Design of seepage control system around a large-scale underground powerhouse: A case study of Baihetan Hydropower Station

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Abstract. Located at the lower reach of Jinsha River, the Baihetan Hydropower Station is the world’s second largest hydropower station. It consists of a double-curvature arch dam with a maximum height of 289 m and two large-scale underground cavern systems on each side of the bank, which is the largest underground cavern system of hydropower project in the world. The construction site is characteristic of complex geological conditions, and multiple interlayer staggered zones are developed between different strata. Based on the results of on-site packer tests, the interlayer staggered zones generally have a higher hydraulic conductivity than the surrounding rocks, and therefore may act as the potential seepage flow path. Since the underground powerhouse is close to the upstream reservoir and there is a large difference of water level between the upstream and downstream reservoirs, the control of groundwater flow in the surrounding rocks of the underground caverns becomes one of the key technological issues. A large-scale seepage control system including grout curtains and drainage curtains was designed around the underground powerhouses. Besides, the hydraulic conductivity of the interlayer staggered zones was systematically characterized and several anti-seepage tunnels were designed and constructed specifically for the control of seepage flow through the interlayer staggered zones. On this basis, numerical simulation of seepage field was conducted, and the results show that the designed seepage control system is effective in lowering the groundwater level and reducing the amount of seepage around the powerhouse.

1. Introduction

Southwest China is rich in hydropower resources. In recent decades, a large number of hydropower projects located in deep valleys have been constructed in Southwest China, such as Ertan, Xiaowan, Xiluodu, Jinping I, Dagangshan, Baihetan, etc. Affected by the topographical and geological conditions, most of these hydropower projects adopt the design of high arch dam and underground powerhouses. In order to meet the operation requirements of multiple large-scale units, the underground powerhouses are often excavated on a large scale. For example, the size of the powerhouse of Baihetan Hydropower Station reaches 438m × 31m × 88.7m (length × width × height). In addition to the powerhouse, the underground power generation system also includes a series of underground caverns, such as the transformer room, the tailrace surge chambers, and the tailrace tunnels. These underground caverns crisscross each other, forming a large-scale underground cavern system inside the mountain.
After impounding, the surrounding rocks of the underground caverns normally suffer from high groundwater pressure and large pressure difference. Besides, the underground powerhouse areas of many hydropower projects have developed faults, shear zones, and other unfavorable geological structures, which further increase the difficulty of seepage control. In order to reduce the leakage of the underground powerhouse and improve the permeability stability of the surrounding rock, the seepage control system including grout curtains and drainage curtains are generally designed around the underground powerhouses. Anti-seepage tunnels and other measures may also be used to cut-off the potential seepage path. The seepage control measures of large hydropower projects are often large in scale. Taking the Baihetan Hydropower Station as an example, the length of grout borehole drilled from grout tunnels in underground powerhouse area exceeds 900,000 m. Nevertheless, abnormal seepage phenomena such as concentrated leakage and seepage failure still occur from time to time in hydropower engineering practice \(^{[1-4]}\). Therefore, the control of groundwater flow in the surrounding rocks of the underground caverns becomes one of the key technological issues affecting the safety and stability of underground caverns.

This case study takes the seepage control system around the underground powerhouse on the left bank of Baihetan Hydropower Station as an example to present the design and evaluation of a seepage control system around a large-scale underground powerhouse. On the basis of the geological features of the underground powerhouse area on the left bank, the design principles and layout of the seepage control system including grout curtain, drainage curtain, and anti-seepage tunnel was presented. Particular concerns are paid to the seepage control of interlayer staggered zone C\(_2\) to prevent potential concentrated seepage flow. Numerical simulation of the seepage field was further performed under the condition of normal pool level to understand the seepage flow behavior around the powerhouse. Besides, the field measurements accumulated during the first impounding was also analyzed, and the field measurements together with the simulation results was used to evaluate the effectiveness of the seepage control system.

2. Site characterization

2.1. Project Description
Baihetan Hydropower Station is located in Ningnan County of Sichuan Province and Qiaojia County of Yunnan Province on the Jinsha River. It is the second cascade hydropower station on the lower reach of Jinsha River. The installed capacity of Baihetan Hydropower Station is 16000 MW. It will be the world’s second biggest hydropower station after the Three Gorges Dam, upon completion. The normal pool level of the reservoir is 825m, and the total storage capacity is about 20.627 billion m\(^3\).

