Analysis of the effect of bedding attitude on relaxation deformation characteristics of the surrounding rock of an underground powerhouse in a layered rock mass

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Abstract. To study the stability of an underground powerhouse in layered rock mass, a series of numerical simulations was conducted using three-dimensional distinct element code to investigate the effect of bedding attitude on the relaxation deformation characteristics of the surrounding rock of an underground powerhouse. The results showed that when the bedding dip angle was less than 30°, the maximum deformation of the surrounding rock occurred at the arch crown and bottom plate. However, when the dip angle was greater than 60°, the maximum deformation occurred at the side wall. Under the same conditions, with the increase in dip angle, the maximum deformation of the surrounding rock and the depth of the relaxation deformation zone (RDZ) increased first and then decreased, and their peak values were observed when the dip angle reached 60°–70°. With the increase in the angle between the bedding strike and longitudinal axis of the cavern, the maximum deformation and depth of the RDZ decreased gradually and stabilized when the angle was greater than the threshold. For the steeply inclined layered rock mass, when designing the underground powerhouse, the angle between the bedding strike and longitudinal axis of the cavern should not be less than 60°.

1. Introduction
The layered rock mass is a common type of rock mass in underground engineering construction, and its deformation and strength have evident characteristics of transverse anisotropy due to its internal bedding[1, 3]. Engineering practice shows that after the excavation of underground caverns, due to the influence of stress release and adjustment, a layered rock mass generally exhibits a relaxation deformation phenomenon, which is manifested as deformation and failure characteristics, such as the opening and sliding between rock layers. The relaxation deformation characteristics of a layered rock mass are significantly asymmetrical due to the influence of bedding attitude[4, 6]. Therefore, the study of relaxation deformation characteristics of underground caverns in a layered rock mass to guide engineering design has great theoretical and practical values.

Scholars at home and abroad have carried out related research on the deformation and failure of underground caverns in a layered rock mass. Fan X et al.[7] conducted a series of uniaxial compression
tests on physical models containing joints and tubes made of high-strength gypsum and obtained the fracturing characteristics of models with joints of different combinations. Zhao J et al.\cite{8} used FLAC 3D software to analyze the failure of layered rock in roadway floors. Xu G et al.\cite{9} investigated the effects of the micro-structure and micro-parameters on the mechanical behavior of transversely isotropic rock by Brazilian tests and used a numerical approach to study the failure process of a layered surrounding rock after tunnel excavation. Guo Z et al.\cite{10} studied the deformation and failure mechanism of surrounding rocks based on a physical model test, and the modeling results showed that concentrated stresses in surrounding rocks were very uneven due to the developed stratified and jointed rock mass structure. Cui Z et al.\cite{11} investigated the influence of dip directions on the main deformation region of a layered rock around a tunnel using a three-dimensional distinct element code (3DEC). By comparison, discontinuous numerical simulation has several advantages in this field.

The current studies on the deformation and failure of layered rock masses mainly concentrated on underground engineering; the research on large-span and high side-wall underground powerhouses is relatively limited, and most of the existing studies only considered the effect of dip angle; a limited number of studies focused on the influence of bedding strike\cite{12-14}. In this work, the influence of bedding attitude on the relaxation deformation characteristics of the surrounding rock of an underground powerhouse in a layered rock mass was investigated based on the three-dimensional discrete element numerical simulation. On this basis, several suggestions were put forward for the axis arrangement and support design of underground powerhouses in layered rock masses. The research results have important reference value for guiding the design of underground powerhouses.

2. Numerical Simulations

2.1. Numerical model

This study focused on the stability of the layered surrounding mass of an underground powerhouse of a pumped storage power station. Aiming at the geological structural features of a layered rock mass, the typical cross-section shape of the underground powerhouse of the pumped storage power station was selected in this study. The buried depth of the underground powerhouse is 250 m, and its cross-section dimensions are 26 m (width) × 58 m (height). The excavation of the underground powerhouse was divided into six steps (CI to CVI). Considering the influence of boundary effect, a generalized model of layered rock mass in an underground powerhouse was established (Figure 1). The dimensions of the model are 200 m (length) × 200 m (width) × 50 m (thickness), and the stratum thickness (h) is 4 m.

![Figure 1. Generalized model of an underground powerhouse in a layered rock mass.](image)

As shown in Figure 1, the included angle (β) between the longitudinal axis of underground powerhouse and the bedding strike was used to characterize changes in the bedding strike in this study. On this basis, numerical models for different dip angles and included angles were established. The
different dip angles considered in the simulations were 0°, 10°, 20°, 30°, 40°, 50°, 60°, 70°, 80°, and 90°, and the models for the dip angles of 0°, 60°, and 90° are shown in Figure 2(a). In addition, under different dip angles, the different included angles considered were 0°, 20°, 40°, 50°, 60°, 70°, and 80°, and the models for the included angles of 20°, 40°, and 60° are shown in Figure 2(b).

