DESIGN AND SECURITY ANALYSIS OF HIGH ASPHALT CONCRETE CORE ROCK-FILL DAM

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ABSTRACT

The dam of Quxue Hydropower Station, located in the asymmetrical narrow and steep valley, is the highest asphalt concrete core rock-fill dam in the world. The maximum dam height of the dam is 173.2m, which exceeds the applicable scope of the existing technical specifications. By the special research on the key technologies such as anti-seepage structure for dam, dam material partition principle, deformation compatibility of core wall at steep slope and anti-seepage safety of core wall joints, the technology solutions for the construction of ultra-high asphalt concrete core wall rock-fill dam are proposed, whose application in the engineering have achieved good effect. Relevant achievements have also promoted the further development of asphalt concrete core rock-fill dam technology in China.

Keywords : *Quxue Hydropower Station; asphalt concrete core rock-fill dam; asphalt concrete mix ratio; deformation coordination*

1. INTRODUCTION

Asphalt concrete has been widely used because of its excellent anti-seepage performance, strong adaptability to deformation and self-healing of cracks. Roller compacted asphalt concrete core wall has good anti-seepage performance and strong ability to adapt to deformation, and can adapt to the uneven settlement of foundation and dam body [1].With the gradual improvement of asphalt concrete construction and paving technology, more and more high earth rock-fill dams with asphalt concrete core wall anti-seepage are used. Yele dam is the highest asphalt concrete core rock-fill dam in China, with the maximum dam height of 124.5m [2]， The highest asphalt concrete core dam built in Austria is the Finsterntal dam, with a height of 149m, but its core wall is only 96m; Storglomvatn dam in Norway, with a height of 125m and its core wall is 123m. At present, the dam height of the existing asphalt concrete core rock-fill dam is basically below 150m, and the applicable range of the dam height specified in the current technical standards is not more than 150m. When the dam height is more than 150m, special demonstration should be made [3].

This paper introduces the design of the 173.2m high asphalt concrete core rock-fill dam, and through the special technical demonstration, puts forward the technical scheme suitable for the construction of the over 150m high asphalt concrete core wall rock-fill dam. The research results can be used for reference for similar projects in the future.

2. SUMMARY

2.1 Engineering survey

Quxue hydropower station is located on the main stream of Shuoqu River, the largest tributary of Dingqu river. The project area is located in Derong County, Ganzi Tibetan Autonomous Prefecture, Sichuan Province. It is about 50km away from the county highway of Derong and 126km away from Shangri La County, Diqing Prefecture, Yunnan Province. The hydropower station is developed in a mixed way. The dam site is located about 6.5km upstream of the plant site. It is a medium-sized hydropower project mainly for power generation, taking into account environmental and ecological water consumption, developing tourism and other comprehensive benefits. The normal water level of the reservoir is 2330m, the total storage capacity is 132.6m^3, and the total installed capacity of the power station is 246MW.

The river closure of the power station was completed on January 31, 2014, the dam construction was completed on December 31, 2016, and the water storage was started in February 2017. On July 30, 2017, both units were put into operation for power generation.

2.2 Natural condition

The dam site of the power station is located in the deep cut mountain and canyon area where the river is relatively smooth and straight is oblique to the strike of the rock stratum, so the valley belongs to oblique valley. The section of valley is in the form of asymmetric "V": the overall slope of the left bank is more than 65 °, the right bank is in the form of steps with steep and gentle slopes and the bedrock is exposed. The lithology of the dam site area is mainly medium thick ~ massive marble fine crystalline limestone, which is a shallow metamorphic rock formed by regional metamorphism. The rock structure is loose and easy to be weathered due to metamorphism, but the dissolution is poor. The karst type of the dam site belongs to the valley type. Because the annual rainfall in the project area is small and the mobility of groundwater is weak, the karst in the dam site area is generally not developed. In the mountain on the right bank of the dam site area, the dissolution fissures and karst pipelines are developed, and the karst pipelines are all full filled by the gray white calcareous volatiles and purplish red mud. The quaternary system is composed of colluvium, proluvium and terrace materials, which are mainly distributed in the area of gentle slope and riverbed. The Holocene alluvial deposit in the riverbed is mainly composed of gray to brownish gray sand gravel and boulder locally, with a thickness of about 14m to 39m. The basic seismic intensity in the dam site area is VIII.

