Stability analysis of the air-cushioned surge chamber of the diversion system for San Gabán III hydropower station through seepage-stress coupling approach

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Abstract. The design scheme of the air-cushioned surge chamber is adopted for the diversion system of the San Gabán III hydropower station. Due to the combined action of both high internal water pressure and external water pressure, it is necessary to demonstrate the stability of the design scheme of the air-cushioned surge chamber. This paper adopts the seepage-stress coupling analysis method to analyse the two working conditions of the air-cushioned surge chamber, i.e., the construction condition and the normal operation condition. A fine numerical analysis model of the air cushion surge chamber including the drainage holes and the drainage belts is established. The numerical simulation adopts the one-way coupling scheme. Firstly, the actual seepage fields in the air-cushion surge chamber area under the actual waterhead boundary conditions are numerically simulated. Secondly, the equivalent seepage volume forces are calculated based on the seepage fields obtained. After that, the equivalent seepage forces are applied to the surrounding rock of the air-cushion surge chamber to carry out the mechanical simulations. Results show that, most of the seepage loads are borne by the surrounding rock mass because of the drainage effects. While the pore pressure differences between the inner and outer edges of the lining are dramatically reduced, which greatly reduces the load borne by the lining and ensures the stability of the lining structure. In general, the surrounding rock deformations of the air-cushion surge chamber are not large, the stress states are normal, the supporting structures are within the bearing capacities, and the plastic zones of the surrounding rock are within the control range of the rock bolts, indicating that the air-cushioned surge chamber is stable.

Keywords. Diversion system, the air-cushioned surge tank, high internal and external water pressure, seepage-stress coupling analysis, stability analysis.

1. Introduction

The air-cushioned surge chamber is an excellent water hammer and surge control facility, which controls the water level fluctuation amplitude in the surge chamber through the "air cushion" formed by the high-pressure air in the air chamber [1]. It is especially suitable for small and medium-sized hydropower stations with high water head and small flow in difficult terrain. It has the advantages of...
low impact on vegetation environment, low investment, and flexible layout of water diversion and power generation systems. Because the air-cushioned surge chamber has its typical advantages and applicable characteristics, more and more hydropower projects adopt the design scheme of the air-cushioned surge chamber [2-5].

The San Gabán III Hydropower Station adopts the air-cushioned surge chamber to regulate water pressure of the diversion system. The surge chamber is located at the rear of the powerhouse, and the axis distance between the two buildings is 463m, as shown in Figure 1. The axis direction of the air-cushioned surge chamber is nearly parallel to the axis of the main powerhouse, and it is connected with the diversion tunnel through a connecting tunnel, with a connecting tunnel length of 72m.

The air-cushioned surge chamber adopts city door-shaped cross section, with a height of 17m, a width of 10m, a length of 90m and a volume of 14333m³. The floor elevation of the surge chamber is 1036m, and the surface elevation of the surge chamber is 1550m~1572.5m. The lithology where the surge chamber is located is mainly quartz sericite slate with hard rock quality and strong weathering resistance. As the air-cushioned surge chamber uses the surrounding rock to bear the internal water or gas pressure, the surrounding rock should be medium hard rock or hard rock, mainly composed of III or above complete rock mass. In this project, the type of surrounding rock is slate, which meets the classification requirements of III type surrounding rock. The suggested value of mechanical parameters of the rock mass are shown in Table 1.

![Figure 1. The location of the air-cushioned surge chamber.](image)

| Lithology          | Weathering zone        | Density g/cm³ | Shearing strength f' (MPa) | c' (MPa) | Deformation modulus E₀ (GPa) | Poisson's ratio U | Permeability coefficient K (cm/s) |
|--------------------|------------------------|---------------|-----------------------------|----------|-----------------------------|-----------------|----------------------------------|
| Quartz sericite slate | Medium weathering      | 2.60~2.70     | 0.64~0.72                   | 0.8~0.96 | 6~8                         | 0.27~0.30       | 1×10⁻⁴~1×10⁻⁵                   |

It is speculated that the groundwater level at the air-cushion surge chamber is about 1376m~1387m, which is 150m~160m below the ground. According to the statistical table of geological borehole water pressure test results, the regional slate is weakly and slightly permeable rock mass, 49.4% of which is the slightly permeable and 28.1% of which is weakly permeable. The permeability of the slightly permeable rock mass is less than 1Lu, while that of the weakly permeable rock mass is 1Lu~3Lu.

2. Numerical Simulation Conditions

2.1. Support measures
The air-cushioned surge chamber is lined with reinforced concrete. The concrete lining is 85cm thick, with 32@20cm circular double-layer reinforcement and 25@20cm distributing bar. The lining mainly
plays the role of fixing the steel lining and bearing the pressure difference between the inside and the outside of the lining.

