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Research on the Key Points of Geological Survey for Risk Removal and Reinforcement of Large Homogeneous Earth Dam Reservoir — Taking Tunliu Reservoir in Guangxi as an Example

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Abstract: *Taking the danger removal and reinforcement project of Tunliu Reservoir in Guangxi as an example, aiming at the engineering geological problems existing in each dam and building during the operation of the reservoir, the permeability of the dam body, dam foundation and abutment rock and soil mass, the filling quality of the dam body, and the weathering state of the dam foundation and abutment rock mass are found out, which provides geological data and suggestions for the danger removal and reinforcement design. The geological investigation and evaluation of the foundation (surrounding rock) and material field of each reinforcement, reconstruction or new building are carried out. The key points of geological investigation of danger removal and reinforcement of large homogeneous earth dam reservoir are summarized, and the key technologies of geological investigation are put forward. It can provide reference for the geological survey work of other similar reservoirs.*

Keywords: *Large reservoir, Homogeneous earth dam, Reinforcement, Engineering geological investigation, Key point*

1. Engineering Overview

Tunliu Reservoir is located in Datang Town, Liangqing District, Nanning City, Guangxi. It belongs to the upstream of Bachajiang, a tributary of Yujian River in the Xijiang River system of the Pearl River Basin. With a total storage capacity of 226 million cubic meters, it is a large-scale water conservancy project primarily used for irrigation, with additional benefits including flood control, power generation, and aquaculture. The normal water level of the reservoir is 146.622 meters, categorized as Grade II engineering, with major structures designed at the secondary level. Construction of the reservoir project commenced in October 1958 and was completed and put into operation in 1960. The main structures of the reservoir project currently include the main dam (1), subsidiary dams (15), spillway (1), water diversion tunnel (1), sluice gate (1), main connecting channels (3), and power station [1].

Both the main dam and subsidiary dams are homogeneous earth dams. The main dam has a crest elevation of 152.83 meters, a maximum height of 35.85 meters, a crest length of 170 meters, and a crest width of 5.0 meters. The 15 subsidiary dams are distributed northwest, east, and northeast of the main dam at straight-line distances ranging from 2 to 11 kilometers. Their heights range from 4.9 to 35.72 meters, with 7 of them having heights exceeding 20 meters. The spillway is arranged in an open wide-crested weir, with a crest elevation of 146.622 meters and a net width of 14 meters, extending longitudinally for 72 meters. The water diversion tunnel is a circular reinforced concrete pressure tunnel with a cross-section of 4×4 meters and a total length of 80 meters. The blind flow sluice gate is constructed of mortar masonry, with the bottom elevation of the inlet gate orifice at 141 meters.

2. Regional Geological Background

The area where the project is located lies to the southeast foothills of the remaining ridges to the northeast of the Shiwandashan Mountains. The terrain slopes from southwest to northeast and is categorized as a low hilly terrain. Geotectonically, it belongs to the residual trough of the Qinzhou in the southern activity zone of the South China Plate, known as the Ten Thousand Mountains Fault Depression. This depression is a residual sea trough of the Late Caledonian Rift Zone in the South China Plate and is situated within the influence zone of the Youjiang Fault Zone and the

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Fangcheng-Lingshan Fault. The peak ground acceleration for seismic activity in this area is 0.1g, with a characteristic period of seismic response spectrum of 0.35 seconds and a corresponding seismic intensity of Grade VII.

3. Overview of Engineering Geological Conditions at the Dam Site Area

The dam site area is characterized by gentle slope low mountains and hills, with the terrain gradually sloping from north to south. The valley in the reservoir area generally exhibits a U-shape, while the gorge tends to be V-shaped. The predominant exposed formations consist of Cretaceous (K) sandstone-mudstone and Quaternary (Q) residual slope deposits containing gravelly clay. Additionally, there are colluvial deposits comprising mud, sand, sandy clay, and gravelly sand in the alluvial fan areas. The lacustrine sediment layer mainly consists of silty clay, silty clay with coarse sand, etc.Two fault zones are prominently developed in the area, both of which are non-active faults. These fault zones exhibit good cementation and impermeability properties. The permeability coefficient of the dam fill soil ranges from $i\times10^{-4}$～$i\times10^{-3}$, categorized as moderately permeable. The rock masses of the dam foundation and abutments are predominantly moderately permeable, with some areas exhibiting low permeability. Issues such as seepage in the dam foundation and seepage around the dam exist, although the reservoir water does not corrode concrete. Weak corrosion may occur in the reinforcing steel in reinforced concrete structures and in steel structures.

