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Safety Assessment Technology of Concrete Gravity Dams

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Abstract. Most reservoir dams in China were built before the 80s of last century, the issue of long-term security had become increasingly prominent. In recent years, with the "high dam, large reservoir, long water diversion" water conservancy project overall construction, safety assessment of some major water conservancy projects will become a major problem for a long time. Taking some gravity dam as an example, this paper introduced and summarized the safety assessment technology of concrete gravity dam, which would provide reference for safety evaluation and technical development of concrete dam in the future.

1. Introduction

China is the country with the largest reservoir dams, dikes and water transfer projects in the world. As of 2013, more than 98,000 reservoir dams have been built. 85% of the dams and other projects have been in operation for more than 30 years, and about 1/3 of them have been in operation for more than 50 years. The long-term safety problems of water conservancy projects have gradually emerged, mainly due to the deterioration of engineering structures such as cracking, freezing and thawing, dissolution, carbonization, aging problems, increased leakage, insufficient flood control standards, and reduced stress and stability safety margin.

When the project has problems, such as the design does not meet the requirements of the specification, the construction quality does not meet the design or specification requirements, the performance parameters of the disease defects are reduced, the operating conditions are greatly changed, and the old and new specifications are different, a safety assessment is required. The following is a detailed description of the safety assessment technology for concrete gravity dams using a project as an example.

2. Research background

A concrete gravity dam was built in the 1930s. The maximum dam height is 91.7m and the total length is 1080m. There are 60 dam sections. The dam from left to right 9#～19# is the overflow dam section, 21#～31# is the power generation dam section, and the rest is the retaining dam section.

Due to the poor construction technology level and poor construction quality when the dam is built, there are some serious defects in the dam construction. It is found that the concrete strength is low, the dam body is divided into blocks, resulting in poor dam body integrity. The upward pressure is high, and the aging phenomenon caused by leakage, frost heaving and chemical dissolution continues to develop. The dam has been in operation for nearly 70 years under adverse conditions. Despite the subsequent construction and reconstruction, and the continuous maintenance and reinforcement for many years, the defects of the dam have been treated to a certain extent, and the aging process of the dam has been alleviated. However, the low-strength concrete strength, leakage, high pressure, corrosion and frost heaving affect the long-term safety of the dam, and it is urgent to fully evaluate the safety of the dam.

3. Technical route

The completion time of this project is relatively early. During the period, it has undergone continuous construction, reconstruction, post-repair and reinforcement, and a large number of scientific research and demonstration work. Therefore, the safety assessment needs to be based on engineering design, construction, safety monitoring and testing and other relevant information, and comprehensively analyze and summarize the previous research results, and carry out the necessary testing, calculation and analysis to evaluate the dam safety. The main research work includes analysis and review of dam safety inspection opinions and related research progress at home and abroad, engineering flood and flood control capacity evaluation, engineering geological analysis and evaluation, dam observation results analysis and evaluation, dam stability and stress state evaluation, metal Structural evaluation, hydraulic machinery and electrical engineering evaluation, as well as strength, aging and durability evaluation of concrete materials.

4. Safety assessment highlights and related technologies

4.1. Design flood control safety review

Due to the congenital deficiency in the design stage of the project and the changes in the hydrological and engineering application conditions, the operational parameters of the reservoir are the content of debates in previous dispatch meetings. The limited water level, the highest regulated water level and the downstream flow of the reservoir have been changed several times and are not fixed until an upstream reservoir is completed, and the joint design of the two reservoirs is completed. In this flood control safety assessment, the storm flood characteristics and flood composition characteristics were analyzed first. The design flood review was carried out using conventional methods and flood random simulation. Then according to the design flood, storage capacity curve, discharge curve and other review results and flood control principle, the actual flood control capacity is evaluated by comparing the water level with the design flood control characteristics. The problems in the flood control safety of the reservoir include the use of remote sensing technology to retest some of the storage capacity curves. The extension between 264.0 m and 267.7 m is still derived from the actual storage capacity curve, which is an uncertainty factor for flood control safety; The existence of reservoirs and ponds and dams in the basin has a great influence on the runoff and catchment of the basin. The reservoir storage of large floods is not yet clear. The accuracy and reliability of flood forecasting need to be verified; In the design flood control calculations, all power generation and outflows are included, which does not meet the existing specifications. Therefore, there are still some problems in flood control basic materials and flood control forecasting. The flood control calculation does not meet the existing norm requirements, and the existing flood discharge capacity of the reservoir cannot meet the flood discharge requirements of the once-in-a-lifetime flood.

