Meticulous simulation and evaluation of seepage control effects at right bank dam foundation and underground powerhouse of Jinping I hydropower station

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Abstract: This case study presents a systematic performance assessment of the seepage control system at the right bank abutment of Jinping I Hydropower Station. By utilizing the in-situ measurements of seepage field, the characteristics of groundwater flow behaviors in the dam foundation and around the underground powerhouse were analyzed. Based on an equivalent continuum method, an anisotropic seepage tensor model of the fractured rock mass in the dam site area was established. Considering the features of topography, geological settings and hydraulic structures, a three-dimensional finite element mesh with complex seepage control structures was generated. A numerical method combining a substructure technique, a variational inequality formulation of Signorini’s type and an adaptive penalized Heaviside function (short for SVA method) is adopted to simulate the three-dimensional seepage field at the dam site. On this basis, the distribution of seepage field during the operation period was predicted, and the performance of the seepage control system was evaluated. Besides, the influence of critically oriented fractures along the direction of NWW on the seepage control effect was also discussed. The methodology presented in this study is useful for understanding the groundwater flow behavior and the performance of the seepage control system in hydraulic engineering.

1. Introduction

The Jinping I Hydropower Station is located in the high mountains and valleys adjacent to the two counties of Muli and Yanyuan in Sichuan Province. It is the middle and lower reaches of the Yalong River where the hydropower resources are most concentrated, and the first class of the fifth-grade hydropower development. The concrete double-curvature arch dam type is adopted, and the underground powerhouse is arranged on the right bank. The geological conditions of the dam area of the first grade hydropower station in Jinping are complex and the rock fracture is very well developed. In order to ensure the safe operation of the dam, prevent the loss of the reservoir water downstream, and maintain the dry working environment of the corridors and the plant area, the project has designed a huge seepage control and drainage system, among which the seepage prevention curtain is extended widely and is surrounded by semi-enclosed structure around the underground plant area. The drainage gallery and drainage hole curtain are set behind the anti-seepage curtain and surround the entire underground powerhouse to ensure that the plant is in a dry working environment. In order to study the distribution of seepage field in the right bank dam foundation and underground plant area under
the conditions of complex geological conditions and seepage prevention and drainage system, and to
demonstrate the rationality of the seepage control scheme, it is necessary to refine the simulate the
seepage control effect of the seepage and drainage systems.

Based on the equivalent continuum model, this paper uses a combination of substructure,
Signorini-type variational inequality and adaptive penalty Heaviside function (referred to as SVA for
short. The specific implementation of the algorithm can be found in [1~3], relying on Jin Pingyi. The
hydropower station has discussed several problems concerning the seepage control effect under the
complex geological conditions in the dam area. First, the characteristics of seepage in the dam area
during the impoundment process were studied, and the permeability of the formation in the right bank
dam area was inversely based on the existing monitoring data. Based on the results of inversion of
formation seepage, the state of seepage field in the right bank and dam area under normal operating
conditions was predicted, and the monitoring measures were evaluated. The analysis results have
important guiding significance for guiding the safe storage of reservoirs.

2. Seepage Monitoring Data Analysis and Rock Mass Penetration Tensor Model

2.1. Rock Formation Permeability and Its Division in Dam Area

The fissures of various types of faults and rock layers in the dam area of the Jinping Hydropower
Station are well developed, and the permeability characteristics have obvious regional and anisotropic
characteristics in space. The zoning rationality of the permeability characteristics of the dam area and
the value of the permeation tensor Accuracy is the basis for the finite element calculation of seepage.
The spatial distribution characteristics of the permeability of the rock mass can be inferred from the Lu
value (Lu) measured in the borehole water pressure test and the development of the fractures in each
area.