4. Construction, Operation, and Hazardous Situations

(1) Construction and Operation: Tunliu Reservoir was constructed in 1958 and put into operation in 1960. In 1999, it was classified as a third-class hazardous reservoir after a safety assessment. However, there are no historical records of major disasters such as floods, earthquakes, or geological hazards since its construction.

(2) Hazardous Situations: Since its construction, the reservoir has experienced several hazardous situations. In the 1980s, there were extensive wet areas on the outer slopes of the Peicha Dam and the Hengqu Dam. These areas were later reinforced by adding plastic concrete impermeable core walls to the outer slopes. Additionally, the Gaoji Dam experienced a longitudinal crack measuring 63.8 meters in length and 0.3 to 1 centimeter in width on its inner slope. After reinforcement and thickening, the dam stabilized. Other dams with severe leakage issues were also addressed during the same period. Despite these reinforcements, the highest recorded water level in the reservoir reached 147.26 meters on September 18, 2014, without resulting in hazardous situations. However, the reservoir's hazard removal and reinforcement efforts were not thorough. Consequently, both unreinforced structures and some reinforced structures continue to exhibit varying degrees of safety hazards during operation.

5. Main Geological Issues of the Project

(1) Leakage Problems. ① Most of the early constructed dam fill materials fail to meet the specification requirements in terms of compaction, permeability, and the quality of the main dam's plastic concrete cutoff wall. As a result, the phreatic line of the dam body is generally too high, leading to phenomena such as seepage, leakage, and even dam failure downstream. There is no seepage observed on the dam crest and inner and outer dam slopes of the Tunliu Reservoir. The seepage prevention effect of the main dam's cutoff wall is average. In some cases, the seepage line on the outer slope of certain dams is almost at the same level as the reservoir water level. In specific instances, observations from boreholes on dam shoulders indicate stable water levels located at the contact zone between the dam base and the shoulders. Leakage occurs when water infiltrates from the contact zone between the dam base and the right shoulder.

② Leakage around the dam. Typically, the dam foundation, dam shoulders, alluvial deposits, residual slope deposits, fully weathered layers, intensely weathered layers, and weakly weathered layers serve as the main pathways for leakage around the dam. In the case of the Milin No.1 auxiliary dam of the Tunliu Reservoir, the permeability rate along the 10(5) Lu line on the outer side of the dam body ranges from 5 to 100 meters below the normal water storage level, indicating lower permeability. Similarly, at the Peicha main dam, both the 10 Lu and 5 Lu lines on the left dam shoulder fail to seal off against the normal water storage level, indicating leakage issues. Both dams exhibit leakage problems around the dam.③ Leakage issues in other structures.In the spillway control weir, the foundation comprises intensely weathered rock with high permeability, while certain areas of weakly weathered rock exhibit localized high permeability, resulting in leakage issues that necessitate curtain grouting. Similarly, the foundation of the blind flow sluice gate dam section rests on intensely weathered rock with significant variations in rock weathering, with a permeability coefficient indicating moderate permeability. This situation requires consolidation grouting and curtain grouting to address severe leakage problems.

(2) Dam deformation and stability issues. Early constructed earth dams often lack a filter layer. After reservoir impoundment, seepage-induced deformation easily occurs within the dam body. In severe cases, localized soil may be punctured, leading to subsidence, bulging, collapse holes on the dam surface, or even slope collapse, which could result in major accidents such as dam breaches during flood seasons. According to the permeation deformation judgment results of the cover layer of the Tunliu Reservoir, the dam fill, residual slope accumulation on the dam shoulder, and alluvial deposits often consist of gravelly clay and silty clay, prone to liquefaction-type seepage deformation. For dams like Nantang, Nazao, Hengqu, and Gaoji, there are relatively weak layers of plastic silty clay that affect the dam base's anti-sliding stability. It is recommended to select typical dam sections for calculation and verification.

(3) Slope stability issues. During the process of the dam's hazard removal and reinforcement survey, it is necessary to evaluate the existing slopes and provide recommendations for excavated slopes during construction. The existing slopes of the Tunliu Reservoir mainly include the reservoir bank slopes, dam slopes, and slopes of structures such as spillway slopes, tunnel entrances and exits, blind flow sluice gate slopes, channel slopes, and flood control road slopes. It is necessary to identify factors affecting slope stability, analyze the effects of changes in water level, geological conditions, and construction excavation on various types of slopes. During the construction of dam slopes, temporary slopes formed by excavating the foundation of the front water-stop groove and the drainage prism foundation behind the dam, if not adequately compacted and with a base elevation lower than the water level and close to the water level, can easily lead to sliding at the foot of the slope after excavation, endangering dam safety. According to current regulations, an engineering geological evaluation of slope stability should be conducted, and reasonable recommendations for geological parameters and measures for slopes should be proposed.

