Optimization design of a large-scale seepage control system at a high arch dam site

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Abstract: The Baihetan Hydropower Station, located in the lower reaches of Jinsha River in southwest China, is the second largest hydropower station in the world. The site is characteristic of extremely complex geological and hydrogeological conditions, with fractures, faults, and shear zones that make water tables wedge-shaped. A large-scale seepage control system that contains grouting curtains covering an area of 780,000 m² and 12,300 drainage holes, together with concrete plugs, were designed to control the seepage in the dam foundation and in the underground powerhouse areas as the reservoir water level will be raised by 225 m during operation. How to assess the performance and optimize the design of seepage control system becomes a key technological issue in the design and construction of this project. In this study, a three-dimensional finite element model that well represents the site conditions is established. The drainage holes are modelled with a substructure technique and the seepage field is solved with the variational inequality method of Signorini’s type. A procedure is proposed to optimize the layout of the seepage control system by taking the amount of leakage, the distribution of uplift pressure, the risk of seepage erosion and cost into account. Numerical results yield the appropriate parameters for the seepage control system, including the extension and depth of grouting curtains, and the spacing of drainage holes. With these optimized parameters, the seepage control system is effective in lowering the phreatic surface and limiting the amount of leakage at the dam site.

1. Introduction
A large number of high arch dams (> 200 m) have been constructed or under construction in southwest China. Examples include the Xiluodu dam [1], the Baihetan dam [2-3] and the Jinping-I dam [4]. Under complex geological and hydrogeological conditions, the rise of reservoir water level up to 200 – 300 m during impoundment and operation may induce water leakage through the foundation rocks, or seepage erosion or even dilation of fractures in the foundation rocks, and thus may threaten the safety of the dam [5-6]. Therefore, a seepage control system comprised of grouting curtains and drainage holes is of paramount importance to reduce pore pressure and the amount of leakage and to
prevent seepage erosion in the foundation rocks. How to assess the performance and optimize the layout of the seepage control system becomes a key technological issue in dam engineering [7-9].

This study aims to propose a procedure for optimizing the layout of the seepage control system by constructing objective functions that take into account the amount of leakage, the distribution of uplift pressure, the risk of seepage erosion and cost. The proposed procedure is applied to optimize the seepage control system at the Baihetan Hydropower Station, located in the lower reaches of Jinsha River in southwest China. By using this procedure, an optimized set of design parameters is obtained through three-dimensional simulations where the site conditions and the seepage control system are properly represented. This ensures effectiveness of the system in lowering the phreatic surface, limiting the amount of leakage at the site, and minimizing the cost of construction.

2. Optimization design method

In the optimization design of a seepage control system, the main design parameters are the extension, depth and the spacing of grouting curtains and drainage hole arrays, as shown in Figure 1. The procedure for optimization design of seepage control systems is shown in Figure 2. Our goal is to achieve a balance between the cost of construction and the desired performance, such that the seepage erosion is largely prevented, the uplift pressure is considerably lowered and the amount of leakage is substantially reduced.

![Figure 1. Layout of grouting curtains and drainage holes.](image1.png)

On this basis, the range of design parameters for the seepage control system could be determined based on design criteria and engineering experience. The design parameters in this study mainly include the extension and depth of grouting curtains and drainage holes. The optimized set of parameters (e.g., \( l_g \), \( d_g \) and \( s_d \), \( d_d \)) can be obtained by optimizing the following objective functions:

\[
\begin{align*}
\min f &= f_{\text{cost}}(l_g, d_g, s_d, d_d) \\
\max g &= g_{\text{performance}}(l_g, d_g, s_d, d_d)
\end{align*}
\]

where \( l_g \) and \( d_g \) are the extension and depth of grouting curtains, respectively, and \( s_d \) and \( d_d \) are the spacing and depth of the drainage holes, respectively.

![Figure 2. Flowchart of optimization design of seepage control systems.](image2.png)
3. Site characterization of the Baihetan Hydropower Station

3.1. Project description and Geological settings
Located in the lower Jinsha River, the Baihetan Hydropower Station (BHS) is the second largest hydropower station in the world. It consists of a double curvature arch dam of 289 m high and two large-scale underground cavern systems. A large-scale seepage control system, mainly consisting of grouting curtains covering an area of 780,000 m² and 12,300 drainage holes, was designed to control the seepage in the dam foundation and the underground cavern system areas as the reservoir water level will be raised by 225 m during operation.

As shown in Figure 3 [10], the bedrocks outcropping in the study area are basaltic formations originated from multiple magmatic and volcanic eruption episodes. Belonging to the upper Permain Emei Mountain group, the formations can be divided into 11 basaltic layers (P1β1 − P3β1) with their thickness ranging between 10 m and 470 m. The basaltic layers are overlain by the lower Triassic Feixianguan formation (T1f) above the elevation of 1105 m on the right bank, with a thickness of about 265 m. The basaltic layers are separated by a number of thin, gently sloping tuff layers (C2 − C10). Shear zones (e.g., LS337, LS3319, LS3318, LS3331, RS331) and subvertical faults (F13, F14, F16 − F20) are also present in the study area.