The right bank project involves rock masses that are all marbles. The drilling water pressure test
results show that [4]: permeability of rock mass, \( q<1Lu \) accounted for 26.7% of the total pressure of the
right bank, \( 1Lu \leq q \leq 3Lu \) accounted for 40.2%, \( 3Lu \leq q \leq 10Lu \) accounted for 18.3%, most of which
belonged to weak partial micro-permeability; moderately permeable rock mass accounted for 12.9%,
and strong permeable rock mass accounted for only 1.9%. The permeability profile of the dam axis
reveals that the rock mass is strong to moderately permeable except for an elevation of 1640m and a
horizontal depth of 40m; the horizontal depth is between 40 and 165m; the rock mass is a weakly
moderately permeable; the horizontal rock depth is between 165 and 360m. Micro-permeability; 360m
rock mass with micro-permeability. Outside the elevation of 1800m and horizontal depth of 85m, the
rock mass is strong to moderately permeable; the horizontal depth is between 85 and 210m, and the
rock mass is weakly moderately permeable; the horizontal depth is between 210 and 320m; the rock
mass is weak and slightly permeable; 320m The rock body is mainly micro-permeable. On the right
bank, there are hydrogeological structures such as \( f_{13} \) and \( f_{14} \) pressure-torsional faults. These geological
structures have a certain degree of control over the movement of groundwater. The permeability of the
faults is poor, preventing groundwater from migrating from their interior, but along the faults and The
inner flow of the dyke strikes, with fractured zones formed on both sides of the fault, is one of the
main leakage passages, and the f13 fault zone (relative water blocking) of the abutment and the plane
of the NWW towards the water-bearing fracture zone in the upper wall The combination is the main
percolation channel that dredges the groundwater flow on the right bank. Due to the heterogeneity of
water permeability in fractured rock masses, the permeability of the right bank rock mass is mainly
controlled by the NWW pilot water fractures. Therefore, in the permeability zoning of the rock mass
on the right bank, it is not excluded that the rock permeability in the weak permeable rock masses A
strong permeable belt consisting of NWW guide water fissures is revealed. The groundwater in the
right bank has relatively stable sources of recharge, and the groundwater level is generally higher than
the water level in the river.

In general, the hydrogeological conditions of each rock formation in the right bank of the Jinping I
Hydropower Station are complex and the infiltration characteristics are not uniformly distributed in
space. Therefore, the rock formation is divided into several regions according to the development of lithology and joint fractures. The major structural planes are modeled and distinguished by solid elements. The zoning diagram of the permeation characteristics is shown in Figure 1. Because of the deep buried depth of T2-3z1 layer, the surface of the dam site is not exposed, and the calculation result of seepage is not obvious, so it is not involved in the inversion calculation; the T2-3z(5) layer and T2-3z(6) layer are The fissure development is similar, the lithology is the same, and the location of the rock formation is relatively high. Therefore, a region is combined for inversion analysis.

2.2. Seepage Monitoring Data Analysis

After the impoundment of the reservoir, groundwater levels measured by osmometers buried at the bottom of various corridors also change accordingly. The typical osmometer monitor water level is shown in Figure 2. As the reservoir water level rises, the measured value of the osmometer before the curtain rises, indicating that the fracture network of some rock layers in the plant and dam area is mature and the rock mass connectivity is good, with the upstream reservoir As the water level increases, the groundwater level will gradually rise.

On the right bank, the amount of water enthalpy arranged, in the current condition of the water level, plays a role in the WEDB-4 layout in the 1595m elevation drainage corridor. The amount of water measured in the remaining corridors is small, and the amount of leakage is small. In flow feedback analysis, it can only be used as a reference for calculations. The WEDB-4 water quantity monitoring flow is shown in Fig. 3. The WEDB-4 water leakage quantity of the 1595m drainage gallery increases with the increase of the water storage level, but the leakage is always smaller, combined with the permeability profile. The drilling water pressure results show that the overall quality of the rock mass is good, and the fracture network development area with strong partial water permeability forms a complete continuous water curtain under the effect of impervious grouting.
2.3. Calculation of Permeability Tensor in Fractured Rock Mass
The permeability of fractured rock mass depends on the geometry and spatial development characteristics of the fracture. Therefore, by measuring the spatial distribution of cracks (gap width, spacing, attitude, etc.), the statistical analysis method can be used to determine the permeability tensor.
of the rock mass \[^5\].