6. Main Content and Workload of Geological Survey Work

Table 1: Geological Survey Workload Table.

Number	Item		Unit	Workload
1	Geology	1/1000-scale geological mapping	km²	0.5
		1/500-scale geological cross-section mapping	km	6.5
		Survey of 4 earth material sites	group-days	12
		Special investigation of hazards	group-days	8
		Borehole television	m/bh	98.7/5
2	Geophysical Exploration	Vertical reflection wave testing method	detection points, shots	1630
3	Drilling	Mechanical drilling	m/bh	2785.8/93
		Spiral drilling		19/6
		Backpack drilling		75.1/12
4	Sampling	Undisturbed soil samples	sets	221
		Disturbed soil samples		45
		Rock samples		98
		Water samples		7
5	Testing	Pressure (injection) water test	sections	557
		Geotechnical test	sets	204
		Standard penetration test	sets	173
		Heavy dynamic cone penetration test	m	0.2
		Compaction test	sets	40

During the preliminary design phase of the reservoir hazard removal and reinforcement project, geological survey and testing work were conducted based on the comprehensive utilization of previous survey results. This aimed to review the hydrogeological and engineering geological conditions of the reservoir project area, analyze the geological causes of hazards, inspect dam fill quality, and provide geological data and physical-mechanical parameters for the design of hazard removal and reinforcement of the reservoir dam. The main contents of the survey work for the hazard removal and reinforcement phase of Tunliu Reservoir include: (1) Reviewing the existing hazards or engineering geological problems of the dam, further investigating the permeability characteristics of the dam body, dam foundation, and dam shoulder rock and soil mass, as well as the compaction quality of the dam body and the weathering status of the dam foundation and dam shoulder rock mass. (2) Conducting geological survey and evaluation of the foundation (surrounding rock) of structures such as water diversion tunnels, spillways, which require reinforcement, reconstruction, or new construction in this preliminary design survey. (3) Investigating the availability of various natural building materials required for the project. The completed main workload of the engineering geological work is summarized in Table 1.

7. Key Points of Geological Survey

(1) Collection of Reservoir Construction, Operation, and Hazardous Situation Data: Due to the long operation time of reservoirs, it is essential to comprehensively collect data on reservoir construction, operation, and hazardous situations. This includes relevant geological information, dam construction details, deformation during dam operation, seepage monitoring data, incident occurrence and emergency response measures. This information guides the arrangement of survey work, with particular focus on areas where hazards have occurred in the past, which should be emphasized during both surveying and construction processes.

(2) Accuracy of Geological Mapping: Reservoirs constructed in the early stages have been in operation for many years. For instance, Tunliu Reservoir has been in operation for 60 years, making it challenging to detect certain geological conditions and phenomena. Therefore, geological mapping work needs to be more precise and meticulous. Geological mapping for hazard removal and reinforcement projects differs from that of new reservoirs. The focus is mainly on the dam site area, including the surface condition of the dam (cracks, settlement, seepage, biological cavities), lithology, geological structures, unfavorable structural surfaces on the left and right dam shoulders (inclination, location, nature, extension length, and relationship). Additionally, targeted mapping of natural building materials is necessary as their reserves and quality directly impact construction investment. If reserves do not meet construction requirements, it may be necessary to search for new material sites during construction, which can significantly affect construction.

(3) Strict Adherence to Relevant Regulations: Strict adherence to relevant regulations and standards for geological surveying of dam hazard removal and reinforcement projects is crucial. This includes compliance with regulations such as the "Code for Geological Investigation of Water Resources and Hydropower Engineering" (GB50487-2022)[2]. Survey stages, arrangement of survey work, technical methods, and survey depth should fully consider the characteristics of hazards and risks while also meeting the requirements of current standards.

