Research Article

Influence of Discontinuities on Rock Failure under Blasting at Shuangjiangkou Hydropower Station

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Received 26 July 2021; Accepted 30 September 2021; Published 23 October 2021

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The underground caverns of Shuangjiangkou hydropower station are under complex geological conditions. During excavation, the stability of the tunnels is severely affected by problems, such as blasting impact and excavation unloading, resulting in abnormal deformation at different locations. On the basis of on-site measurement, the characteristics of rocks at the main powerhouse and the main transformer room are compared through dynamic tests, and a numerical model is established using discrete element method (DEM) to analyze the special influence of fault SPD9-f1 on the deformation after excavation. It is revealed that the surrounding rock of the main powerhouse has stronger impact resistance than that of the main transformer room and that the existence of fault SPD9-f1 accounts for the abnormal deformation. In this study, the failure characteristics and mechanism of surrounding rock deformation controlled by stress and fault are revealed, providing important references for the subsequent excavation and support design of underground projects.

1. Introduction

As an efficient and clean source of energy, hydropower plays an important role in the national electricity generation. To meet the increasing demand for electricity, many hydropower stations are being built across the world in regions with abundant water resources. During construction of the hydropower stations, complex geological conditions, such as high geostress and discontinuities, are potential threats to the safety of these projects [1–3]. These geological conditions not only seriously delay the construction progress but also cause great harm to the construction personnel and equipment. Therefore, it is necessary to monitor the key factors to ensure the safety of underground caverns under excavation. As one of the key factors for safety monitoring, the surrounding rock deformation is particularly important, and it is widely used to evaluate the stability of the caverns due to its easy access and direct indication [4].

There are many factors that cause abnormal deformation of surrounding rock, which is mainly determined by the external force (such as blasting) and internal structure (such as discontinuities), and thus, exploring the influence of discontinuities on rock failure under blasting is essential to the construction of hydropower stations [5, 6]. Some scholars believe that abnormal deformation of surrounding rock is caused by lithology, such as strength and hardness, whereas others demonstrated that it is mainly influenced by the internal discontinuities. Liu et al. [7] assumed that the hardness of the surrounding rock is the main reason for the deformation; when there is a stress difference between the surrounding rock, the weak rock will deform greatly, leading to abnormal deformation. Li et al. [8] analyzed the deformation of a deep roadway with intercalated coal seam in roof according to the unique fracture mode by site detection; it was found that the low overall strength of coal seam in roof is the main reason for failure of self-bearing structure and loss of self-bearing capacity,
which eventually led to failure of the surrounding rock. Studies have found that in some engineering cases, the weak structural plane is the main reason for the large deformation of surrounding rock. Hu et al. [9] revealed the deformation of bedded rock in Wudongde hydropower station by means of field monitoring and numerical simulation; it was found that the deformation has a close connection with the dense of the bedding joint, and the excavation will trigger the activity of bedding joint, leading to the damage of the surrounding rock. In addition to the above-mentioned reasons, it is also found that deformation is affected by many factors in other engineering cases. He et al. [10] used geological survey, theoretical analysis, and numerical calculation to examine the mesozoic compound soft rock roadway and concluded that the failure of soft rock is controlled by the combined effect of molecular expansion, structural plane, and excavation disturbance. Li et al. [11] analyzed the surrounding rock of Baihetan hydropower station and found that the deformation was large under the combined effect of high geostress and weak geological structure.

