DESIGN OF CONCRETE ARCH DAM FOR JINPING CASCADE 1 HYDROELECTRIC POWER STATION

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Abstract: The study mainly introduces some thoughts, methods and principles of design during the process of design of concrete double arch dam with a height of 305m, primarily including selection of foundation surface, design of shape, calculation of stability, foundation treatment, etc., which are critical technical problems in the design of concrete arch dam.
Key words: foundation surface, weak unloaded rock mass, weak decayed rock mass, dam axis shape design, abutment stability, reinforcing treatment

1 Forword

Jinping Cascade 1 Hydroelectric Power Station is located at the boundary of Yanyuan County and Muli County of Sichuan Province, as the first one in five cascades of hydroelectric development in middle and downstream river sections of Ya-lung River. The multi-purpose project is mainly for power generation, concurrently for flood-prevention, sediment trapping, etc. Installed capacity of power station is 3600MW.

Normal water storage level of the water reservoir is 1880.00m. Total storage capacity is 7,760 million m^3. The Adjustable storage capacity is 4,910 million m^3, as an annual regulating reservoir.

The engineering scale of Jinping Cascade 1 Hydroelectric Power Station is huge. The dam site is located in remote mountains and gorge with high and steep natural valley side, relatively high level of ground stress, strong unloading of rack mass and especially complicated engineering geology. The height of concrete arch dam is 305m, as the No. 1 high arch dam in the world. Fault, deep fractures as well as low wave-speed tension fracture loosening belt, etc. are distributed nearby arch dam abutment. These unfavorable geologic defects will cause the foundation at left and right banks to be asymmetric extremely and deformation of both banks to be non-homogeneous, which will produce adverse impact on the anti-slide stability and deformation stability of arch dam abutment and increase the difficulty of design of concrete arch dam.

2 Main geologic condition in dam site

The dam area is a typical deep cut "V" gorge with relative height difference of 1500.00m～1700.00m. The rock mass is mainly composed of ommon marble, ruin marble, metasandstone, silty sand slate, greenschist as well as lamprophyre. The thickness of marble is about 600m, mainly located in the middle and lower parts of left bank, lower parts of right bank and river bed; green schist is buried deeply 190m below river bed and 350m below the right bank with thickness of higher than 90m; the thickness of sand slate is about 400m, exposed in the left bank between elevations of 1820m.

The rock mass in dam site area is slightly weathered, being featured by typical fracture and interbedded weathering. For rock mass on both banks, except sand slate in elevation of above 1900m on the left bank is partially weathered, no strong wreathing at other positions. The depth of weak weathering of rock mass on both banks is usually less than 20m, which can reach 62m in partial sections, being featured by relatively shallow in right bank and relatively deep in left bank.

The depth of horizontal unloading of rock mass in left bank is relatively high. The unloading of rock mass in right bank is relatively shallow. The horizontal depth of strong unloaded marble in left bank is 15m – 20m. The horizontal depth of weak unloading is 40m – 50m below the elevation of 1720m and 50m – 75m above the elevation of 1720m; the horizontal depth of strong unloaded sand slate at the upper part of the bank slope is 50m – 70m, which could reach 95m at most; The depth could reach more than 200m at most for weak unloading. The horizontal depth of strong unloaded marble mass on slope of easy flow direction in right bank is 5m – 10m. the horizontal depth of weak unloading is 20m - 30m. The overlying stratum at the river bed is of 11.4m – 37.94m thick. The elevation of top surface of bedrock in river bed is 1589.92m～1619.10m. The vertical depth of moderate weathering is 0m -10m; the average elevation of lower limit of weak unloading is 1583.40m (the depth is between 6.94m～36.10m).

The engineering geologic condition in dam site is very complicated. Main geologic faults include fault, interbedding extrusion slippage belt, joint fissure, lamprophyre, deep fractures as well as tension fracture loosening rock, etc. The complexity of geologic condition of dam is rare in and out of the country. These geologic defects have relatively much impact on selection of foundation surface of arch dam and shape design of arch dam.