The static waterhead of the surge tank exceeds 600m. Steel lining is externally hung on the side wall, the top arch, of the air chamber and the both ends of the concrete lining of the air chamber. Drainage belts are arranged between the concrete lining surface and the steel lining. The drainage belt is semicircle in the plane with a diameter of 150mm. The horizontal drainage belts and the vertical drainage belts intersect with each other, so that the steel lining can withstand less internal and external pressure difference, which is easier to meet the structural design requirements. Drainage holes are arranged at the intersection positions of the drainage belts, which is 4m deep into the bedrock, with 2m row spacing and rectangular arrangement. The drainage pipes are arranged in the drainage holes. One end of the drainage pipe is 70cm deep into the bedrock hole, and the other end is connected with the drainage belts. The drainage belts then connect with the water-pillow in the air chamber to balance the internal and external pressure of the concrete lining. The structure of the air-cushioned surge chamber is shown in Figure 2.

![Figure 2. Structure of the air-cushioned surge chamber](image)

2.2. Working conditions and numerical simulation method

Two working conditions are simulated to analyse the stability of the surge chamber, i.e., the construction period that does not consider the effect of water loads and the normal operating condition during the operation period considering both the effects of the external and internal water, as shown in Table 2. According to the design suggestion, the boundary condition of the external water head is multiplied by the reduction coefficient of 0.1 on the basis of the actual water head, while the internal water pressure acts uniformly on the concrete lining of the surge chamber. During numerical simulation, the permeability coefficient of the type III surrounding rock is set as 1Lu, and the initial permeability coefficient of concrete lining of the surge chamber is set as 0.5Lu.

| Rock type          | Mechanical parameters of surrounding rock | Numerical simulation conditions | Buried depth and waterhead condition |
|--------------------|------------------------------------------|---------------------------------|-------------------------------------|
| Slate Class III    | High value of the medium weathering       | The construction period        | External waterhead × Reduction factor | Internal water pressure     |
|                    |                                          | The normal operating condition during the operation period | 366m×0.1                             | 3.74MPa                    |
The one-way seepage-stress coupling scheme is used to simulate the stability of the air-cushioned surge chamber. First, according to the actual waterhead boundary conditions of each working condition, the distribution of the seepage field in the surrounding rock is calculated. Then, according to the seepage field distribution in the surrounding rock, the seepage volume force corresponding is calculated. The calculation formula of the seepage volume force can be expressed as:

\[
\begin{bmatrix}
    f_x \\
    f_y \\
    f_z
\end{bmatrix}
= \gamma_w \begin{bmatrix}
    -\frac{\partial p}{\partial x} \\
    -\frac{\partial p}{\partial y} \\
    -\frac{\partial p}{\partial z}
\end{bmatrix}
- \begin{bmatrix}
    \frac{\partial H}{\partial x} \\
    \frac{\partial H}{\partial y} \\
    \frac{\partial H}{\partial z}
\end{bmatrix}
\]

In which, \( f_x, f_y, f_z \) are the components of the seepage volume force in the three axes directions, \( p \) is the pore pressure, \( \gamma_w \) is unit weight of the water, \( H \) is the water head. The seepage volume force is then applied to the numerical model to represent the seepage load, and the surrounding rock displacements and the lining stresses are calculated.

2.3. Numerical model
To consider the most unfavourable situation, the section closest to the connecting tunnel in the air-cushioned surge chamber is selected to establish the numerical model. The quasi-three-dimensional numerical simulation method and the Flac3D software is adopted to perform the numerical simulation. The deformation and plasticity of the surrounding rock as well as the force characteristics of support system is analysed to study the stability of the air-cushioned surge chamber. During numerical simulation, the ideal Mohr-Coulomb elastoplastic model with tensile cut-off is selected to be the rock mass constitutive model, while the elastic constitutive model is used for the concrete lining. The parameters of the constitutive model are selected according to the rock mass mechanical parameters suggested by geology. The high values of the medium weathering slate are selected to be the parameter series. The numerical model is established for the air-cushion surge chamber. The model range is 315m×665m(X×Z), with 162141 elements and 50803 nodes. The calculation model was shown in Figure 3.

For the convenience of discussion, two measuring lines are selected in the model, namely, the measuring line A and the measuring line B. The measuring line A is along the direction of the extension line of the central axis of the drainage hole, while the starting point of the measuring line B is located in the middle of the two drainage holes, with direction parallel to the measuring line A. The positions and directions of the two measuring lines are shown in Figure 4.
3. Discussion of the Numerical Results

3.1. Construction period

Firstly, the stability of the surrounding rock and the force of the supporting system during the construction period are calculated and analysed. For the working conditions of operation period, only the corresponding seepage load or water pressure needs to be considered on the basis of the results of the construction period.