Assuming that the rock mass has \( n \) groups of structural planes, each group of structural planes are parallel to each other, the average spacing and average opening of the \( i \)-th structural planes are \( s_i \) and \( b_i \), respectively, and the permeation tensor of the rock mass can be expressed as \[^6\]:

\[
K = \frac{g}{12\nu} \sum_{i=1}^{n} \frac{b_i^3}{s_i} \left( \delta - n_i \otimes n_i \right)
\]

Where \( K \) is the permeation tensor of the rock mass; \( \delta \) is the Kronecker Delta tensor; \( n_i \) is the unit normal vector of the \( i \)-th group structural plane.

Assuming that the spatial \( x \)- and \( y \)-axis directions of the rectangular coordinate system coincide with the geographical \( N \) and \( W \) directions, the permeation tensor of the rock mass can be expressed as:

\[
K = \frac{g}{12\nu} \sum_{i=1}^{n} \frac{b_i^3}{s_i} \left[ \begin{array}{ccc}
1 - \sin^2 \alpha_i \cos^2 \beta_i & \sin^2 \alpha_i \sin \beta_i \cos \beta_i & -\sin \alpha_i \cos \alpha_i \cos \beta_i \\
\sin^2 \alpha_i \sin \beta_i \cos \beta_i & 1 - \sin^2 \alpha_i \sin^2 \beta_i & \sin \alpha_i \cos \alpha_i \sin \beta_i \\
-\sin \alpha_i \cos \alpha_i \cos \beta_i & \sin \alpha_i \cos \alpha_i \sin \beta_i & 1 - \cos^2 \alpha_i
\end{array} \right]
\]

Where \( \alpha_i \) and \( \beta_i \) are the inclination and inclination of the \( i \)-th group structural plane (clockwise rotation angle from \( N \) direction).

Due to the partial filling and connectivity problems of the fractures, the statistical analysis method preliminarily determines that the permeation tensor of the rock mass needs to be corrected numerically in order to take into account the direction and value of the percolation tensor.

The modified rock permeability coefficient tensor \( K_m \) is expressed as \[^5\]

\[
K_m = \frac{K}{\sqrt{K_1 \cdot K_2 \cdot K_3}} K_0
\]

Where \( K_1, K_2, K_3 \) are the three main values of the permeability coefficient tensor \( K \) before the correction, and \( K_0 \) is the inversion coefficient of the isotropic permeability of the rock mass.

According to the data of Pingshuo and surface survey \[^4\], the characteristics of the dominant joint fractures in the marble area of the dam area were calculated and the permeability matrix was calculated as shown in Table 1. Since the cracks in the measured data do not provide an accurate evaluation of the fracture opening, the crack opening is taken as 0.1 mm according to the description of the fracture.

| Area | Joint fissure occurrence and spacing | Directional matrix |
|------|-----------------------------------|--------------------|
| \( T_{2-3Z}^{(1)} \) | \( 0.8m \) | 0.7860 -0.1412 -0.1384 |
| \( 0.5m \) | -0.1412 1.0255 -0.1685 |
| \( 0.4m \) | -0.1384 -0.1685 1.3339 |
| \( T_{2-3Z}^{(2)} \) | \( 0.8m \) | 0.8860 -0.0852 -0.2342 |
| \( 0.5m \) | -0.0852 1.0669 -0.2526 |
| \( 0.4m \) | -0.2342 -0.2526 1.1994 |
2018 International Conference on Civil and Hydraulic Engineering (IConCHE 2018) IOP Publishing
IOP Conf. Series: Earth and Environmental Science 189 (2018) 022021 doi:10.1088/1755-1315/189/2/022021

\[ \begin{bmatrix}
0.6332 & -0.0547 & -0.3641 \\
-0.0547 & 1.2251 & -0.1343 \\
-0.3641 & -0.1343 & 1.5260
\end{bmatrix} \]

\[ \begin{bmatrix}
1.0774 & -0.4108 & -0.4726 \\
-0.4108 & 1.2811 & -0.4256 \\
-0.4726 & -0.4256 & 1.3591
\end{bmatrix} \]

\[ \begin{bmatrix}
0.8892 & -0.4241 & -0.3767 \\
-0.4241 & 1.2885 & -0.2704 \\
-0.3767 & -0.2704 & 1.3814
\end{bmatrix} \]

\[ \begin{bmatrix}
0.8749 & 0.4859 & -0.6789 \\
0.4859 & 1.5899 & 0.2605 \\
-0.6789 & 0.2605 & 1.7005
\end{bmatrix} \]

Note: The permeability directionality matrix must be combined with the permeability coefficient derived from the inversion of the area to perform finite element calculations. (3) cracks in each rock formation are NWW fracture groups.