3 Features of design of Jinping Cascade 1 arch dam

Although the geologic condition of Jinping Cascade 1 Hydroelectric Power Station is complicated, the dam area is provided with favorable topographic conditions for construction of high arch dam. With a height of 305m and total water thrust of bearing of about 12 million tons, the concrete arch dam is featured by high dam, high water thrust, narrow river valley and large engineering scale.

There are some particular engineering geologic problems existing in the dam site, such as fault of f_5, f_8, f_{13} and f_{14}, crack in deep part, interbedding extrusion belt as well as tension fracture loosening rock mass, etc., which have relatively much impact on the selection of foundation surface of arch dam, shape design, behavior of stress on dam body, anti-slide stability and deformation stability of abutment as well as seepage control of foundation, etc. The design of arch dam is mainly established on the treatment of dam foundation. The determination of foundation surface of arch dam must be conducted in combination with the foundation treatment. Therefore, the main principles for design of arch dam of Jinping Cascade 1 Hydroelectric Power Station are:

(1) The depth of horizontal unloaded rock mass at the upper part of left bank is relatively high, which can reach 95m at most; that for weak unloading can reach more than 200m at most. Sand plates exposed on the surface of foundation of nearly 100.0m are of IV_2 type and III_2 type rock mass of weak unloading. The modulus of deformation is relatively low. Simultaneously, faults of f_5 and f_8 exist, the measures and effects of foundation treatment for which directly affect the selection of foundation surface of arch dam. Therefore, foundation treatment measures in medium and high elevations in the left bank must be strengthened to reduce the amplitude of distortion and improve the difference of distortion in left and right banks.

(2) The left bank is an adverse slope. There are faults of f_5, f_8 and f_2, lamprophyre, interbedding extrusion slippage belt and deep fractures in development of dam abutment. There are a large number of NE-SE unloading fissures as well as fissures in the same direction with unloading crack in the unloading belt in shallow surface. The right bank is a bedding slope composed of marbles. There are faults of f_{13}, f_{14} etc. in northeast leaning to mountain as well as bedding green schist lens interlayer in northeast leaning to the outside of the mountain at the downstream in medium gentle angle in the development of dam abutment. The treatment for these faults shall be strengthened to improve the integral stability of arch dam.

(3) The height of arch dam is 305, as the highest arch dam in the world today. Since the geologic condition of foundation is asymmetric, the geometric symmetry of arch dam shall be strengthened by adjusting the center line of arch dam and arrangement for shape of arch dam. And the thrust angle shall be improved as much as possible, which is beneficial for stability of abutment. Simultaneously, considering the factors of alkali activity of concrete aggregate, uneven distortion of foundation, etc., the stress level of dam body shall be lowered appropriately to enable the arch dam to possess relatively strong adaptability to the distortion of foundation and strength the integral safety of arch dam.

4 Dam line of arch dam

There are faults of f_5 and f_8, lamprophyre, deep fractures as well as low wave-speed tension fracture loosening belt, etc. poor geologic conditions in the left bank of dam site. The rive reach is divided into two sections at the I-I line, upstream section and downstream section. The fissure development in the downstream section is numerous with a high density and width of fracture. The scale and number for development of deep fracture in upstream section is less than that in the downstream section obviously. The deep fractures in the upstream section have larger intervals and less width than those in the downstream section. The arch dam is relatively far from f_1 fault in the downstream and the Shoupa Ditch. Therefore, the range for selection of location of the dam line is mainly in the upstream river section, namely from the I-I survey line to the river section of Pushiluogou in the upstream.

In the river section from I-I survey line to Pusiluogou, if the location of dam line is moved slightly to the upstream, the left bank will be far from deep fractures and tension fracture loosening rock mass, which is beneficial for deformation and stability. However, the elevation of exposed sand slate is lowered. The problem of non-uniformity of rock mass and stability in excavation of high slope is prominent, which increased the difficulty of treatment and quantities of f5 fault; the right bank is more closer to Pusiluogou with more difficulties in excavation of dam abutment, which increase the disturbance for excavation of water inlet and is adverse for arrangement of the multi-purpose project. If the location of dam line is moved to the downstream, the utilization of sand slate in upper foundation of left bank will be reduced relatively, however, the tensile and crown in conditions of fracture zone represented by deep fractures and f_5 fault will be intensified and the stress on arch dam and impact on stability of dam abutment will aslo be increased along with the movement of dam line to the downstream. In combination with above analysis, the following will be mainly considered in the selection for position of dam line of arch dam:

(1) Force resisting body of dam abutment shall avoid the parts where type I and II deep fractures develop so as to enable the major dam to be far away from the development zone of deep fractures;

(2) The force resisting body of dam abutment shall avoid the meeting place of f_5 and $_8$ faults as much as possible;

(3) The arch dam shall be arranged at relatively narrow places in river valley as much as possible.