The results of construction period are shown in Figures 5~7. According to the results, the overall deformation of the surrounding rock of the surge chamber is 2.0mm~42.9mm, of which the deformation of the surrounding rock at the top arch of the surge chamber is 26mm~30mm, and the deformation of the side wall is 26.0mm~42.9mm. The depth of the plastic zone of the surge chamber is 2.4m~8.5m as a whole. The depth of the plastic zone of the surrounding rock at the top arch is 2.4m, while the depth of the plastic zone of the surrounding rock at the side wall is larger, with a maximum of 8.5m. The first principal stress of the rock surrounding the cave is -24.95MPa ~ -0.22MPa, while the third principal stress is -10.64MPa ~ 0.74MPa. The tensile stresses mainly appear in the surrounding rock at the middle of the side wall and only distributed in the shallow surface. The maximum bolt stress is 186MPa.

In all, it can be seen that the surrounding rock deformation during the construction period of the surge chamber is generally small, the surrounding rock deformation at the middle and lower of the side wall is slightly larger. The plastic zone of the surrounding rock is within the control range of the bolt length. The stress state of surrounding rock is generally normal, and the supporting structure is in normal working condition. Therefore, the stability of the surrounding rock during the construction of the surge chamber can be guaranteed.
3.2. Normal operating condition during operation period

In normal operating conditions during operation period, the internal water pressure of 3.74MPa and the external waterhead of 366m are combined effecting. Based on the saturated seepage simulation method, after the above water head boundary conditions are applied to the boundary of the numerical analysis model, the stable seepage field around the surge chamber is obtained. Figure 8 shows the seepage field nephogram and Figure 9 shows the distribution diagram of the pore water pressure along the two measuring lines during the normal operating conditions. It can be seen that, affected by the drainage effect of the drainage holes and the drainage belts, the pore water pressure of the surrounding rock within the scope of the drainage holes basically maintains a high value above 3.5MPa. Specifically, it can be seen from Figure 9 that, along the measuring line A, the pore water pressure of the surrounding rock within the drainage hole area is maintained at 3.74MPa. While the pore water pressure along the measuring line B of the surrounding rock within the drainage hole area is gradually reduced from 3.74MPa to 3.66MPa. This indicates that, during the normal operation period, the internal water pressure on the inner surface of the lining transfers from the drainage hole to the deep part of the surrounding rock. Thus, the surrounding rock and the concrete line at the drainage hole region maintain lower hydraulic gradients. It can be seen from equation (1) that the smaller the hydraulic gradients, the smaller the seepage volume forces in the surrounding rock and lining. Therefore, due to the drainage effects of the drainage holes and the drainage belts, the water load on the concrete lining and the surrounding rock within the drainage hole area are greatly reduced, that is, the stability of the surrounding rock and the lining structure under normal operating conditions is greatly improved.

Figure 10 shows the lining stress nephogram of the air-cushioned surge chamber under normal operating condition. It can be seen that under normal operating condition, the minimum principal stress of the lining is -0.6MPa~0.3MPa and the maximum principal stress of the lining is 0.3MPa~3.3MPa. Due to the influence of the connecting tunnel, the lining stress is not symmetrical. The lining is mainly subjected to tensile stress, while the compressive stress it bears is very small.

Figure 7. The principal stress nephogram.

Figure 8. Pore pressure nephogram (Pa).

Figure 9. Pore pressure of the measuring lines.
The principal air-cushioned stability within the chamber, these working conditions of the air-cushioned surge chamber, i.e., the construction period and the normal operation period, are numerically simulated through the one-way seepage-stress coupling approach.

Results show that the surrounding rock deformation is generally small, the plastic zone of the surrounding rock is within the control range of the bolts, the stress state of surrounding rock is generally normal, and the supporting structure is in normal working condition. Thus, the stability of the surrounding rock of the surge chamber is guaranteed.

In addition, it is found that, affected by the drainage effects of the drainage holes and the drainage belts, the hydraulic gradients of the surrounding rock within the drainage hole regions and the concrete lining are both very small. This brings about the great reduction of the water load that acting on the concrete lining and the surrounding rock within the drainage hole zones. The water load is transferred to the deep region of the surrounding rock to a certain extent due to the drainage effects, which greatly improves the stability guarantee of the air-cushioned surge chamber.

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References
[1] Fang G D 2005 Application of air-cushion surge shaft for hydropower station and its main design problems Water Power 31(2) 44-47 (in Chinese).
[2] Liu D Y, Zhang J, Suo L S 2000 Advances in Research on Air-Cushioned Surge Chamber International Journal HYDROELECTRIC ENERGY 18(4) 1-5 (in Chinese).
[3] Guo W C, Yang J D, Chen J P, Teng Y 2014 Study on the stability of waterpower-speed control system for hydropower station with air cushion surge chamber IOP Conference Series: Earth & Environmental Science 22 042004.
[4] Luo G J, Hu Y S, Huang K 2012 Research on the effect of gas leaking and gas-supplementing measurements of air cushion surge chamber Applied Mechanics & Materials 238 414-418.
[5] Hua F G 2006 Research on the main design problems of air-cushioned surge chamber Water Conservancy Science and Technology and Economy 12(4) 221-226 (in Chinese).