The Baihetan Hydropower Project is mainly composed of a concrete double-curvature arch dam, flood discharge and energy dissipation facilities, as well as power generation systems on the left and right banks. The maximum dam height of the concrete double-curvature arch dam is 289m. Two large-scale underground powerhouses are arranged on each side of the river, and each one is equipped with 8 hydro-generator units with a single unit capacity of 1000 MW. The underground cavern system, which includes the machine hall, transformer room, surge chambers, and tailrace tunnels, is also the largest underground cavern system of hydropower project in the world. The sizes of the machine hall and transformer room are 438.0 m × 34.0 m × 88.7 m (length × width × height) and 368.0 m × 21.0 m × 39.5 m (length × width × height).

The impounding of the reservoir began on April 1, 2021. After that, and the reservoir water level was gradually raised from 640m to 760m by about 120 m in 50 days. After that, the reservoir water level fluctuated around 760m preparing for power generation. The first two generators will begin operating in late June 2021.

2.2. Geological Settings
The main strata outcropping at the dam site consist of a series of basalt of Emei mountain group (P\(_2\)β). The Emei mountain group (P\(_2\)β) basalt is divided into 11 rock layers (P\(_2\)β\(_1\)~ P\(_2\)β\(_{11}\)). The rock layers
mainly contain tholeiitic basalt, cryptocrystalline basalt, microcrystalline basalt and amygdaloidal basalt, typically with a layer of tuff developed on the top of each rock unit [5-6]. The columnar jointed basalt, in which the joints are organized as a regular array of polygonal prisms, is fully developed among the P3β1 layer [7]. The rock formations dip gently towards the upstream and right bank, with an attitude of N35°–55°E, SE/15°–18°.

The basalt in the powerhouse area has developed interlayer staggered zones between each two rock layers, and the attitude of the interlayer staggered zones is consistent with the rock layers. The interlayer staggered zones cut across the left bank main powerhouse cavern on the upstream and downstream side walls. The basalt is generally a low-permeable rock mass, while the interlayer staggered zones have a higher hydraulic conductive comparing to the surrounding rocks, and may act as potential groundwater flow paths. Several faults (such as F17, F19, and F20) are also developed in the left bank powerhouse area.

3. Seepage control system design

3.1. Grout system
A large-scale seepage control system including grout curtains and drainage curtains was designed and constructed around the underground powerhouses. As shown in Figure 1, the underground powerhouses on both banks of the Baihetan hydropower stations are arranged in the mountains on the upstream side of the dam axis, and the grout curtain is located on the upstream side of the underground powerhouse. The seepage control system around the underground powerhouses on the left and right banks are both firmly connected to the seepage control system in the dam foundation.

![Figure 1. Layout of the Baihetan Hydropower Project.](image)

The grout curtain in the left bank powerhouse area is executed from five tunnels with about 50~70m vertical distance. The elevations of the five grout tunnels are about 825m, 760m, 706.6m, 653m, 590 m, respectively, as shown in Figure 2. The bottom elevation of the grout curtain in the left bank powerhouse area is controlled by the interlayer staggered zone C2 to ensure that the grout curtain extended 5m below the interlayer staggered zone C2 and with a maximum bottom elevation of 550m.
3.2. Treatment of potential seepage path

The interlayer staggered zone C₂ cuts across the left bank powerhouse on the upstream and downstream side walls. Since its hydraulic conductivity is larger than the surrounding rocks [6, 8], the interlayer staggered zone C₂ may act as a potential concentrated flow path, and affect the stability of underground powerhouse. Although the grout curtain is extended below the interlayer staggered zone C₂, the cement grouting from the lowest grout tunnel may have limited effect on the interlayer staggered zone C₂.

In order to further control the seepage flow through the interlayer staggered zone C₂, an anti-seepage tunnel is designed and constructed. The anti-seepage tunnel for interlayer staggered zone C₂ is located at the bottom of the grout curtain of the left bank underground powerhouse area, with a total length of 778.57m. The axis of the anti-seepage tunnel is located 10m upstream of the grout curtain constructed from the lowest grout tunnel. The anti-seepage tunnel was excavated along the direction of the interlayer staggered zone C₂. The excavation section was 4m×4.5m, and the slope was 5.95%-20.62%. After the excavation and concrete lining is completed, curtain grouting is carried out on the downstream side wall to set up a short curtain which is connected with the main grout curtain. Besides, the curtain grouting is also conducted on the bottom of the anti-seepage tunnel with the borehole length of 10m. Finally, the second-stage concrete is backfilled in the entire section of the anti-seepage tunnel after the curtain grouting is completed and examined.