3. Analysis of Seepage Field in Dam Foundation and Underground Plant Area on the Right Bank

3.1. Finite Element Model

Through the analysis of the engineering geological conditions in the dam area and the centerline of the river as the boundary, a three-dimensional integral finite element model of the right bank has been established. The scope of the finite element model is as follows: (a) Taking the upstream boundary about 600m away from the dam axis and the downstream boundary about 1000m away from the dam axis; (b) The groundwater of the left and right banks has its own occurrence characteristics. The two regard the riverbed as the hydraulic connection. In order to reflect the actual hydrogeological characteristics and reduce the model scale, the centerline of the river bed is selected as the left boundary of the model; (c) The minimum elevation of the model is about 580m below the normal water level of 1880m, and the minimum elevation of the model is about 1300m; (d) The upper and lower boundaries of the entire calculation model are about 1600m apart and the right boundary is 750m away from the centerline of the river.

Right bank model to the right part of concrete dam body, seepage prevention curtain (including curtain corridor) in dam foundation and slope, dam foundation drainage corridor and its drainage screen, resistance body drainage hole and its drainage hole screen, main Impervious drainage systems such as geological structures, diversions, water conveyance systems, factories, anti-seepage and drainage galleries, and drainage holes and curtains were simulated. The hexahedron isoparametric elements and partially degraded tetrahedral elements were used for the subdivision. A total of 1521433 elements were divided. There are 630,912 nodes, as shown in Figure 4. Among them, the right bank dam curtain curtain corridors and seepage screens, right bank dam drainage corridors and drainage holes, right bank resistance drainage holes and drainage holes, underground powerhouse main cavern,
water diversion, power generation, tail water system structure plant anti-seepage Curtains and drainage curtain structures are shown in Figure 5.

Fig.4 Three-dimensional integral finite element model of right bank dam, abutment slope and powerhouse

Fig.5 Workshop cavern and seepage drainage system

3.2 Boundary Conditions
The water head submerged area of the dam and the concrete lining section of the diversion tunnel take the boundary of the fixed head, and the water head value is taken as the upstream head; the downstream of the dam is set as the boundary of the water head, and the value is the downstream head; the right side of the model is located in the right bank in the distance from the river channel. The center line is 750 m. The groundwater level is determined by the geological survey data to be 1920m, and the boundary of the water head is taken; the pressure pipe section of the diversion tunnel, the bottom boundary of the model, and the boundary wall of the tailrace surge chamber are taken to remove the water barrier; the upper surface of the model is dewatered The areas beyond the inundation area, the main and auxiliary buildings and the side walls of the main transformer room, the boundaries of the corridors, and the wall surfaces of the drainage holes are all set as potential overflow boundaries.

The permeation coefficient of the anti-seepage curtain is $0.2 \times 10^{-5}$ cm/s according to the water
pressure test provided by the designer after the irrigation curtain inspection hole; considering that the diversion tunnel is a permanent structure, the construction quality of the lining is better than that of the temporary diversion tunnel. In many cases, the permeability coefficient of the diversion tunnel lining is taken as an empirical value of $0.5 \times 10^{-6}$ cm/s under normal conditions.

3.3. Inversion Analysis of Seepage Field

The groundwater seepage field on the right bank of Jinping I Hydropower Station has evolved along with fluctuations in surface water levels, construction processes and other factors. In order to master the permeability of the rock mass in the dam area, it is necessary to carry out inversion analysis of the seepage field.