The underground caverns of Shuangjiangkou hydropower station are located in an area with great depth and high geostress, where rock mass are mostly monolithic structures, with weak structural planes and faults in some parts. Blasting was adopted as the excavation method for the caverns of this hydropower station. Before the excavation, the rock mass is under high geostress of triaxial compression. After blasting, the stress state of the natural rock mass is redistributed, resulting in tangential stress concentration and inducing rock bursts and slabs when the tangential stress exceeds tensile strength [12–14]. At the same time, cracking, collapsing, and large deformations occur in the surrounding rock mass with weak structural planes. In order to ensure the safety of the Shuangjiangkou hydropower station, the surrounding rock deformation during the excavation of the pilot tunnel in the main powerhouse and main transformer room was monitored in real time. The monitoring results indicated that the two caverns present different degrees of deformation, and the surrounding rock mass of the main transformer room shows abnormal deformation in some sections. Based on the above-mentioned phenomenon, the aim of this study was to explore the causes of the large deformation of the surrounding rock masses at the hydropower station.

In order to explore the influence of lithology on the deformation of surrounding rock, it is necessary to carry out rock dynamic tests to simulate the blasting response. The Split Hopkinson pressure bar (SHPB) system, as recommended by International Society for Rock Mechanics (ISRM) [15], can be used to examine the rock damage under explosion and high-speed impacts and to obtain the dynamic strength of rocks under high strain rates. The SHPB apparatus has been combined with other techniques on dynamic tests for various mechanical properties of engineering materials. Wang et al. [16] obtained failure pattern and displacement fields of rock mass with different joint angles through SHPB and digital image correlation (DIC) technology; the results revealed the failure mechanism of jointed mass under dynamic loads. Wu et al. [17] modified the Split Hopkinson pressure bar to test Brazilian disc (BD) specimens under prestress and found that the dynamic tensile strength of rock decreases with the pretension. Ning et al. [18] discovered that the strength of the anchored specimen increases with strain rate under the combined dynamic and static load using the SHPB system and proposed reasonable suggestions for the support design of the surrounding rock in large underground chamber. Man et al. [19] performed dynamic mechanical tests on rocks from the preselected area of high-level radioactive waste disposal using SHPB system and provided reference for disposal site selection.

However, laboratory tests have limitations in terms of studying the impact of cracks and faults on large-scale projects; for example, the size, angle, and composition of the fault cannot be reconstructed accurately by laboratory tests. On the contrary, numerical simulation, as a widely used tool to study large-scale engineering-related issues, can effectively address the above limitations. Some of the numerical methods that have been used to simulate the deformation of underground caverns are the finite element method (FEM), the finite difference method (FDM), the discrete dipole approximation (DDA) method, and the discrete element method (DEM); but not all of them are well suitable for engineering practice. For example, some scholars applied FEM to the modeling of rock deformation [20, 21], but FEM cannot deal with large deformation problems and cannot identify new blocks during the destruction process. Meanwhile, FDM has certain difficulties in dealing with fractures, complex boundaries, and heterogeneous materials, making it impossible to be applied well in rock deformation problems. But DEM is widely used in engineering practice due to its ability to effectively solve large nonlinear deformation problems [22–24]. As a discrete element method, UDEC is widely used in the modeling of excavation of underground caverns. Hu et al. [25] obtained the stress and deformation fields of the surrounding rock during the excavation process using UDEC and analyzed the deformation mechanism of the structure planes. Xu et al. [26] used UDEC and figured out the mechanism of deformation and failure of rock slope. These studies demonstrated the applicability of DEM in the modeling of geotechnical excavation.

In the present study, laboratory tests and numerical simulations are both used to analyze the influence of discontinuities on rock failure under blasting at Shuangjiangkou hydropower station. This article is organized as the following structure: Section 1 introduces the overall situation of the hydropower station, as well as the on-site monitoring data of surrounding rock deformation and depth of broken rock zone; Section 2 introduces the test results of dynamic compressive strength by SHPB system, wave velocity measurement is used to measure the damage of rock specimen after blasting excavation, and CT scanner is utilized to analyze the internal fissures in surrounding rocks in different loading rates. In order to better explain the rocks containing fault, Section 3 obtains the influence of fault SPD9-f1 on deformation using discrete element method (DEM) and obtained the failure mechanism of underground caverns. Results and discussions are present in Section 4, and conclusions are drawn in Section 5.
2. Project Overview