3. DESIGN OF ASPHALT CONCRETE CORE ROCK-FILL DAM

3.1 Division principle of dam materials

Considering the requirements of structural function, dam slope stability, dam material strength, dam body permeability, compressibility and other aspects of Quxue ultra-high asphalt concrete core rock-fill dam, the dam material uses the basalt fusion breccia mined by the Nubaxue quarry and the weakly weathered and slightly weathered basalt fusion breccia excavated in the hub area. The saturated compressive strength of basaltic fused breccia is 116 MPa ~ 125mpa, and the softening coefficient is 0.86, which meets the requirements of dam filling.

The deformation of dam materials shall be coordinated to minimize the adverse effect of dam deformation on asphalt concrete core wall, and at the same time, the requirements of dam material seepage and reverse filtration protection and structural function shall be considered. The asphalt concrete core wall whose height is 132m is a flexible force transmitting structure. In order to control the deflection and deformation during the construction and operation period, special attention should be paid to the design of the filling indexes of the transition materials and the rock-fill materials at the upstream and downstream of the core wall. In addition, the left bank slope of the Quxue dam site is steep, and the working conditions of the core wall and its contact surface with the base are poor. In order to minimize the deformation of the dam body at this part and improve the working conditions of the core wall and its contact surface with the base, a rolling and mold increasing area is set at the contact part of the bank slope with the left bank slope steeper than 1:0.5, so as to improve the filling index of the dam materials and make the modulus of the dam body transition in gradient to reduce the impact of the steep slope on the foundation, which can reduce the amount of the dam body's uneven deformation near the core wall of the left bank.

3.2 Partition design of dam body

The dam crest elevation is 2334.2m, the dam crest width is 15.0m, the dam crest axis length is 219.85m, the maximum dam height is 173.2m, and the core wall height is 132M. The upstream slope of the dam is 1:1.9, and the upstream dam body is combined with the upstream cofferdam. The downstream dam slope is provided with a zigzag dam access road with a pavement width of 10.0m. The dam slope between pavements is 1:1.3 and a comprehensive slope ratio is 1:1.841. From the upstream to the downstream, the dam building materials are: upstream dry masonry slope protection, rock-fill Ⅰ area (roller compacted and mold increased Ⅰ area), upstream transition layer Ⅱ area, upstream transition layer I area, asphalt concrete core wall, downstream transition layer Ⅰ area, downstream transition layer Ⅱ area, rock-fill Ⅱ area (roller compacted and mold increased Ⅱ area), rock-fill Ⅰ area and downstream dry masonry slope protection.

The thickness of upstream and downstream transition layer Ⅰ is 2m, and the thickness of upstream and downstream transition layer Ⅱ is 2~4m. The top elevation of the left bank rolling and mold increasing area is 2305.00m, with a slope of 1:0.5 to the right bank at a width of 5.0m from the concrete base and with a slope of 1:0.5 to the riverbed at the upstream and downstream respectively. The asphalt concrete core wall adopts the rolling type, the top elevation of the core wall is 2333.0m, and the top thickness is 0.6m. The slope ratio of core wall upstream and downstream is 1:0.0035. A 3.0m-high enlarged foot is set at the bottom of the core wall and smoothly connected with the upper core wall. The thickness of the enlarged foot of the maximum dam height section changes from 1.5m to 3.0m. Design indexes of dam material filling on Quxue dam are listed in Table 1, and typical cross section of dam body division is shown in Figure 1.

Table 1 : Design indexes of main fillers of dam body

Name	ρ d (g/cm³)	P (%)	K (cm/s)	dmax (mm)	<P10 (%)	<P5 (%)	<P0.075 (%)
Upstream Rockfill I	≥2.32	≤21	10^{-2}~10^{-3}	800	10~25	<15	<5
downstream Rockfill I	≥2.32	≤21	>10^{-1}	800		<10	<5
downstream Rockfill II	≥2.35	≤20	10^{-1}~10^{-2}	800	10~20	<10	<5
transition material I	≥2.35	≤20	≥10^{-3}	60	—	25~40	≤5
transition material II	≥2.32	≤21	≥10^{-2}	150	—	15~25	3~5
Rolling and mold increasing I	≥2.35	≤20	10^{-2}~10^{-3}	800	10~25	<15	<5
Rolling and mold increasing II	≥2.38	≤19	10^{-1}~10^{-2}	800	10~20	<10	<5