![Figure 3. Geological settings and groundwater flow system.](image)

3.2. Permeability of rocks
The hydraulic properties of the rock at the site were well characterized. A large number of packer tests were performed at the site, including 4413 conventional packer tests at 173 boreholes and 669 high pressure packer tests at 26 boreholes [11-12]. In addition, a large number of pumping tests, recovery tests, slug tests, and seepage tests, were carried out to estimate the hydraulic conductivities of the fractured basalt rocks, the loose sediments, and the rocks in the geological structures (i.e., faults, tuff zones, and shear zones). The statistical distribution of hydraulic conductivity at the site was investigated in an earlier study [12]. According to the magnitude of hydraulic conductivity K, the rocks can be classified into six categories or permeability zones (PZs, Figure 3): high PZ (K ≥ 10⁻⁵), high-moderate PZ (10⁻⁵ > K ≥ 3 × 10⁻⁶), moderate PZ (3 × 10⁻⁶ > K ≥ 10⁻⁷), moderate-low PZ (10⁻⁷ > K ≥ 3 × 10⁻⁸), low PZ (3 × 10⁻¹⁷ > K ≥ 10⁻¹⁷), and very low PZ (K < 10⁻¹⁷), with K in units of m/s. Table 1 lists the representative values of hydraulic conductivity for the rocks at the site.
3.3. Layout of the seepage control system

According to the hydrogeological conditions at the site, a seepage control system consisting of grouting curtains, drainage tunnels and drainage holes was proposed in the dam foundation and the abutments, as shown in Figure 4(b). The grouting curtains were designed to extend to the fresh bedrocks with \( q < 1 \) Lu, where \( q \) is the Lugeon value, with the aim of effective blocking of the potential leakage pathways in the dam foundation, the underground cavern area, and the abutments.

Five layers of grouting tunnels were used to construct the grouting curtains at the elevations of 600, 656, 704, 753 and 796 m, respectively. Each curtain consisted of two rows of drilled holes. The grouting holes, with a spacing of 2 m, extended downwards to elevation \( \sim 440 \) m in the foundation rock. Besides, drainage holes of 90 mm in diameter and 3 m in spacing were to be drilled from five layers of drainage tunnels, and the drainage holes were located at about 15 m downstream of the grouting curtains. The drainage holes extended to elevation \( \sim 470 \) m in the foundation. The drainage tunnels connected all the drainage holes to form a drainage system.

4. Seepage control optimization in the Baihetan Hydropower Station

4.1 The finite element model

A 3D finite element mesh was generated for performance assessment of the seepage control system, which contains 23,655,984 elements and 6,092,582 nodes, as shown in Figure 4(a). The size of the simulation domain is 3680 m and 2621 m, on the direction perpendicular and along the river flow, respectively. The topographic and geological features at the site, the hydraulic structures and the seepage control system were well represented. The drainage holes in the seepage control system were modelled with a substructure technique [13-15] to accurately represent the seepage boundary and to reduce the complexity in mesh generation.

The hydraulic boundary conditions were prescribed as follows. On the upstream surface of the dam where the ground surface was submerged in the reservoir, constant hydraulic head boundary was specified according to the designed reservoir water level. Potential drainage boundary was specified for the ground and dam surfaces above the reservoir or river water levels as well as the walls of the drainage tunnels and holes [13-15], except the drainage holes drilled in the lowest level of drainage tunnels where the water head boundary condition was applied. The groundwater levels on the left- and the right-hand side boundaries (looking in the direction of river flow) was assumed to follow a prescribed function from upstream to downstream [16]. The lower boundary of the simulation domain was assumed to be impermeable.
4.2 Optimization design of the seepage control system

To evaluate the performance of the seepage control system, the discharge, hydraulic gradient of tuff zone C3 and uplift pressure reduction coefficient are selected as the evaluation indices. The site characterization data shows that the hydraulic gradient of tuff zone C3 should be controlled below 3.5. According to the Technical Specification for Concrete Dam Safety Monitoring (SL601-2013) in China, the uplift pressure reduction coefficient behind the grouting curtains and the drainage holes should be no more than 0.4 and 0.2, respectively. The uplift pressure reduction coefficient is defined as:

$$\alpha = \frac{h_m - z}{h_u - z}$$

where $h_m$ and $z$ is the total head and vertical elevation at the measuring point, and $h_u$ is the upstream water level.

