	Heavy silty loam	1.39×10-5	1.39×10-5
	⑦	Medium silty loam	1.39×10-5	1.39×10-5
	⑧	Clay	1.39×10-5	1.18×10-5
Cutoff wall	⑨	Clay column	1.00×10-6	1.00×10-6

According to the table and calculation result graph, the calculated water level of the pressure pipes is consistent with the measured water level. The trend of the seepage line is similar. The inverted calculation parameters are reasonably accurate.

5 Conclusion

After several years of operation, the various zones of the embankment undergo settlement and hydraulic effects, leading to local redistribution of soil and fine-grained content. This results in changes in some of the design seepage parameters. When re-evaluating the seepage safety of the embankment, it is necessary to adjust the soil permeability coefficients based on monitoring data and determine the parameters that align with the measured values. This coupling process is particularly crucial for accurate calculations.

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