2.1. Engineering Conditions. Shuangjiangkou hydropower station is located in southwest of China with maximum dam height of 314.70 m and crest elevation of 2510m. The underground station includes the main powerhouse, the main transformer room, and the tail water surge chamber. The surrounding rock of the main powerhouse and the main transformer room is mainly biotite K-feldspar granite. The main powerhouse is excavated by eight floors, and the main transformer room is excavated by three floors as shown in Figure 1. This study mainly focussed on the deformation characteristics of the surrounding rock of the first layer, which was excavated by two steps as illustrated in Figure 2. The first step is to excavate the pilot tunnel, and the second step excavates the upstream and downstream parts on both sides. The excavation of the pilot tunnel is of vital importance to the overall stability of the underground caverns, during which the in-situ stress state of the surrounding rock is disturbed. At the same time, the surrounding rock is quickly unloaded, which induces rock deformation, such as spalling and rock burst, seriously affecting the stability of the surrounding rock.

In addition to the influence of lithology, local discontinuities, such as small faults and lamprophyre vein, also affect the deformation of the surrounding rock. The figure mainly includes the main powerhouse and the main transformer room, which are connected by the exhaust tunnel; all chambers are connected through the drainage system as marked in red dash. The section number is marked above the main powerhouse. In the main transformer room, there is a fault marked as SPD9-f1 near 0 + 15 m~0 + 20 m of the downstream sidewall and 0 + 7 m~0 + 12 m of the upstream sidewall as illustrated in Figure 3. The width of fault SPD9-f1 crushing zone is 50 cm~60 cm, which is composed of cataclasites mixed with 1~4 mm thick mud. On-site monitoring results show that the surrounding rock deformation where fault SPD9-f1 exists is bigger than other sections, and there are more cracking, falling blocks compared with other sections.

The deformation of four sections have been monitored in the main powerhouse and the main transformer room; piles of both tunnels are located at the K0 + 00 m, K0 + 30.2 m, K0 + 60.4 m, and K0 + 90.6 m in the main powerhouse, as marked in Figure 3. The upstream and downstream arch foot are measured at each position. The measured deformation is shown in Table 1 as of January 20, 2019. The deformation of each section in the main powerhouse shows a gradual change. The maximum deformation of main transformer room is 3.14 mm at K0 + 00 m, where there is a fault SPD9-f1, which is much larger than other areas, indicating that large deformation is related to the fault.

2.2. Depth of Broken Rock Zone. After excavation of the rock mass, the initial stress balance is disturbed so that the normal stress unloading and tangential stress concentration would occur, leading to a stress releasing area around the free surface. This area is called the broken rock zone [27]. The depth of the broken rock zone is also valuable for the design of excavation and support [28]. In order to accurately evaluate the damage of surrounding rock, the depth of broken rock zone has been monitored on five pile positions after the excavation of the main powerhouse and the main transformer room. The piles are located at K0~30 m, K0 + 10 m, K0 + 40 m, K0 + 70 m, and K0 + 100 m, respectively, with each pile position measures the depth of broken rock zone at the upstream and downstream arch foot, as shown in Table 2 and Figure 4. The depth of broken rock zone is between 0.4 and 0.8 m at the main powerhouse and between 1.6 and 3.4 m at the main transformer room, which is about three times deeper than that of the main powerhouse. Among these measured locations, the depth of the broken rock zone at K0+10 is more than five times larger at the transformer room than at the main powerhouse due to the influence of fault SPD9-f1.

Tables 1 and 2 show the obvious difference between the main powerhouse and the main transformer room. Under the disturbance of blasting excavation, the surrounding rock deformation and depth of broken rock zone of main powerhouse are smaller than those of the main transformer room. The deformation and depth of broken rock zone are abnormal in the presence of fault SPD9-f1. In order to explore the lithology of the two caverns and the influence of fault SPD9-f1 on the deformation of the surrounding rocks, rock dynamic test and numerical simulation are carried out and introduced in the following sections.