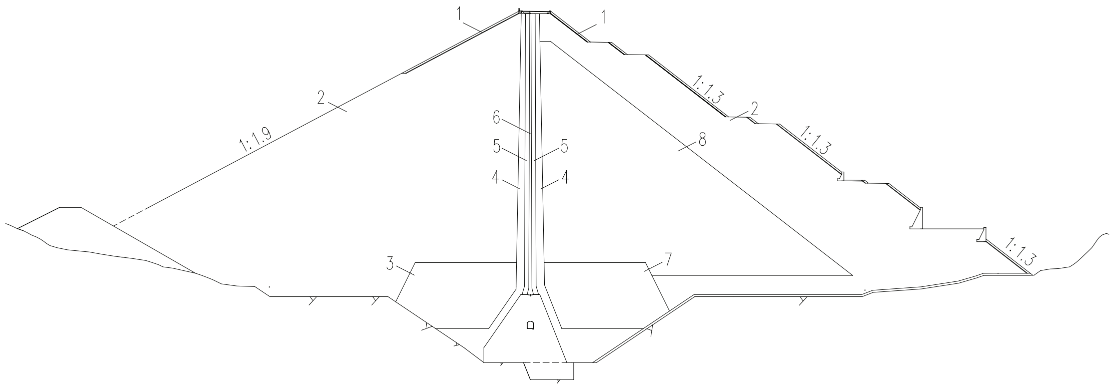

Figure 1 : Typical cross section of dam body

1—Dry stone pitching; 2—Rock-fill Ⅰ; 3—Rolling and mold increasing Ⅰ; 4—Transition layer Ⅰ; 5—Transition layer Ⅱ; 6—Asphalt concrete core wall; 7—Rolling and mold increasing Ⅱ; 8—Rock-fill Ⅱ

3.3 Seismic measures

The basic seismic intensity of the project site is Ⅷ. Due to the dam height, narrow river valley and steep bank slopes on both banks, in order to ensure the safety of the dam under earthquake conditions and reduce the impact of earthquake damage, the following seismic measures have been adopted for the dam:

(1) Dam zoning: According to the characteristics of stress and deformation, topography and geological conditions of the dam body, the dam body shall be divided reasonably, and the stone materials with good grading and performance shall be used for filling construction, and the rolling standard shall be properly improved. The core wall is asphalt concrete with good flexibility which have crack self-healing ability and strong adaptability to vibration and deformation.

(2) Safety superelevation of dam crest: Considering the height of seismic surge and the actual situation of the project and the experience of the project, the seismic settlement is reserved to make the dam crest elevation meet the requirements of super elevation during the earthquake, and no overtopping of reservoir water occurs.

(3) Dam crest structure and dam slope: In order to improve the integrity and stability of the dam crest during the earthquake and reduce the permanent deformation caused by the earthquake, the width of the dam crest shall be appropriately increased to 15.0m; the two-way polypropylene geogrid shall be laid above elevation 2305.0m; the upstream dam slope above elevation 2300.0m to the dam crest elevation and the downstream dam slope shall be protected with 80cm thick dry block stone.

(4) Asphalt concrete core wall: The connection between the core wall and the base adopts the form of gradual expansion of the core wall thickness, and the contact surface is provided with asphalt mastic and copper waterstop to improve the anti-seepage performance during the earthquake.

4. DAM SAFETY ANALYSIS

4.1 Research on asphalt concrete mix proportion of core wall

The raw materials of asphalt concrete mainly include asphalt, coarse aggregate, fine aggregate, filler, etc. When carrying out the Quxue asphalt concrete mix proportion test, Karamay hydraulic 70 asphalt is used, the coarse, fine aggregate and filler are processed from the limestone in the stock yard, and the local annual average temperature of 14.6℃ is used in the performance test of asphalt concrete core wall.

According to the engineering experience, two sets of parameters, i.e. oil stone ratio B =6.5%, mineral powder content F =11% and B =6.8%, F =13%, are selected firstly. Based on the results of porosity, indirect tensile strength and splitting displacement, the gradation index of asphalt concrete is 0.38. Under the condition that the maximum aggregate size (Dmax=19mm) and grading index remain unchanged (r=0.38), according to different mineral filler content and different bitumen aggregate ratio, four groups of 20 mix proportions are formed. In order to ensure the reliability of the test data, three test pieces were prepared under the same conditions for each mix proportion and 60 test pieces in total. According to the test results of mix proportion, considering the performance of seepage prevention, deformation, strength and construction, safety and economy, and combining with the actual situation of the project, No.13 and No.7 mix proportion are recommended for further performance tests. Recommended mix proportions are listed in Table 2.