4.2. Engineering geological conditions evaluation and review of mechanical parameters

The rationality of engineering geological conditions and selection of mechanical parameters of rock and soil were evaluated from the aspects of regional structural stability, geological analysis of engineering area and stability of dam foundation rock mass. The basic intensity of the project area is VII degree, and the seismic horizontal acceleration of the site surface with a 50% surpassing probability of 1% is 0.131 g. The dam foundation has a single lithology and consists of the Permian deep metamorphic conglomerate with thick to thick layered structure. In addition to the influence of the F67 large fault zone, the 34#～36# dam section has better engineering geological conditions and high compressive strength of the rock mass, which can meet the dam bearing requirements. Most of the foundations of the

35# and 36# dam sections are crushed rocks (breccia), which are unfavorable to the overall anti-sliding stability. It is a control dam section with anti-sliding stability. Therefore, the selection of the shear-off parameters of the dam foundation is more critical. This safety assessment did not carry out on-site exploration work, mainly based on the supplementary exploration and test results in 1973, and analyzed the consultation opinions of the 1997 Geological Parameters Review Conference. It is generally considered that the value of the shear-off parameters of the dam foundation is reasonable, that is, the shear index of the dam foundation concrete and the type II rock mass in the non-fault dam section is recommended to use f'=1.2, c'=1.0; The Class IV rock mass in the structural fracture zone adopts the shearing parameters f'=0.85, c'=0.5 MPa; the 34#～36# dam section has been deep excavated, and shear strength indicators can still be used in the shear strength index of Class IV rock mass.

4.3. Analysis of safety monitoring results

The dam observation system mainly includes external deformation and seepage observation. In the long-term operation process, the observation methods and equipment are continuously updated and modified, and the operational status of the dam can be basically grasped. In terms of dam deformation, the deformation of the dam is still within the normal or empirical control range. The “double peak” phenomenon in the early horizontal and vertical displacements is obviously weakened after reinforcement, but the frost heaving effect still exists. There is still some time-dependent deformation in the horizontal and vertical displacement of the dam, and the aging displacement still develops at a certain rate and has not stabilized. In terms of dam foundation pressure, the longitudinal pressure coefficient of the dam foundation measured in 2005 except for the 22# dam section is less than 0.2, compared with the historical water level measurement, there are nearly 67% of the longitudinal uplift of the dam section and 43% of the lateral uplift of the dam section. Except for the vertical uplift of the 22# section and the horizontal uplift of the 35# dam section, the other dam sections have not increased much. In terms of dam leakage, the leakage of dam foundation at high water level in 2005 is compared with the previous water level measurement. The leakage of dam foundation of 36#～39#, 43# and 54# dam sections is obviously reduced, and other sections are not obvious. The total leakage of the dam foundation is also correspondingly reduced; the leakage of the dam body in each dam section is significantly reduced. Through the analysis of the monitoring data from 1997 to 2005, it is believed that there is no abnormal phenomenon that endangers the overall safety of the dam, and the working condition of the dam is basically normal.

4.4. Dam stability and stress analysis

The special reason for the anti-sliding stability is that three longitudinal joints are set up to divide the dam cross section into four parts, which seriously weakens the integrity (Figure 1). The presence of longitudinal joints has an adverse effect on the stability and safety of the dam. This safety assessment firstly uses the rigid body limit equilibrium method to review the dam's anti-sliding stability. The research results show that when the influence of longitudinal joints is not considered, the safety factor of anti-sliding stability under basic combined conditions (normal water storage level) is K'=2.82, which is slightly smaller than the standard requirement of K'=3.0, the dam's anti-sliding stability and safety margin is insufficient, which is also consistent with the previous research results (K'=2.66~2.93); The calculation results of other working conditions all meet the requirements of the specification; if considering the influence of long-term leakage and dissolution on the density of the dam, the study found that when the density of the dam is reduced from 2350 kg/m^3 to 2300 kg/m^3, the safety factor of anti-sliding stability is reduced by about 1.4%.