2.2. Initial in-situ stress and boundary conditions
In the numerical simulation, only gravity was considered in the initial in-situ stress field, and its lateral pressure coefficient in the horizontal direction was 0.5. The buried depth of the underground powerhouse was 250 m, and it was simulated by applying a gravity load of rock mass with a buried depth of 180 m on the model top (Figure 1). In addition, to eliminate the influence of the boundary effect, we used a zero velocity for the nodes around the model boundary except the top.

2.3. Parameters of numerical simulation
For the layered rock mass, the constitutive Mohr–Coulomb model was used to simulate the mechanical behavior of rock bedding, and Coulomb slip model in 3DEC was used to simulate the contact mechanical behavior between rock layers. Table 1 lists the parameters of Mohr–Coulomb and Coulomb slip models used in the simulation.

| Model          | Parameters | Values | Model          | Parameters        | Values |
|----------------|------------|--------|----------------|-------------------|--------|
| Mohr–Coulomb   | Density (kg/m³) | 2500.0 | Normal stiffness (N/m) | 8.0 × 10⁶ |
|                | Elasticity modulus (GPa) | 15.0   | Shear stiffness (N/m) | 8.0 × 10⁶ |
|                | Poisson's ratio | 0.23   | Friction angle (°) | 25.0 |
|                | Friction angle (°) | 45.0   | Normal cohesion (MPa) | 0.5 |
|                | Cohesion (MPa) | 2.0     | Shear cohesion (MPa) | 0.3 |

3. Analysis of the Influence of Bedding Attitude on Relaxation Deformation Characteristics of the Surrounding Rock of an Underground Powerhouse

3.1. Influence of dip angle
To analyze the influence of changes in the dip angle, we used the simulation results under different dip angles for comparative analysis, in which the included angle between the longitudinal axis of an underground powerhouse and the bedding strike for the models was 0°. Figure 3 shows the displacement nephogram of the surrounding rock after excavation under different dip angles.

Figure 3 shows that the displacement distribution of the surrounding rock after the excavation of the underground powerhouse exhibited significant differences under various dip angles. When the dip angles were 0° and 90°, the displacement distribution was in the form of left–right symmetry, whereas a left–right asymmetry was observed when considering other dip angles. In addition, when the dip angle was less than 30°, the maximum displacement of the surrounding rock after excavation occurred at the arch crown and bottom plate of the underground powerhouse. When the dip angle exceeded 30°, an evident slip deformation between rock layers occurred at the side wall. Afterward, with the increase in the dip angle, when the dip angle reached 60°, the maximum displacement of the surrounding rock occurred at the side wall.

For the layered rock mass, when the dip angle was less than 30°, more attention was paid to the deformation and stability of the surrounding rock at the arch crown and bottom plate under the condition of gravity, whereas when the dip angle was greater than 60°, more attention was paid to the deformation and stability of the surrounding rock at the side wall.

![Figure 3. Displacement nephogram of the surrounding rock after excavation under different dip angles.](image)

Figure 4 shows the curve of the maximum displacement versus the change in dip angle. As presented in Figure 4, when the dip angle was less than 30°, the maximum displacement of the surrounding rock showed no significant change with the increase in the dip angle. When the dip angle started from 30°, the maximum displacement increased first and then decreased with the increase in the dip angle, and when the dip angle increased to 60°–70°, the maximum displacement reached the peak. When the dip angle was less than 30°, its change slightly influenced the maximum displacement of the surrounding rock after excavation. However, when the dip angle was more than 30°, its change showed a significant influence on the maximum displacement of the layered surrounding rock.
Figure 4. Maximum displacement curve versus change in dip angle.

For the layered rock mass, the failure of contact state between rock layers after excavation always occurred. Figure 5 shows the failure of contact state between rock layers under different dip angles. As shown in Figure 5, tension and sliding failures of the contact state between rock layers occurred around the chamber after excavation under different dip angles, and the distribution of relaxation deformation zone (RDZ) of the surrounding rock also exhibited evident differences. By contrast, when the dip angle was less than 30°, the change in the dip angle had minimal effect on the depth of RDZ, and the RDZ was mainly distributed at the arch crown and bottom plate. When the dip angle exceeded 30°, the RDZ distributed at the side increased significantly. Moreover, with the increase in the dip angle, the distribution range and depth of the RDZ after excavation expanded continuously. When the dip angle increased to 60°–70°, the depth and distribution range of the RDZ reached the maximum. Afterward, with the increase in the dip angle, the depth of the RDZ decreased gradually. The variation in the distribution depth and range of RDZ with the dip angle was consistent with that of the maximum deformation with the dip angle in Figure 4, which explains the significant difference in the deformation characteristics of the surrounding rock under different dip angles after excavation.

Figure 5. Failure of contact state between rock layers under different dip angles.