The inversion method is based on the rock permeability parameters determined during the engineering exploration phase, combined with the actual measured data of the seepage pressure and seepage values, and the comparison between the seepage field analysis results and the actual measurement results using the BP neural network and the genetic algorithm (GABP). The method of combined monitoring and feedback analysis of the change process of the seepage field in the dam area of Jinping I Hydropower Station [7-10] has been widely applied and will not be described here. Determine the percolation parameters and boundary conditions of the rock formation, and comprehensively consider the representativeness and effectiveness of the monitoring data, and select the porch pressure gauge PRG-2, PRG-3, from December 7, 2012 to October 11, 2013. PRG-7, PRG-10, PRG-12, PRG-15, PRG-17 monitoring heads and drainage corridor volume WEDB-4 monitoring flow was used as the inversion analysis target value. The input layer parameters of the BP neural network are a combination of 81 groups of permeation coefficients, and the output layer parameters are a series of calculated values at different times corresponding to the selected monitoring quantities obtained by finite element simulation of the permeation coefficient combinations of the groups.

According to the regional permeability of the Jinping I hydropower station (see Figure 1), and the most likely range of permeability changes, after inversion analysis, determine the permeability coefficient used in Table 2.

| Inversion area number | Area | Permeability coefficient range (unit: $10^{-5}$ cm/s) |
|-----------------------|------|-----------------------------------------------------|
|                       |      | Lower limit  | Upper limit | Inversion coefficient |
| A1                    | $T_{2-3z}^{2(1)}$ | 0.1          | 30.0        | 0.8                   |
| A2                    | $T_{2-3z}^{2(2)}$ | 0.1          | 30.0        | 1.5                   |
| A3                    | $T_{2-3z}^{2(3)}$ | 0.1          | 30.0        | 3.0                   |
| A4                    | $T_{2-3z}^{3(4)}$ | 1.0          | 50.0        | 8.2                   |
| A5                    | $T_{2-3z}^{2(5)}$ | 1.0          | 50.0        | 12.0                  |
| A6                    | $f_{13}$         | 0.1          | 30.0        | 2.0                   |
| A7                    | $f_{14}$         | 0.1          | 30.0        | 2.0                   |
| A8                    | Unloading area   | 1.0          | 300.0       | 100.0                 |

Note: This value must be combined with the permeation directional matrix of the area to perform finite element calculations.
The curtain pressure meter PRG-12 is located on the upstream side of the anti-seepage curtain. Therefore, the water head value at the location is very different from the water level in the reservoir. Figure 6 shows the curve of PRG-12 over time, and the calculated value and monitored value can be seen. The trend is exactly the same, and it is highly related to the upstream reservoir level. Figure 7 is a comparison of calculated and measured values for WEDB-4. As can be seen from the figure, the calculated value is consistent with the monitoring value, and it has a good correspondence with the curve of the reservoir water level change process.

If the finite element calculation of the isotropic permeability coefficient of the rock obtained by the inversion matrix is not considered directly, the influence of the permeability anisotropy caused by the fracture network is neglected, and the difference between the calculated value and the monitored value of the seepage is ignored. Larger, does not reflect true seepage conditions.

In summary, the inversion coefficient obtained from the inversion is in good agreement with the pressure test value, and the permeation directionality matrix of each rock formation can form the permeation tensor of each area to reflect the water permeability of the rock. Uniformity and anisotropy can be considered at the same time as the role of the fracture network in groundwater flow, providing a basis for calculation of seepage field during operation.

3.4. Seepage Field Analysis and Seepage Control Evaluation

In the simulation calculation, considering the study of the seepage field during operation, six kinds of calculation schemes are set, as shown in Table 3.