Through comparison and analysis, it is suitable to arrange the location of dam line in the range of river section at the upstream side of I-I survey line, namely, the II-II line will be the dam line of arch dam.

5 Foundation surface of arch dam

In Code for design of concrete arch dam, it is stipulated that excavation of common high dam shall reach fresh or slightly weathered bedrock as much as possible. For project with dam in height of above 200m or with particular problems, special studies shall be conducted in the design. For Jinping Cascade 1 Hydroelectric Power Station, due to the features of weathering and unloading of rock in dam site area, while grading the quality of mass body, slightly weathered ~ fresh class II rock masses shall be degraded to class III_1 rock mass if located in range of weak unloading. The available rock mass on foundation surface of arch dam is also dividied mainly by the strength of unloading of rock mass. Therefore, most of the dam foundations at left bank are on the Class III_1 and III_2 rock masses, Class III_2 and IV rock masses are also contained in the lower part of foundation. Reinforcing treatment shall be conducted to satisfy the requirements for distortion, then the foundation of arch dam can be used.

The elevation of bedrock top in riverbed at dam site is 1589.92 m～1619.10m. The rock mass at the dam foundation is weak unloading ～ slightly fresh rock mass. The elevation of foundation in riverbed of arch dam is 1580m. The depth of horizontal unloading of rock mass in left bank of dam site is relatively high. The depth of weak horizontal unloading can reach 95m at most. If excavation is to be implemented to reach the slighted fresh bedrock without unloading, the quantities of excavation of dam abutment would be very huge. The ground survey work reveals that except sand slate in left bank is to be excavated for weak unloading rock mass, other parts shall be feasible for partial utilization after treatment. Therefore, in selection of foundation surfaces, the following problems are studies mainly:

(1) Range and position of utilization of rock mass subject to lower limit of weak unloading as well as their impact on stress and stability of dam body. (2) In cooperation with the treatment for foundation with geologic defects of fault, lamprophyre, etc., studies are conducted on arrangement of facilities, including force transfer tunnel (wall), gravity pier, concrete pillow, etc. in the upper elevation of left bank; arrangement of thrust pier on the upper elevation of right bank, arrangement of concrete pillow, etc. at the elevation of 1670.0m to improve the conditions of stress, deformation and stability of dam body.

(3) The shape of foundation surface of arch dam shall be smooth as much as possible. The intensity change of different bedrocks shall avoid conflicts as much as possible for fear of producing adverse impact on stress of arch dam.

In combination with measures for treatment of dam foundation, four programs are compiled for foundation surfaces on left and right bank of arch dam for comparison:

Program 1: the azimuth of center line of arch dam is N28°E; part of abutment of left bank in elevations of 1885.0m～1750.0m is in the rock mass subject to lower limit of weak unloading; abutment in elevation below 1750.0m is in the fresh rock mass subject to lower limit of weak unloading; all abutment of right bank is in the fresh rock mass subject to lower limit of weak unloading; in order to ensure the smoothness of foundation surface of arch dam, abutment of left bank in elevations of 1710.0m～1600.0m and of right bank in elevations of 1870.0m～1710.0m are embedded deeply.

Program 2: center line of arch dam is the same with that in program 1; utilization of rock mass subject to lower limit of weak unloading of left bank is the same with that in program 1; parts of abutment in elevations of 1885.0m～1830.0m and 1670.0m～1580.0m of the right bank utilize rock mass subject to lower limit of weak unloading. Abutment in elevations of 1830.0m～1690.0m is arranged on fresh rock mass subject to lower limit of weak unloading.