3.3. Drainage system

In addition to grout curtain and anti-seepage tunnel, a large-scale drainage system around the underground powerhouses was also designed and constructed to lower the underground water level and reduce the leakage in the underground caverns.

The drainage hole arrays in the underground powerhouse area are arranged between the penstock shaft (with steel lining) and the underground powerhouse, and it’s located about 60.0 m downstream of the grout curtain. Drainage holes of 90 mm in diameter and 3 m in spacing were drilled from fix layers of drainage tunnels excavated at elevations of 759.40m, 706.00m, 652.28m, 617.40m, 590.15m, and 555.00m, respectively. The excavation section of the drainage gallery is 3.0m×3.5m. The drainage tunnel and the grout tunnel are combined at the elevation of 825m. The drainage tunnels LPL2–LPL4 at the elevation of 759.40m, 706.00m, 652.28m is basically arranged parallel to the grout tunnel, and the drainage tunnels LPL5–LPL7 are generally around the powerhouse and transformer room.
4. Numerical modelling

4.1. Computational model
A three-dimensional finite element mesh was generated for the simulation of the groundwater flow through the left bank powerhouse area, as shown in Figure 3. The hydraulic structures (such as the arch dam, the underground caverns, the headrace tunnels, and the tailrace tunnels), the seepage control system (such as the grout curtain, the drainage curtain, and anti-seepage tunnel), and the geological settings (such as the strata and interlayer staggered zones) were all well represented.

The finite element code THYME3D [9] was adopted for simulations, in which the discretized parabolic variational inequality (PVI) algorithm for steady-state groundwater flow problems [10] were implemented. This code has been widely verified with laboratory tests and field data [1, 4, 6].

![Figure 3. Finite element mesh for the left bank of Baihetan Hydropower Project.](image)

4.2. Hydraulic conductivity
To obtain the hydraulic properties of the rock masses at the dam site and powerhouse area, a large number of borehole packer tests were conducted in the left bank slope. According to the packer test results and geological condition, a zonation of permeability is created. The equivalent Lugeon value of each zonation is determined based on the various packer test results, so that only 10% of the packer test results in its zonation are larger than the equivalent Lugeon value. The permeability of each zonation or geological structure is then calculated from the equivalent Lugeon value through Hvorslev formula [11], and further used in the numerical simulation, as listed in Table 1.

| Classification | Zonation/ Structure                | Equivalent Lugeon value (Lu) | Permeability (cm/s) |
|----------------|------------------------------------|-----------------------------|---------------------|
| Rock mass      | Medium permeability zone           | 31.49                       | 3.99×10⁻⁴           |
|                | Moderate permeability zone         | 8.36                        | 1.06×10⁻⁴           |
|                | Weak permeability zone             | 3.30                        | 4.19×10⁻⁵           |
|                | Low permeability zone              | 0.92                        | 1.17×10⁻⁵           |
| Discontinuity  | Interlayer staggered zones C₂     | 16.32                       | 2.07×10⁻⁴           |
|                | Interlayer staggered zones C₃     | -                          | 2.00×10⁻⁴           |
|                | Interlayer staggered zones C₃₋₁   | -                          | 2.00×10⁻⁴           |
|                | Fault F₁₇                         | -                          | 1.50×10⁻⁴           |
| Hydraulic      | Grout curtain                      | 0.25                        | 3.17×10⁻⁶           |
| structure      | Concrete block                     | -                          | 1.00×10⁻⁷           |

4.3. Boundary condition
The normal pool level (825m) was specified on the upstream surface of the dam and the ground surface submerged in the reservoir. Similarly, the downstream surface of the subsidiary dam and the ground surface submerged in the downstream river channel were prescribed with the corresponding
water level, which is 600 m. The base of the model and the transverse lateral boundaries perpendicular to the river were assumed to be impermeable. According to the groundwater level observation at boreholes, the lateral boundary condition on the mountain sides of the model is taken as fixed water head boundary, and the fixed groundwater level is taken as 950 m.

The drainage holes drilled downwards in the lowest drainage tunnel were imposed with a hydraulic head equal to the floor elevation of the connected drainage tunnel. The remaining drainage holes, the ground and dam surfaces above the upstream and downstream water levels and the boundaries of the drainage tunnels were all taken as the potential seepage boundaries satisfying the Signorini’s complementary condition [110].