(4) Targeted Arrangement of Exploration Work: Survey work should be arranged based on the type of dam and impermeable engineering, the type and severity of hazards, relevant geological factors, operational environment, and time requirements. The arrangement of survey work and technical methods should be distinctly targeted and adaptable[3]. ① Tunliu Reservoir, based on the main engineering geological problems, strategically arranged exploration of 93 boreholes in areas such as the dam body, structures, and slopes, with reasonable spacing between exploration points. ② Drilling on existing dam bodies differs from drilling for new reservoirs. To ensure the original dam body remains undamaged and no new hazards are left after drilling, boreholes must be strictly sealed after completion, and drilling during flood seasons is prohibited. ③ Rational arrangement of geophysical exploration work is crucial. High-density electrical methods, geological radar, transient electromagnetic methods, etc., are mature techniques for detecting seepage hazards such as emptying under the spillway floor and cracks in the dam body. Emerging technologies and equipment such as drones, unmanned boats, underwater robots, and robotic dogs are gradually being utilized[4]. Tunliu Reservoir utilized methods such as vertical reflection wave testing, high-density electrical methods, and natural source surface wave methods to detect stripping and emptying areas under the spillway, as well as sliding zones and sliding surfaces of the Wenbian subsidiary dam landslide, with good results.

(5) Accuracy of On-Site Drilling Data: On-site data is one of the main bases for evaluating the condition of the dam. Due to the rapid drilling speed through soil, important information can be easily missed. It is essential that the drilling conditions, in-situ test results, and water injection test results reflect the actual condition of the soil as accurately as possible. For rocks, it is crucial to accurately reflect the degree of weathering, especially the presence of weathered interlayers, variations in hardness within rock layers, and significant differences in permeability. These factors can have a significant impact on later design and excavation during construction.

(6) Determination of Rock and Soil Parameters. ① Based on data from each borehole, combined with indoor and outdoor rock and soil test data, statistical analysis of physical and mechanical properties indicators of each fill material in the dam body and dam foundation soil (rock), zoning, and stratification is conducted. This provides a comprehensive and accurate reflection of the permeability characteristics of the dam body, the quality of fill materials, and the weathering status of the dam foundation and dam shoulders. According to relevant regulations, combined with indoor geotechnical

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test results, indoor rock test results, and field survey data, after engineering analogies, proposed recommendations for the physical and mechanical parameters of rock and soil are made. ② When proposing parameters, it is essential to consider the impact of conditions during the initial construction of the reservoir on relevant geological parameters. For example, the lack of large machinery during reservoir construction, poor compaction of fill materials, especially in the upper layer above the normal water level or the surface layer of 5~10m thickness, where uniformity of fill, compaction, and permeability are inferior to lower layers. During the construction of the core wall, there is a risk of slurry flowing through the pores of the soil and seeping from the dam slope, threatening the safety of the dam slope. Therefore, when proposing geological parameter recommendations, zoning should be provided, considering the significant differences between upper and lower parts of the dam body.

(7) Targeted Geological Recommendations: The rationality of survey recommendations during the hazard removal and reinforcement phase, and whether they accurately reflect the current engineering geological problems of the dam, directly affects the effectiveness of excavation during construction. As most dam impermeability measures currently adopt the method of pouring plastic concrete impermeable core walls, grooving on the dam body for pouring imposes high construction requirements. Due to the poor quality of the soil itself, during concentrated rainfall periods, the moisture content of excavated dam soil increases sharply, leading to a decrease in shear strength. If the construction process is not controlled properly, it can have irreversible effects on the stability of the dam. Therefore, when providing survey recommendations in the early stages, there should be both general recommendations for common engineering geological problems in the main dam and subsidiary dams, as well as targeted measures for specific issues present in each dam.

8. Conclusion

The geological survey work during the phase of remediation and reinforcement of large-scale hazardous reservoirs is crucial for engineering construction. In the preparatory stage, it is necessary to fully collect data on problems during the construction and operation periods of the reservoir, as well as information on past incidents and their resolutions. During the survey phase, strict adherence to relevant regulations and standards is required, and various methods and equipment should be used to accurately identify existing engineering geological problems. In the reporting stage, accurate descriptions of various rock and soil characteristics, engineering geological features, and their impacts on construction need to be provided. Additionally, recommendations tailored to both the common and specific geological issues of the reservoir project need to be proposed to provide survey support for the smooth progress of the construction phase and the safe operation of the reservoir. In this project, it is recommended to promote the practice of providing geological parameter recommendations for different sections of the dam where significant differences exist in geological conditions.

Looking ahead, the accuracy of geological surveys is crucial for the future automation, prediction, and timely warning of reservoir hazards. It also plays a key role in the intelligent operation of reservoir projects throughout their lifecycle.

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