4.2.1 Optimization design of grouting curtains

To optimize the design of grouting curtains, numerical simulations are performed by changing the length $l_g$ (from 800 to 920 m) and the depth $d_g$ (from 250 to 290 m) of grouting curtains. Figure 5 shows a comparison of the hydraulic head for different lengths of grouting curtains (800 m, 860 m and 920 m) of plane section at the elevation of 597 m. The results show that no significant difference in the distribution of hydraulic head can be observed, likely due to the properties of the deeply buried rocks. Figure 6 shows a comparison of hydraulic head and phreatic surface at the cross section of machine hall for different depths of grouting curtains (250 m, 270 m and 290 m). Increasing the depth of grouting curtains does not significantly affect the seepage field, but does lower the phreatic surface in the mountain side as well as the pore pressure of the surrounding rock in the underground powerhouse area.

Figure 7 shows the seepage control performance and cost (normalized by the corresponding values at $l_g = 800$ m and $d_g = 250$ m) of the curtains under different extended lengths and buried depths. It can be observed that the amount of discharge, hydraulic gradient and the uplift pressure decrease slightly with increasing length and depth of the grouting curtains. Meanwhile, the cost of construction increases sharply. When the length $l_g > 840$ m and the depth $d_g > 265$ m, the uplift pressure reduction coefficient and the hydraulic gradient of tuff zone C3 is controlled below 0.4 and 3.5, respectively, which meet the requirements of seepage stability (according to the Code for Hydropower Engineering Geological Investigation, GB50287-2016). Therefore, to ensure the long-term safety of the project, the length of 860 m and the depth of 270 m of the grouting curtains can be taken as the optimal design parameters for a reasonable cost. Furthermore, the construction quality of grouting curtains should be guaranteed to cut off all of the potential leakage paths effectively.
Figure 5. Comparison of the hydraulic head of plane section at 597 m elevation (m): (a) left bank (b) right bank.

Figure 6. Comparison of hydraulic head contours and phreatic surface (m): (a) left bank (b) right bank.

Figure 7. Seepage control performance and construction cost for different grouting curtains design parameters: (a) extension length $l_g$ and (b) buried length $d_g$.

4.2.2 Optimization design of drainage system

To further optimize the drainage system, another set of numerical simulations are performed by varying the spacing $s_d$ (from 3 to 6 m) and the depth $d_d$ (from 46 to 106 m) of drainage holes. With the increase of the spacing from 3 to 6 m, the rise in the phreatic surface is small, as shown in Figure 8. This indicates that the seepage discharge and hydraulic gradient are not significantly altered when the spacing changes from 3 to 6 m. Figure 9 shows a comparison of hydraulic head and phreatic surface at the longitudinal section of the machine hall for different depths of drainage holes (46 m, 76 m and 106 m). When the depth of the drainage holes increases, the phreatic surface declines only marginally.
Figure 10 shows the control effect and cost (normalized by the corresponding values for $s_d = 3$ m and $d_d = 46$ m) of the drainage holes under different spacings and buried depths. It can be observed that due to the increased spacing of the drainage holes, the amount of discharge, hydraulic gradient and the uplift pressure reduction coefficient increase and the cost of construction decreases slightly. As the depth of the drainage holes increases, the amount of discharge, hydraulic gradient and the uplift pressure reduction coefficient decreases, while the cost of construction increases. When the spacing $s_d < 3.5$ m and depth $d_d > 68$ m, the uplift pressure reduction coefficient and the hydraulic gradient of tuff zone $C_3$ is controlled below 0.2 and 3.5, respectively, which satisfies the requirements of seepage stability. Therefore, the spacing of 3 m and the depth of 76 m of the drainage holes can be taken as the optimal design parameters by balancing the performance and cost.

**Figure 8.** Comparison of phreatic surface with different spacing of drainage holes (m): (a) left bank (b) right bank.

**Figure 9.** Comparison of hydraulic head contours and phreatic surface with different depth of drainage holes (m): (a) left bank (b) right bank.
Figure 10. Seepage control performance and cost of construction for different design parameters of the drainage system: (a) spacing of drainage holes \( s_d \) and (b) buried length of drainage holes \( d_b \).

5. Conclusions

In this study, a procedure considering the performance and cost was proposed for optimization design of seepage control system. The proposed procedure was applied to the Baihetan Hydropower Station through three-dimensional finite element modelling with detailed site characterization data and complex configuration of grouting curtains and drainage holes. The amount of discharge, hydraulic gradient of tuff zone \( C_3 \) and uplift pressure reduction coefficient are used to evaluate the seepage control performance. The results show that a length of 860 m and a depth of 270 m for the grouting curtains and a spacing of 3 m and a depth of 76 m of the drainage holes are the optimal design parameters to achieve a good balance between performance and cost. With these optimized parameters, the seepage control system is effective in lowering the phreatic surface and limiting the amount of leakage at the dam site.

6. References

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