Program 3: the azimuth of center line of arch dam is rotated for 5° to NE direction based on that in program 1; part of abutment of left bank in elevations of 1885.0m～1690.0m is in the rock mass subject to lower limit of weak unloading; abutment in elevation below 1690.0m is in the fresh rock mass subject to lower limit of weak unloading; parts of abutment in elevations of 1885.0m～1850.0m and 1700.0m～1580.0m of right bank are arranged in rock mass subject to lower limit of weak unloading, abutment in elevations of 1850m～1700.0m is set in fresh rock mass subjected to lower limit of weak unloading.

Program 4: center line of arch dam is the same with that in program 1. Parts of abutment in elevations of 1885.0m～1710.0m of left bank are arranged in rock mass subject to lower limit of weak unloading; Abutment in elevation of below 1710.0m is arranged on fresh rock mass subject to lower limit of weak unloading; parts of abutment in elevation of 1885.0m～1850.0m and 1700.0m～1580.0m of right bank utilize rock mass subject to lower limit of weak unloading; abutment in elevation of 1850.0m～1700.0m is arranged on fresh rock mass subject to lower limit of weak unloading.

In 4 drafted programs for foundation surface, depth of horizontal embedding of abutment at the downstream of arch dam is reduced gradually from 60m or so in program 1 to 40m or so in program 4. Refer to Figure 1 for Elevation View of Arch Dam in 4 Programs for Foundation Surface.