| Option | Water level /m | Instructions                                           |
|--------|----------------|--------------------------------------------------------|
|        | Upstream water level | Downstream water level |                                   |
| 1      | 1880           | 1646         | Predict normal operating conditions               |
| 2      | 1880           | 1646         | Option 1 + drain hole 50% failure                   |
| 3      | 1880           | 1646         | Option 1+ Curvature permeability increase 2 times   |
| 4      | 1880           | 1646         | Option 1+ curtain permeability coefficient increased by 4 times |
| 5      | 1880           | 1646         | Option 1 + NWW-to-fissure group spacing reduced by 2 times |
Option 1 is the basic plan, which is the predicted normal operating conditions; Option 2 to Option 6 are based on Option 1, and focuses on the following comparative analysis: Option 2 mainly considers the 50% failure of drainage holes; Option 3 and Option 4 mainly focus on the possible uncovered strong permeable belt consisting of NWW pilot water cracks, taking into account the influence of NWW-to-fissure gap spacing on the seepage field; Option 5 mainly focused on the possible uncovered strong permeable belt consisting of NWW pilot water cracks, taking into account the influence of NWW-to-fissure gap spacing on the seepage field; Option 6 When calculating the permeation tensor of each rock, the influence of NWW to fracture group was removed to analyze the control effect of NWW fracture group on the seepage field.

In this paper, Option 1 and Option 6 in the table are used as typical solutions to analyze the results. The necessary results of other projects are only briefly explained. Mainly through the seepage field head distribution and the key parts of the seepage flow analysis of the effects of the osmotic measures. The seepage flow of each calculation scheme is shown in Table 4.

(1) Analysis of Seepage Field Characteristics of Option 1 and Option 6

Option 1 is the normal working condition during operation. The cross section of the plant section and other headlines are shown in the solid line of Figure 8. Affected by the impoundment of the reservoir, when the normal impounding level, the groundwater level in the right bank in front of the impervious curtain is higher. There was a clear downward trend when the free surface passed through the curtain, indicating that the anti-seepage effect of the anti-seepage curtain was significant, preventing the leakage of the reservoir water level from the upstream to the downstream, through the dam foundation anti-seepage curtain, the drainage hole screen and the resistance body drainage. With the joint action of the screens, a large drainage area was formed in the area of resistance, and the free surface overflowed through the third-floor drainage gallery of the plant and overflowed at the bottom of the side walls of the main powerhouse. On the downstream side, the free surface passes through the factory drainage gallery and overflows at the bottom of the side wall of the main powerhouse. The main transformer room is located above the free surface of the seepage. The longitudinal lines of the main and auxiliary plant center are shown in solid line in Figure 9. The groundwater in the mountain reaches the plant area. The elevation of the free surface before the curtain is above 1820m. It falls sharply under the action of the factory curtain and drainage screen, and enters the plant area. The 1730m drainage gallery overflowed, and then it passed through the second gallery of the plant. The bottom wall of the installation hall overflowed, and the underground water in the river overflowed through the third floor of the factory building and overflowed at the bottom wall of the auxiliary building. The seepage and drainage effect of the drainage hole screen is significant, so that a clear landing funnel is formed in the surrounding rock of the plant site. As shown in the solid line of the 1630m elevation flat section of the plant as shown in the solid line in Figure 10, the surrounding seepage field of the factory building has obvious seepage. The water head line is bent at the end of the anti-seepage curtain, the water head line at the curtain is denser, and the water line behind the curtain is higher. Sparser, the head value before and after the curtain is very large, and the head of the plant cavern area is low, indicating that the anti-seepage curtain and the drainage hole screen in the plant area play a powerful role in reducing the head of the higher groundwater in the mountain and ensure the underground powerhouse hole. The surrounding rock of the chamber group has a lower pore water pressure value.

Option 6 focuses on the effect of NWW-fractured fractures on the seepage field. When calculating the permeation tensor of each rock, the influence of NWW-fractured fractures is eliminated. The free surface and head distribution are shown in dotted lines in Figures 8~10. Compared with Option 1, the water head difference assumed by the anti-seepage curtain in Option 6 is reduced. The water head line is slightly sparse at the anti-seepage curtain, indicating that the effect of the anti-seepage curtain is reduced and the free surface is slightly decreased. But the general trend has not changed much. It can be seen from the flat cuts of the 1630m elevation plant that the water head before the curtain of the plant in Option 6 is significantly reduced, indicating that the difference between the permeability of
the rock formation and the curtain is reduced and the seepage control pressure of the anti-seepage curtain is reduced without considering the NWW fracture. At the same time, it can be seen from Table 4 that, regardless of the NWW fracture group, the percolation of the various parts of the dam area is significantly lower than that of Option 1. In summary, the NWW-to-fissure group has a significant impact on the seepage-proof effect of the anti-seepage curtain and the seepage volume of the dam area.