3. Experimental Inspection

3.1. Experimental Material. The rock blocks are selected from the engineering site without no obvious defects, and they are processed into specimens with a diameter of 50 mm and a height of 100 mm. The nonparallelism of the specimen surface is less than 0.05 mm, and the diameter difference is smaller than 0.3 mm. Specimens from the two caverns are tested to obtain the uniaxial compressive strength. A detailed physical and mechanical description of the specimens is shown in Table 3.

The average uniaxial compressive strength of the rock in the main powerhouse is 163 MPa, which is 131 MPa of the main transformer room; the difference of 32 MPa indicates that the compressive strength and the integrity degree of rock in main transformer room is lower than that at the main powerhouse. The elastic modulus of main transformer room is lower than that of main powerhouse, which means that even in elastic state, the deformation of the rock in the main transformer room is slightly greater than that of the main powerhouse; this is consistent with the on-site observation.

3.2. Specimen Preparation. The rock specimens were collected from the main powerhouse and main transformer room after blasting excavation. According to the suggested method by ISRM [15], all specimens are polished into 38.00 mm in diameter and 38.00 mm in height with the height-to-diameter ratio of 1 as shown in Figure 5.
The initial damage degree can be characterized by the acoustic wave velocity of rock masses effectively [29]. In order to analyze the damage degree of the rock specimens, the physical properties, such as the longitudinal wave velocity, were measured before the tests as shown in Table 4. The longitudinal wave velocity of fresh intact granite is about 5300 m/s; however, the average longitudinal wave velocity of the specimens from the main powerhouse and the main transformer room are 3895 m/s and 3208 m/s, respectively. The wave velocity of the rock specimens from the main transformer room is about 80% of that from the main powerhouse. It indicates that after blasting excavation, rocks from both caverns are weakened, but the degradation degree of the rock mass from the main transformer room is greater than that of the main powerhouse.

3.3. Experimental Apparatus and Data Analysis. The tests were conducted on the Split Hopkinson Pressure bar (SHPB) system in the Tianjin University. It consists of a striker bar, an incident bar, and a transmitted bar. The lengths of the three bars are 350 mm, 3000 mm, and 1800 mm, respectively; all three bars are 50 mm in diameter. The bars are made of high strength maraging steel, with longitudinal wave velocity of 5017 m/s and Young’s modulus of 211 GPa.

The test procedure is described as follows. A striker bar is launched to hit the incident bar and generate a pulse as the incident wave that propagates through the bar system. When the stress wave arrives at the bar-specimen interface, part of it would be reflected and propagated back in the incident bar as the reflected wave, while the rest keeps propagating through the transmitted wave. The unit of elevation in the figure is “m”, and all other units are “cm” unless marked.

Figure 1: Schematic diagram of the excavation procedure.

Figure 2: Schematic illustration of layer I under excavation.
Figure 3: Distribution of fault SPD9-f1 in the main transformer room. Deformation of surrounding rock.

Table 1: Deformation of each pile position in main powerhouse and main transformer room.

| Pile position (m) | Upstream arch foot (mm) | Downstream arch foot (mm) | Average (mm) |
|-------------------|-------------------------|---------------------------|--------------|
| The main powerhouse |                         |                           |              |
| K0 + 00           | 0.65                    | 0.40                      | 0.53         |
| K0 + 30.2         | 0.62                    | 0.41                      | 0.52         |
| K0 + 60.4         | 0.56                    | 0.49                      | 0.53         |
| K0 + 90.6         | 0.56                    | 0.48                      | 0.52         |
| The main transformer room |           |                           |              |
| K0 + 00           | 0.41                    | 3.14                      | 1.78         |
| K0 + 30.2         | 0.49                    | 2.56                      | 1.53         |
| K0 + 60.4         | 0.51                    | 1.18                      | 0.85         |
| K0 + 90.6         | 0.48                    | 0.63                      | 0.56         |