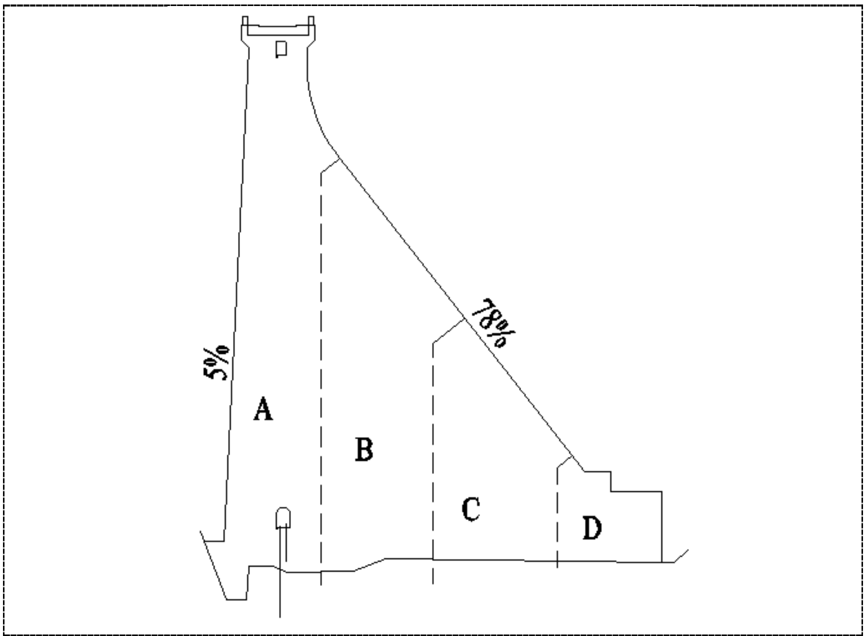

Figure 1. Sectional view of dam retaining section

Considering the influence of longitudinal joints, the nonlinear finite element method is used to analyze the stress and stability of the dam. The results show that the stability safety coefficient of the dam is reduced to some extent. The stress stability of the dam is obviously affected by the longitudinal joint friction coefficient. When the friction coefficient is assumed to be f=0.4, the safety coefficient of dam anti-sliding stability under the normal water storage level and the check flood level is reduced by 1.65% and 3.21% respectively; When the coefficient of friction between the longitudinal joints is less than 0.6, different degrees of vertical tensile stress will occur along the longitudinal direction of the longitudinal joint. The smaller the friction coefficient, the larger the tensile stress value; with the increase of the friction coefficient of the longitudinal joint contact surface, the dam's integrity is obviously enhanced. When f=0.8, the analysis results under static conditions are close to the overall result. In order to evaluate the real working behavior of the dam, the whole process simulation analysis of the dam structural safety degree and the longitudinal joint is carried out. The 47# dam section is selected as the research object. Firstly, the temperature coefficient of the concrete of the dam is 0.0043 m2/h, the coefficient of linear expansion is 7×10-6 ℃-1, and the macroscopic elastic modulus of the concrete is 11.0 GPa. Then the whole process simulation analysis of the actual construction process of the dam was carried out, and finally the nonlinear overload analysis was carried out. The calculation results show that considering the influence of stress history and longitudinal joint, the hydraulic overload coefficient is 1.11 (winter) and 1.14 (summer), regardless of stress history and longitudinal joint influence, the overload coefficient is 1.67. For example, the gravity dam with good quality in the same section constructed according to the existing design level and construction level has an overload coefficient of 3.26, reflecting that the dam safety margin is significantly lower. Combining the results of the above various research methods, the dam's anti-sliding stability and safety margin are low. In particular, poor integrity leads to further deterioration of its stability and stress state.

4.5. Dam concrete material strength, aging and durability

The quality of concrete is evaluated through data analysis during construction period and statistics of post-core core sampling results. According to the construction record and operation and maintenance records during the construction period, from the statistical results of the average cement dosage and average compressive strength of concrete poured from 1939 to 1944 (table 1), it can be seen that the quality of pouring in the initial stage of construction is good, accounting for 17.7% of the total concrete. Concrete with a guarantee rate of more than 80% accounted for 73.2%; the quality of concrete poured after 1942 was poor, accounting for 56.7% of all engineering concrete, and 12.5% of the concrete has a guarantee rate exceeded 80%. In 1969, 1970, 1977, 1986 and 1991-1992, several core drilling tests were carried out. The results show that the core sample acquisition rate is low, the average strength of the core sample is 21~26 MPa, and the minimum strength is 7~11 MPa, the maximum strength is 38 ~ 53MPa, the average dispersion coefficient is 0.33, indicating that the concrete is very uneven. Statistics and analysis of defects and diseases affecting concrete durability such as leakage, cracks, freeze-thaw, frost heaving, etc. are carried out. The fundamental cause of dam durability is leakage, which causes corrosion and compactness of concrete and keeps the concrete in a saturated state. In winter, concrete is damaged by freezing, the surface layer falls off, deep frost heaves, and the top of the dam rises, which aggravates the aging of concrete. The main channels of leakage are dam concrete defects and weak interlayers, cracks, joints and construction joints, which cause the concrete to suffer from erosion, freezing and thawing and frost heaving. Leakage, dissolution, and freeze-thaw, frost heaving damage usually occur at the same time and increase each other, resulting in continuous aging of concrete and continuous reduction of mechanical properties. Therefore, to curb the rapid deterioration of dam concrete caused by severe leakage is the primary problem that should be solved in the dam reinforcement plan.

Table 1. Concrete Pouring Parameters from 1939 to 1944.

Year	Average cement consumption (kg/m^3)	Average compressive strength at 91 days (MPa)	Amount of concrete to be poured annually (10^{4}m^3)	Accumulative amount of pouring concrete (10^{4}m^3)	Guarantee rate of 80% strength （MPa）
1938	—	—	3.0	3.0	—
1939	273.5	25.1	11.1	14.1	21.0
1940	282.9	18.0	20.4	34.5	12.5
1941	268.5	13.3	29.0	63.5	9.6
1942	265.9	11.0	50.9	114.4	8.1
1943	219.0	8.42	32.3	146.7	6.4
1944	214.4	7.0	18.2	164.9	5.2
1945	—	—	5.5	170.0	—

5. Conclusion

This paper introduces the characteristics of dam safety assessment technology, discusses the technical route of concrete gravity dam safety assessment, and takes a concrete gravity dam built in the 1930s as an example, introduces the ideas and key points of the safety assessment of concrete gravity dams and the main technical means adopted in detail. The research results reveal the main safety problems of concrete gravity dams such as poor concrete mass and integrity, dam anti-sliding stability and low structural safety margin, prominent dam leakage problems, poor concrete durability and insufficient dam flood discharge capacity. It also provided reference for the safety assessment of old dams and insecure dams.

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