4.4. Seepage flow behaviour

Figures 4(a) and 4(b) show the hydraulic head contours of the seepage field at the transverse and longitudinal section of left bank machine hall under the condition of normal pool level. One observes from the figures that the phreatic surface is relatively high on the upstream side of the grout curtain. The phreatic surface drops slightly when passing through the grout curtain, while the drainage curtain leads to a significant depression of the phreatic surface. Besides, the upper part of the powerhouse and transformer room are in the dry state.

![Figure 4](image.png)

**Figure 4.** Hydraulic head distribution and phreatic surface at the transverse and longitudinal section of machine hall (unit: m).

The numerical results indicate that, under normal operating conditions, the seepage control system is effective in lowering the groundwater level and reducing the pore water pressure in the surrounding rocks of powerhouse. The above results show that the seepage field around underground powerhouse area under the condition of normal pool level has been effectively controlled.

5. Field measurements

5.1. Hydraulic head

The piezometers numbered from UPzc-GL6-1 to UPzc-GL6-4 were installed in the boreholes drilled downwards from the grout tunnel LGL6 at the elevation of 590 m. Besides, another 8 piezometers numbered from UPzc-PL6-1 to UPzc-PL6-8 were installed in the boreholes drilled downwards from the drainage tunnels LPL6 at the elevation of 590 m, as shown in Figure 5. The piezometers numbered from UPzc-GL6-1 to UPzc-GL6-4 are located on the downstream side of the grout curtain.

The measured hydraulic heads at the piezometers install from the grout tunnel LGL6 and drainage tunnels LPL6 are shown in Figure 6. It can be seen from the figures that as the water level of the reservoir rises, the measurement of UPzc-GL6-1 to UPzc-GL6-4 installed from grout tunnel increased gradually, and has a good correlation with the changes of the reservoir water level. On the other hand, the measurement of UPzc-PL6-1 to UPzc-PL6-8 installed from drainage tunnels generally remain unchanged. It indicates that in the process of reservoir impounding, the groundwater level is
gradually raised near the grout curtain. However, under the influence of the densely drilled drainage hole in the drainage tunnels, the impounding of reservoir basically has no effect on the piezometers installed from drainage tunnels LPL6. The results show that the groundwater level near the left bank underground powerhouse has been effectively controlled.

**Figure 5.** Layout of piezometers deployed in the grout and drainage tunnels at the elevation of 590m.

**Figure 6.** Measured hydraulic heads at the piezometers whose locations are shown in Figure 5.

### 5.2. Discharges

The weirs were installed on each grout and drainage tunnels of various elevations for collecting the seepage flow rates out of the tunnels. Figure 7 shows the variations of the measured discharges of the drainage tunnel LPL7 at the elevation of 555m, as well as the grout tunnels LGL3 and LGL4 at the elevation of 706.60m and 653.00m. Other measurements are not available due to the influence of construction water supply.

**Figure 7.** Measured discharges of drainage and grout tunnels.

It can be seen from the figure that the seepage flow rate of the drainage gallery LPL7 changes significantly with the reservoir water level, and the two have a good correlation. During the impounding process of the reservoir, the seepage flow rate of the drainage gallery LPL7 gradually increased, at May 21, 2021 when the reservoir water level reaches 760m at the first time, the seepage flow rate of the drainage tunnel LPL7 is about 330L/min. The seepage flow rate of grout tunnels LGL3 and LGL4 is relatively stable and less affected by the increase of reservoir water level, indicating that the grout system has played a great role in the control of seepage flow. At May 21,
2021, the total seepage flow rate out of the various grout and drainage tunnels in left bank powerhouse was about 500 L/min.

6. Conclusions
This study focuses on the design and evaluation of the seepage control system around the left bank underground powerhouse of Baihetan Hydropower Station. The underground powerhouse area is characteristic of complex geological conditions. Based on the geological characteristics, a large-scale seepage control system was designed and constructed around the powerhouse. Particular concerns are paid to the seepage control of interlayer staggered zone C2 to prevent potential concentrated seepage flow. Numerical simulation was further performed to obtain the seepage field characteristics and to evaluate the performance of the seepage control system.

The numerical results show that drainage curtain leads to a significant depression of the phreatic surface on the powerhouse area, and the upper part of the powerhouse and transformer room are in the dry state. The field measurements show that during the first impounding, the piezometers installed from drainage tunnels generally remain unchanged, and groundwater level near the underground powerhouse has been effectively controlled. Both the numerical results and the field measurements demonstrate that the seepage control system is effective in lowering the pore water pressure and limiting the amount of discharge in the powerhouse area.

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