Table 2: Depth of broken rock zone in main powerhouse and main transformer room.

| Pile position (m) | Upstream arch foot (mm) | Downstream arch foot (mm) | Average (mm) |
|-------------------|-------------------------|---------------------------|--------------|
| Main powerhouse   |                         |                           |              |
| K0 − 30           | 0.6                     | 0.4                       | 0.5          |
| K0 + 010          | 0.6                     | 0.6                       | 0.6          |
| K0 + 040          | 0.6                     | 0.6                       | 0.6          |
| K0 + 070          | 0.8                     | 0.6                       | 0.7          |
| K0 + 100          | 0.8                     | 0.6                       | 0.7          |
| Main transformer room |                   |                           |              |
| K0 − 30           | 1.8                     | 1.6                       | 1.7          |
| K0 + 010          | 3.4                     | 3.0                       | 3.2          |
| K0 + 040          | 2.4                     | 2.4                       | 2.4          |
| K0 + 070          | 2.4                     | 2.8                       | 2.6          |
| K0 + 100          | 2.4                     | 2.8                       | 2.6          |
bar as the transmitted wave. According to the stress wave signals recorded by strain gauges attached on the incident and transmitted bars, the axial compressive stress $\sigma(t)$, strain $\varepsilon(t)$, and strain rate $\dot{\varepsilon}(t)$ of the specimen can be derived by equations 1–3 [15]:

$$\sigma(t) = \frac{AE}{2A_S} [\varepsilon_i(t) + \varepsilon_r(t) + \varepsilon_t(t)],$$

$$\varepsilon(t) = \frac{C}{L_S} \int_0^t [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)] dt,$$

$$\dot{\varepsilon}(t) = \frac{C}{L_S} [\varepsilon_i(t) - \varepsilon_r(t) - \varepsilon_t(t)],$$

where $A$, $E$, and $C$ are the cross-sectional area, Young’s modulus, and 1D stress wave velocity of the bars, respectively. $A_S$ and $L_S$ are the cross-sectional area and length of the specimen. $\varepsilon_i$, $\varepsilon_r$, and $\varepsilon_t$ refer to incident, reflected, and transmitted strain of the bars recorded by the strain gauges.

During the dynamic loading of a valid test, the stress balance should be achieved. Otherwise, the specimen will be destroyed when the dynamic stress is not yet balanced due to inertial effect [30]. A typical stress curve of a valid test with dynamic stress balance is shown in Figure 6. During the tests, a C11000 copper disc with a diameter of 10 mm and a thickness of 1 mm is selected as the pulse shaper to achieve the dynamic stress balance [31].

### 3.4. Dynamic Compressive Test and Results.

According to the recommended method by ISRM, the specimens were tested by SHPB system. The test results of dynamic compressive strength at different loading rates are shown in Figure 7. As can be seen, a positive correlation between dynamic compressive strength and loading rates is established. The dynamic strength of the main powerhouse is higher than that of the main transformer room at similar loading rate.

In order to quantitatively analyze the positive correlation between rock dynamic compressive strength and loading rate, a linear equation is proposed, and the following results are obtained.