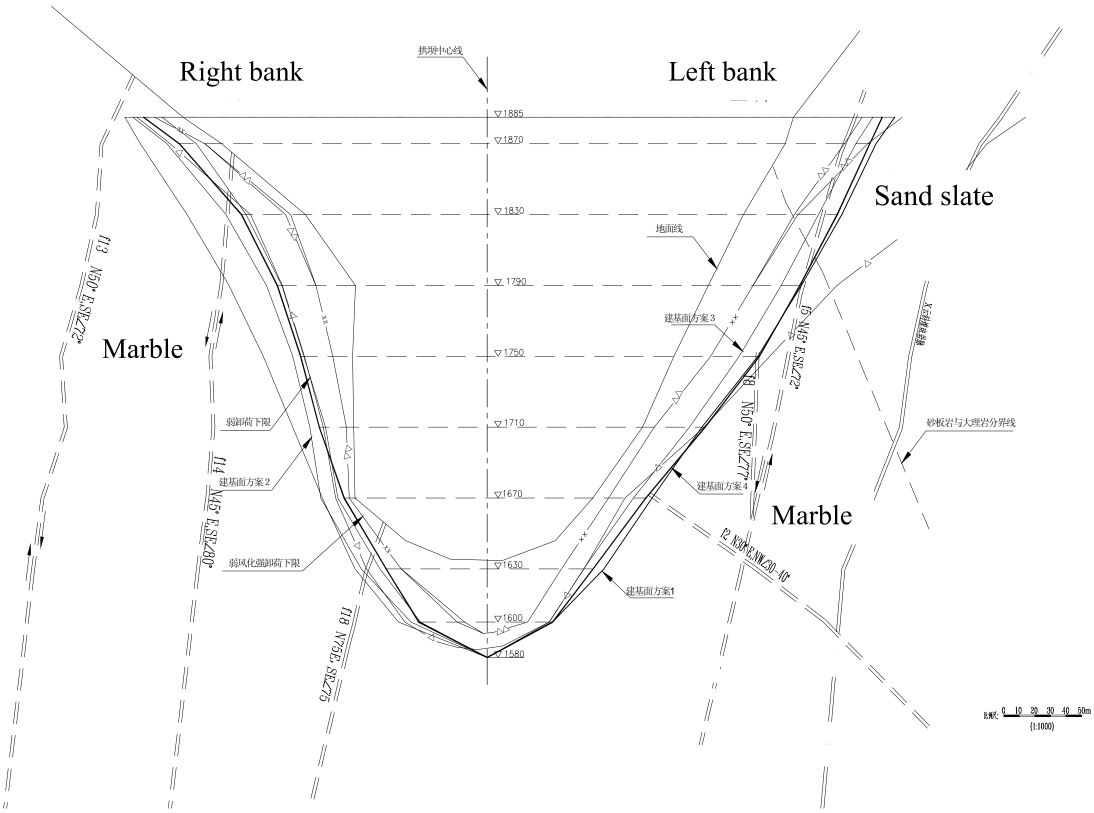

Figure 1 Elevation View of Arch Dam in 4 Programs for Foundation Surface

For all left banks in 4 programs for foundation surface, measures of foundation treatment are adopted to different extents, such as setting concrete pillow, etc. In program 1 for right bank, slightly weathered ~ fresh rock masses are utilized completely basically. Depth of embedding at the ends of abutment in left and right banks is relative high, which cause the quantities of concrete of dam body and foundation excavation to be relatively large. Foundation treatment is required to be implemented also. In addition, the problem of high slope is relatively prominent and the difficulty of construction is relatively great. Therefore, program 1 is not a favorable program for foundation surface of arch dam. In program 2 ~ program 4, it is considered to utilize the rock mass subject to lower limit of weak unloading partially separately in combination with corresponding and effective measures of foundation treatment. Geologic defects of dam foundation are treated to satisfy the requirements for bearing of foundation of high concrete arch dam.

In the four programs for foundation surface, through analysis and comparison in terms of shape design of arch dam, displacement of arch dam, stress, stability of dam abutment, measures of engineering treatment, high slope, difficulty of construction, construction period, construction cost, etc. it is suggested that each program for foundation surface shall adopt necessary and effective measures for foundation treatment due to some particular engineering geologic problems to guarantee the safety of major dam. To compare with the measures of treatment adopted in design at present, the measures for engineering treatment adopted for each program are basically the same without much difference in terms of quantities of processing, construction period, construction cost and conduction difficulty, which has no effect of controlling the selection of program for foundation surface. Affects of quantities of concrete, foundation excavation and foundation treatment of dam body have relatively great impact. Therefore, through comparison from utilization of rock mass subject to lower limit of weak unloading, shape design of arch dam, analysis of stress and stability, measures and quantities of foundation treatment, the program of setting concrete pillow on the upper elevation of left bank based on program 4 is adopted as the program for foundation surface of arch dam.

6 Line style of arch ring and shape of arch dam

At present, shape design of arch dam in and out of the country usually adopts non circular horizontal section with variable thickness, such as three-centered circle, parabola, log spiral, ellipse and uniform curve of second degree, etc. Variant of shape design of arch dam mainly include azimuth of centerline of arch dam, curve of arch crown beam, arch crown, thickness of arch abutment, radius of curvature, etc. Constraint functions include stress of dam body, overhanging degree, central angle, construction stress, etc. Based on almost the same foundation surfaces of arch dam of Jinping Cascade 1 Hydroelectric Power Station, shape design of various arch ring line types are conduced separately, including parabola, mixing curve, uniform curve of second degree, log spiral, multiple centered circle, etc., so as to study the relationship between safety of arch dam and the concrete quantities, stress of dam body, deformation of foundation and integral stability of dam body under the same condition of design and determine a arch ring line type that is suitable for Jinping Cascade 1 Arch Dam. Refer to table 2 for characteristic value of geometric parameter of various arch ring line types of dam.

Table2 Characteristic value of geometric parameter of shape

Line type	Parabola (bidding)	Parabola (feasible)	Mixing curve	Curve of second degree	log spiral	Multiple centered circle
Thickness of crest (m)	16.00	13.00	16.27	17.70	15.03	15.04
Max. thickness of arch crown (m)	63.00	58.00	54.89	55.00	55.79	55.60
Max. thickness of arch abutment (m)	66.00	62.00	59.26	59.33	62.95	62.81
Arc length of center line of umbrella arch (m)	552.23	568.62	576.30	570.10	569.00	568.50
Max. central angle (^{o})	93.12	95.71	93.99	96.41	102.69	100.74
Thickness-height ratio	0.207	0.19	0.180	0.180	0.183	0.182
Arc length-height ratio	1.811	1.864	1.890	1.869	1.866	1.864
Volume of dam body(10,000 m^3)	473.66	435.59	437.55	444.33	451.12	428.63

Due to the particularity of geologic condition of Jinping Cascade 1 project, locations of dam line and abutment of arch dam do not possess the condition of intensive readjustment. Under the condition with the same position of dam line of arch dam, through analysis of stress and stability, displacement, stress of dam body of various arch ring line types shall satisfy the design requirements. The condition of stability of dam abutment is basically the same. Considering various factors of engineering geology, design, construction, etc., in combination with various measures of foundation treatment, through optimized design for plane layout of arch ring and shape of arch dam, parabola arch ring line type is selected finally. Based on the selected ring line type, shape of arch dam can be optimized as per the principle of design for arch dam. Refer to Table 2 for parameters of shape of parabola double arch dam selected in the bidding design.