Fig.8 Section cross section of the power plant section isometric

Fig.9 Main and auxiliary factory center longitudinal profile etc. Head line
Option 2 shows the situation where the drain hole is 50% failure. As can be seen from Table 4, the drainage capacity is reduced due to partial failure of the drainage hole, so the seepage flow of the dam foundation and the gallery of the factory is slightly reduced, but the seepage curtain has a strong anti-seepage effect. The performance and drainage screens are densely arranged. Therefore, even if the drainage screen part fails, groundwater can still find a nearer drainage boundary overflow through a long path. Therefore, the seepage flow in most areas does not change much, but it needs attention. Keep drainage holes with lower arrangement elevations, prevent excessive infiltration pressure or infiltration and destruction.

Option 3 and 4 simulate the expansion of the seepage curtain's permeability coefficient by 2 and 4 times respectively. It can be seen from Table 4 that the seepage flow of the drainage gallery of the dam foundation and the plant area is significantly increased compared to that of the scheme 1, while the resistance is increased. The body fluids and the main sub-factory's seepage flow did not change significantly. It shows that the arrangement of the seepage control measures is reasonable, and a considerable safety margin is reserved. Under the condition that the curtain impervious performance is greatly weakened, through the joint action of the dam foundation curtain drainage system and the factory curtain drainage system, the resistance area and workshop can still be ensured. There was no significant change in the seepage volume of the area, ensuring that the surrounding rock mass of underground powerhouse caverns has a lower pore water pressure value.

Option 5 focuses on the effect of strong permeable zones consisting of undisclosed NWW guide water fissures on the seepage field. Take NWW to fissure group spacing reduced by 2 times. From Table 4, it can be seen that, compared with Option 1, the seepage flow of each drainage gallery is significantly increased except for the outside of the factory building. It shows that when the gap between NWW and fissures is reduced, the gap between the permeability of rock formation and curtain becomes larger, highlighting the seepage prevention effect of the curtain, but increasing the drainage pressure of the drainage gallery. Therefore, the design of drainage capacity at key locations should take into account possible unexplained NWW fracture effects.

Table 4 Permeability of each calculation option (unit: m³/d)

| Site                | Option 1 | Option 2 | Option 3 | Option 4 | Option 5 | Option 6 |
|---------------------|----------|----------|----------|----------|----------|----------|
| Dam foundation      | 640.9    | 622.0    | 781.2    | 935.3    | 996.7    | 529.4    |
| Drainage            |          |          |          |          |          |          |

Fig.10 Plant 1630m elevation flat cut surface head line
4. Conclusions
Based on the measured seepage data, a sub-structure, variational inequality, and self-adaptive penalty function method (abbreviated as SVA method) were used to invert the permeability characteristics of the fractured rock mass on the right bank of Jinping I Hydropower Station. The analysis of the seepage field under the complex geological conditions and the seepage control structure and the rationality of the seepage control program were evaluated and the following conclusions were drawn:

(1) Under normal operating conditions, the seepage control system composed of the anti-seepage curtain and the drainage hole screen has a significant effect, and the free surface has significantly decreased before the resistance body and the plant area, forming a wide range of landing funnels. And it ensures that the surrounding rock of the underground powerhouse has a lower pore water pressure value, which is beneficial to the stability of the surrounding rock, and provides a dry environment for the construction and operation of the underground powerhouse.

(2) The NWW fissure zone has a significant impact on the seepage control effect of the seepage curtain and the seepage volume of the dam area and is one of the main seepage channels.

(3) Under the condition that the anti-seepage effect of the anti-seepage curtain is weakened or part of the drainage hole curtain fails, due to the rational arrangement of the seepage control measures, the impact on the seepage field of the workshop area is not obvious, and it can still ensure that the seepage flow of the plant cavern does not change significantly.

Acknowledgments
This research was supported in part by the National Nature Science Foundation of China (51709237) and the science and technology plan project of Department of Water Resources of Zhejiang Province (RA1604).

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