3.2. Influence of bedding strike
To analyze the influence of changes in the bedding strike, we considered cases of low and steep dip angles, with values of 30° and 60°, respectively.

Figure 6 shows the displacement nephogram of the surrounding rock under the different included angles between the longitudinal axis of the underground powerhouse and bedding strike after excavation. Figure 6 also reveals that under the same dip angle, the maximum displacement of the surrounding rock after excavation of the underground powerhouse decreased gradually with the increase in the included angle. Moreover, for two cases of low and steep dip angles, the increase in the included angle caused a different influence on the displacement distribution of the surrounding rock after excavation. Specifically, in the case of a low dip angle, the change in the included angle had a relatively minimal influence on the displacement distribution of the surrounding rock (Figure 6(a)). However, in the case of a steep dip angle, the change in the included angle has a relatively large influence on the displacement distribution of the surrounding rock, and with the increase in the included angle, the occurrence of maximum displacement after excavation gradually shifted from the side wall to the arch crown and bottom plate (Figure 6(b)).

![Displacement nephogram](image)

**Figure 6.** Displacement nephogram of the surrounding rock under different included angles between the longitudinal axis of the underground powerhouse and bedding strike.

Figure 7 shows the curve of the maximum displacement versus the change in the included angle between the longitudinal axis of the underground powerhouse and bedding strike. Figure 7 also reveals that under the same dip angle, with the increase in the included angle, the maximum displacement of the surrounding rock gradually decreased, and when the included angle exceeded a certain threshold angle, its change exhibited no remarkable effect on the deformation of the surrounding rock. Specifically, in the case of low dip angles, when the included angle exceeded 50°, its change presented an almost no evident effect on the deformation of the surrounding rock. In the case of steep dip angles, when the included angle exceeded 60°, its changes almost showed no notable effect on the deformation of the surrounding rock.
Figure 7. Maximum displacement curve versus the change in the included angle between the longitudinal axis of the underground powerhouse and bedding strike.

Figure 8 shows the failure of contact state between rock layers under different included angles between the longitudinal axis of the underground powerhouse and bedding strike after excavation. Figure 8 also displays that under the same dip angle, with the increase in the included angle, the distribution depth and range of RDZ decreased gradually, and when the included angle exceeded a certain threshold angle, despite its continued increase, the distribution depth and range of RDZ showed no evident decrease. Specifically, in the case of a low dip angle, when the included angle exceeded 50°, with the increase in the included angle, the distribution depth and range of RDZ exhibited no significant change. In the case of a steep dip angle, when the included angle exceeded 60°, the distribution depth and range of RDZ also showed no significant change. Thus, the variation in the distribution depth and range of RDZ with the included angle was consistent with that of the maximum deformation with the included angle in Figure 7.

\[ \beta = 0° \quad \beta = 20° \quad \beta = 40° \quad \beta = 50° \]

\[ \beta = 60° \quad \beta = 70° \quad \beta = 80° \]

(a) Dip angle = 30° (low dip angle)
Figure 8. Failure of contact state between rock layers under different included angles between the longitudinal axis of the underground powerhouse and bedding strike.

4. Conclusion
In this work, the effect of bedding attitude on the relaxation deformation characteristics of the surrounding rock of an underground powerhouse in a layered rock was investigated based on 3D discrete element numerical simulation analysis. On this basis, several suggestions were put forward for the axis arrangement of underground powerhouse in layered rock masses and the design of support.

(1) The maximum displacement and RDZ of the layered rock mass after excavation were closely related to the bedding attitude. Under the same conditions, with the increase in the dip angle, the maximum deformation and depth of the RDZ of the surrounding rock increased first and then decreased, and they reached the peak when the dip angles increased to 60°–70°. Meanwhile, the maximum deformation and depth of the RDZ of the surrounding rock gradually decreased with the increase in the included angle between the longitudinal axis of the underground powerhouse and bedding strike.

(2) Under gravity stress field, more attention should be paid to the deformation and stability of the surrounding rock at the arch crown and bottom plate during the excavation process of the underground powerhouse for gently inclined layered rock mass (dip angle of less than 30°). For steeply inclined layered rock mass (dip angle of more than 60°), more attention should be paid to the deformation and stability of the surrounding rock at the side wall, and the included angle of the longitudinal axis of the underground powerhouse and bedding strike should not be less than 60° when designed. Given the evident asymmetric distribution of the RDZ for the layered rock mass after excavation, the asymmetric support measures should be adopted in the support design, and the reasonable support scheme should be determined based on the distribution range and depth of RDZ.

Acknowledgments
The project was funded by National Key R&D Program of China (2018YFC0407006), National Natural Science Foundation of China-Yalong River Joint Fund Key Project (No. U1965204), and Natural Science Foundation of Shanxi Province (Grant No. 2019JLZ-13, Grant No. 2019JLP-23).

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