Table 2 : Materials and grading parameters of two recommended asphalt concrete mixes

Mix No	Gradation parameters			
	maximum aggregate size（mm）	grading index	Filler content（%）	Bitumen aggregate ratio（%）
13	19	0.38	13	6.8
7	19	0.38	11	6.5

Through the performance tests of tension, compression, bending, water stability and permeability, the two mix proportions show that each performance can meet the requirements of high asphalt concrete core wall. The main performance indexes of the recommended mix proportion of asphalt concrete are listed in Table 3.

Table 3 : Main performance indexes of asphalt concrete with recommended mix proportion

Mix No	density (g/cm^3)	porosity (%)	stretching		Compression resistance		Coefficient of water stability	Bend		Permeability (cm/s)
			Strength (MPa)	strain (%)	Strength MPa)	strain (%)		Strength (MPa)	strain (%)	
13	2.479	1.53	0.60	1.21	3.27	4.37	0.99	0.85	5.12	5.14×10^{-9}
7	2.491	1.78	0.55	1.21	3.12	3.47	0.98	0.92	3.12	4.90×10^{-9}

4.2 Safety analysis of core wall joint structure of seepage control

The dam site area of Quxue hydropower station belongs to the high steep asymmetric valley terrain. The structural form of the joint between the asphalt concrete core wall and the concrete base is directly related to the safety of the dam anti-seepage system. In order to study the anti-seepage safety of the contact part between the asphalt concrete core wall and the base, the model test of the joint of the asphalt concrete core wall was carried out, including the asphalt mastic at the joint part, the type of the contact surface between the core wall and the base, whether the core wall and the base are equipped with copper water stop, etc. For the joint structure with 30mm thick asphalt mastic and copper waterstop on the surface of arc base, the joint model test of asphalt concrete core wall was carried out under the condition of 14.6 ℃ and 1.5MPa vertical stress, the joint with a shear deformation of 39mm (limited by equipment) can still maintain its impermeability, even if 2.4Mpa water pressure was applied at the bottom of asphalt concrete core wall, no leakage occurred.

The test results show that under the condition of possible stress and deformation at the joint of the core wall under simulated operation conditions, asphalt mastic is set at the joint, and copper waterstop is set at the arc base, and the lower part of the asphalt concrete core wall is enlarged locally, and no leakage occurs at the joint.

4.3 Study on deformation compatibility of asphalt concrete core wall in steep slope

The height of asphalt concrete core wall of Quxue hydropower station is large, the river valley at the dam site is narrow, and the slopes on both banks are asymmetric, especially the cement concrete base slope on the left bank is designed as 1 (vertical): 0.33 (horizontal). During the construction and operation of the dam, the asphalt concrete core wall may have a large shear deformation at the joint of the steep slope, which will affect the anti-seepage safety of the core wall. Therefore, the asphalt concrete core wall should have a large deformation capacity at the joint of the steep slope.

Based on the creep stability modulus obtained from the long-term creep test of asphalt concrete with different mix proportion, a simplified two-dimensional finite element method is used to calculate and analyze the influence of changing the mix proportion of asphalt concrete along the left bank steep slope on the performance of the joint between the core wall and the base. The results show that adjusting the bitumen aggregate ratio has little effect on the deformation and stress-strain of the core wall near the base, which is mainly reflected in the influence on the shear strain. The shear strain increases obviously when the bitumen aggregate ratio is adjusted to 7.4%. When the bitumen aggregate ratio is adjusted to 7.0%, the deformation ability of asphalt concrete is improved to meet the engineering requirements, but the excessive shear strain is not caused.

4.4 Analysis of dam stress and deformation

The three-dimensional finite element method and Duncan E-B model are used to calculate the stress and deformation of the dam body to simulate the process of graded filling and water storage loading. The static and dynamic conditions are calculated respectively, and the main calculation parameters of the model are shown in Table 4.