7 Analysis of stability of abutment of arch dam

Analysis of stability of arch dam is one of main contents of arch dam design. Main structural surfaces of left and right banks that affect the stability of abutment of Jinping arch dam include:

(1) Slip surfaces constituting possible sliding blocks of left bank include $f_5(f_8)$ fault, lamprophyre (X), deep fractures, bedding fracture as well as advantageous fracture in the downstream

force resisting body, etc.; slip surfaces constituting possible sliding block of left bank include f_2 bedding fault, interlaying extrusion slippage belt in $T_{2-3Z}^{2(6)}$ layer, shearing rock mass considering the impact of greenschist lens in $T_{2-3Z}^{2(6)}$ and $T_{2-3Z}^{2(8)}$ layers.

(2) Slip surfaces constituting possible sliding block of right bank include f_{13} fault, f_{14} fault as well advantageous fracture as well as erosion fracture in force resisting body in the downstream; slip surfaces constituting possible sliding block of right bank mainly include possible slip surface formed by bedding developed greenschist lens distributed in marble $T_{2-3Z}^{2(4)}$ layer at random. Therefore, it is assumed that shearing rock mass of bedding developed greenschist lens along $T_{2-3Z}^{2(4)}$ layer will be used as slip surface of sliding block.

Through stability calculation of various combinations of possible sliding blocks of "one steep slope and one gentle slope, two steep slopes and one gentle slope and stepped slopes", it is determined that sliding block of one steep slope and one gentle slope is controlling sliding block of stability of abutment of Jinping Cascade I arch dam. Main calculation results of rigid-body limit equilibrium are as below:

(1) For safety factors of anti-slide stability of all possible combinations of sliding blocks of left bank, all pure frictions are more than 1.30 and all shear frictions are more than 3.50 under various working conditions of osmotic pressure, satisfying the requirements in design control standards;

(2) The sensitivity analysis for occurrence and different design working conditions of slip surface of control sliding block of left bank suggests that when occurrence of each sliding surface changes in the possible range, all safety factors of pure friction and shear friction of various control sliding block satisfy the requirements in specification; under the working conditions of basic combination I and particular combination I, all safety factors of pure friction and shear friction of each control sliding block satisfy the requirements in the specification.

The sensitivity analysis for occurrence and different design working conditions of slip surface of control sliding block of left bank suggests that when occurrence of each sliding surface changes in the possible range, all safety factors of pure friction and shear friction of various control sliding block satisfy the requirements in specification; under the working conditions of basic combination I and particular combination I, all safety factors of pure friction and shear friction of each control sliding block satisfy the requirements in the specification and anti-slide stability of abutment in left bank has no controlling effect.

(3) For safety factor of anti-slide stability of control sliding block formed by special structural surface f13, f14 fault and SN-direction fissure, under two working conditions of osmotic pressure, all pure frictions are less than 1.30, but above 1.00; shear friction is less than 3.50, but above 2.50. Test of three-dimensional geologic mechanical model suggests that after the foundation treatment, under normal load, if dam heel in the upstream cracks above 2P, its nonlinearity overloading multiplying factor K2＝3～4, limit load K3＝7.5; results of nonlinear calculation shall be 2P, K2＝3.5, K3＝7.0 respectively.

For the stability condition of abutment of right bank, affected by $T_{2-3Z}^{2(4)}$ bedding medium gentle layer, the deadweight of rock mass is main acting force in stability analysis. Since SN fracture is not a dominant fracture, simultaneously, in combination with analysis through various methods and means, such as nonlinear finite element calculation, three-dimensional geologic mechanical model test, etc., it is suggested that the integral stability of abutment in right bank satisfies the design requirement basically.