Table 4 : Calculation parameters of Duncan Zhang E-B model

Specimen name	ρ_d (g/cm^3)	*c*(kPa)	φ_0(°)	$\Delta\varphi$(°)	*K*	*n*	R_f	K_b	*m*
Transition zone Ⅰ	2.35	0	50.8	7.5	901.0	0.30	0.67	358.8	0.23
Transition zone Ⅱ	2.32	0	50.2	7.5	980.8	0.27	0.69	561.1	0.05
Rock-fill area Ⅰ	2.26	0	52.3	8.5	912.0	0.21	0.73	398.2	0.06
Rock-fill area Ⅱ	2.25	0	52.0	8.5	944.1	0.20	0.69	389.3	0.03
Rolling and mold increasing area	2.26	0	52.3	8.5	1003	0.21	0.73	438	0.06
Overburden	2.10	0	44.0	3.8	400	0.45	0.75	250	0.1
asphalt concrete	2.467	320	26.3	0	160.4	0.12	0.40	1035.6	0.99

The results show that:

(1) At the completion of the project, the maximum value of the main stress of dam body is 2.5MPa and 0.95mpa respectively, and there is no tensile stress in the core wall; after water storage, the maximum value of the main stress of dam body is 2.2MPa and 1.15mpa respectively, and the local tensile stress of the core wall is about -0.108MPa, which is less than the allowable tensile strength of asphalt concrete 0.6MPa, and the core wall will not be damaged by tensile force.

(2) During the completion period, the maximum settlement of the dam body is 99cm, accounting for 0.57% of the dam height, and the maximum settlement occurs in the middle and lower part of the dam body. The maximum settlement of the dam after impoundment is 113cm, accounting for 0.65% of the maximum dam height.

(3) During the filling period, the maximum settlement of the core wall is 106cm, and the maximum settlement of the water storage period is 118cm; the maximum horizontal displacement along the river is 17cm, which is located at the top of the core wall. The maximum deflection span ratio of core wall is 1.7 ‰. The maximum stress level of the core wall is 0.48, which is located in the upper area of the middle of the left bank and the area near the bottom of the core wall. The storage period increases to 0.67, which is located in the upper area of the middle of the left bank.

(4) During the completion period, the maximum shear deformation of the core wall and the bank slope base is 3.80cm, and the maximum shear deformation increases to 4.12cm in the full storage period. The maximum shear deformation is located at the top of the left bank. In order to improve the anti-seepage safety of the joint between the base and the core wall, the engineering measures of widening the core wall are taken at the position with large shear deformation.

(5) The results of dynamic time history analysis show that the overall response of acceleration in the dam body is small, but it is obvious in the dam crest area and dam slope, showing whiplash effect. Due to the short time of peak acceleration, it will not cause great harm to the safety of the whole dam. The maximum vertical permanent displacement is 26cm, which occurs near the middle of the dam crest, accounting for about 0.15% of the dam height. The main form of deformation of the dam body after the earthquake is seismic subsidence.

4.5 Analysis of main monitoring results

According to the design of dam type and dam area, the deformation monitoring of dam with multi section and multi elevation is carried out. Up to now, the main deformation of dam rock-fill and core wall is as follows:

(1) The maximum settlement of the dam body is 72.6cm.

(2) According to the array displacement meter monitoring data of the maximum profile of the core wall rock-fill dam (Dam 0+70.00m), since the impoundment of water, the core wall has been displaced to the downstream as a whole, with the maximum displacement of about 9.0CM, between the elevation of 2225-2235m;

(3) The monitoring data of the shear deformation between the left and right bank core wall and the base show that the maximum shear deformation between the left bank core wall and the base of the bank slope is 5.2mm, which is located at the elevation of 2315m;

The above monitoring results show that the dam body settlement accounts for only 0.42% of the maximum dam height; the displacement of the core wall to the downstream is 9.0CM, less than the calculated value; the displacement of the asphalt concrete core wall and the bank slope base along the bank slope is 5.2mm, far less than the calculated value. The deformation values of dam body and asphalt concrete core wall are generally small.

5. CONCLUDING REMARKS

The maximum dam height and the maximum height of the core wall of the Quxue asphalt concrete core wall rock-fill dam, which is 173.2m and 132m respectively, are both the first of the similar projects in the world. In view of the key technologies such as the partition of the dam body, the deformation coordination of the core wall of the steep slope, the anti-seepage structure of the core wall joint, and the anti-seismic of the high asphalt concrete core wall rock-fill dam, through the comparative analysis of the scheme, the model test and the three-dimensional numerical calculation, the solutions are proposed and applied to the Quxue asphalt concrete core wall rock-fill dam. The monitoring data of the dam show that the dam is in safe operation state since the hydropower station impoundment and operation for more than two years. The construction and application of Quxue 173.2m high asphalt concrete core wall rock-fill dam will further develop the excellent dam type of asphalt concrete core wall rock-fill dam, and the relevant technical achievements will also promote the technical progress of asphalt concrete core wall rock-fill dam, and also can improve and supplement the relevant technical standards at the same time.

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