8 Treatment of dam foundation

Treatments of Jinping Cascade 1 Arch Dam mainly include concrete replacement and consolidation grouting. Through treatment of dam foundation, the rigidity and integrity of foundation shall be improved to satisfy the design requirements of concrete arch dam.

(1) Concrete pillow

Sand slate, weak loaded IV2 type and Ⅲ2 type rock masses exposed on foundation surface in elevations of 1885.00m～1800.00m at upper part of left bank has relatively low modulus of deformation. Concrete pillow shall be used to conduct replacement treatment for elevations between 1885.00m～1800.00m. Refer to Figure 2 for basic forms of pillow.

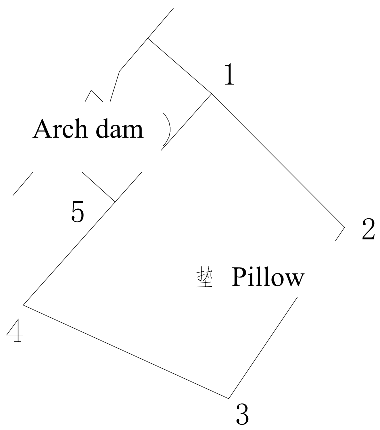

Figure 2 Schematic drawing for locations of pillow and feature point

(2) Consolidation grouting

① Comprehensive consolidation grouting is conduced for rock mass of foundation surface. The range of consolidation grouting is expanded beyond the foundation surface into a range of angle hole-grouting area for 5.00m to the upstream dam and 10.00m to the downstream dam site.

② For weak loaded IV_2 type and III_2 type rock mass, interbedding extrusion belt, deep fractures, fault, lamprophyre and weak rock mass in the force resisting body of abutment of arch dam, treatment of consolidation grouting is adopted.

(3) Replacement of concrete in left bank

Main objectives: lamprophyre and faults of f_5 and f_8 in left bank

For lamprophyre, concrete replacement anti-seepage inclined shaft is adopted and arranged on the center line of curtain along the trend of lamprophyre.

Treatments of f_5 and f_8 fault are divided into two parts, individually exposed part on foundation surface and the deep layer (force resisting body).

① Exposed part on foundation surface

f_5 and f_8 faults are exposed in elevations of 1800.00m～1750.00m. Concrete pillow is used for replacement treatment of fault in combination with the replacement treatment of concrete pillow in upper elevation.

② For f_5 and f_8 faults in excavation slope in deep force resisting body and inside of abutment end, treatment shall be conduced by using the concrete replacement grid system composed of inclined shaft and adit. The horizontal widths of inclined shaft are determined according to the width of fault and all of its lengths are 10.00m. The widths of adit are determined according to the width of fault at the elevation and all of its heights are 10.00m. Simultaneously, for f_5 and f_8 faults in concrete grid composed of inclined shafts and adits in elevations between 1850.00m～1680.00m, treatment of consolidation grouting is adopted.

(4) Replacement of concrete in right bank

① f_{13} and f_{14} faults

Exposed f_{13} and f_{14} faults on foundation surface will be replaced with concrete. f_{13} and f_{14} faults in deep part below the replacement will be treated with concrete anti-seepage inclinded shaft, which will be arranged on the center line of curtain along the trend of fault.

② f_{18} faults

Exposed f18 fault on foundation surface will be replaced with concrete. Fault in deep part below the concrete replacement will be treated with consolidation grouting.

(6) Treatment of other fault

Other faults exposed on foundation surface of right bank will be replaced with concrete. Faults below the concrete replacement will be treated with consolidation grouting.

9 Conclusion

The geologic condition of arch dam of Jinping Cascade 1 Hydroelectric Power Station is very complicated. No matter deep embedding or shallow embedding, the foundation surface of arch dam will encounter particular geologic defects unavoidably. The range of effect of treatment for these geologic defects will affect the safety of arch dam directly. Therefore, treatment of geologic defects of dam foundation by adopting reasonable and effective measures of foundation treatment can satisfy the requirements of high concrete arch dam for loading of foundation and improve the integral safety of arch dam, which is also critical for the design of high concrete arch dam of Jinping Cascade 1 Hydroelectric Power Station.

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