$$\sigma_1 = 0.022\dot{\sigma} + 154.41, \quad R^2 = 0.8862,$$

$$\sigma_2 = 0.022\dot{\sigma} + 120.97, \quad R^2 = 0.9077,$$

where $\sigma_1$ is the dynamic compressive strength of main powerhouse, $\sigma_2$ is the dynamic compressive strength of main transformer room, and $\dot{\sigma}$ is the loading rate. The dynamic compressive strength of the main powerhouse and main transformer room increases linearly with the loading rate, revealing the so-called rate dependency. The dynamic compressive strength of the rock specimen in the main powerhouse is about 33 MPa larger than that of the main transformer room under similar loading rates. It shows that the rock deterioration in the main transformer room is higher than that in the main powerhouse.
3.5. CT Scan Results. The tested rock specimens were scanned by the computerized tomography system. The scanned microstructures were reconstructed and analyzed to observe the internal crack distribution and development. The CT scan images of the intact specimens from the two caverns are shown in Figure 8. Substances with different densities are featured with different X-ray transmittances. The dark areas of specimens represent components with lower density, whereas the bright areas represent components with higher density. The CT scan image of the rock specimen in the main powerhouse has more bright areas than that in main transformer room, indicating that the surrounding rock density of main powerhouse is greater. Figures 9–12 present the cross-sectional images and the 3D distribution of the microstructures of the damage rock specimens from the two caverns. As the loading rate increases, the crack propagation and coalescence shows a gradual change in the configuration, i.e., when the loading rate is relatively small, two main cracks are connected within the specimen, leading to the V-shaped damage. As the loading rate increases, the number of cracks increases, and more cracks are interconnected in a Y-shaped distribution. When the loading rate becomes further higher, multiple cracks are interlinked with each other, revealing an approximately X-shaped damage. The difference is that the internal cracks of main powerhouse specimens develop slowly with the loading rate, whereas that of the main transformer room collapse quickly, which generates more cracks under the same loading rates, as can be compared through the images from Figure 9 to Figure 12.

Through the dynamic tests and the CT scan results, the strength of main powerhouse and main transformer room are determined to be different, which plays an important role in the different deformation of the two caverns. However, it cannot explain the cause of deformation anomalies in some sections of the main transformer room. There is no demonstration that the existence of fault SPD9-f1 causes abnormal deformation of surrounding rocks according to the geological survey report. Rock dynamic tests have limitations in verifying the influence of faults on large deformation. In order to investigate the influence of fault SPD9-f1 on abnormal deformation, discrete element method (DEM) is employed to explore the influence of fault on surrounding rock deformation.

4. Numerical Model of Underground Caverns
4.1. Establishment of the Numerical Model. According to the geological conditions and previous research of the underground caverns of the hydropower station, the deformation of the surrounding rock and the depth of the broken rock zone in main transformer room at section K0+00m are abnormal. The fault SPD9-f1 may be the main cause of abnormal deformation. A numerical model was built on the K0+00m section with fault SPD9-f1 using discrete element method (DEM), as shown in Figure 13. The numerical model is 250m in length and 200m in height. The entire numerical model contains 51 blocks, 21188 nodes, and 39840 deformable bodies. Constraints in X direction are applied on the left and right boundaries, and constraints in both X and Y directions are applied on the bottom boundary. The stress constraints in Y direction are applied on the top and bottom boundaries. The mechanical properties of surrounding rock are given in Table 3. According to the engineering geological exploration report, the fault mechanical parameters used in the model are given in Table 5.

The distribution of in-situ stress before excavation is shown in Figure 14. It illustrates that the first principal stress and the third principal stress increase gradually from top to bottom, and negative signs represent the direction of stress. The first principal stress is between 19 and 24 MPa, and the third principal stress is mainly between 4 and 9 MPa, which is consistent with the gravity stress field. However, the principal stresses increase sharply due to the presence of the fault SPD9-f1.

4.2. Analysis of Numerical Results. Through numerical simulation, the stress distribution after excavation of the underground caverns is revealed as shown in Figures 15 and 16. From the figures, it can be read that stress concentration occurs at the top arch of the tunnels, whereas stress releases at the sidewall area. The stress distribution of the main transformer room is also affected by the fault SPD9-f1 that the stress unloading area transfers along the fault SPD9-f1 to deep rock mass. The

| Location | Main powerhouse | Main transformer room |
|----------|----------------|-----------------------|
| Location | Main powerhouse | Main transformer room |
| Longitudinal wave velocity (m/s) | 3414 | 2780 |
| | 3848 | 3265 |
| | 4066 | 3385 |
| | 4121 | 3123 |
| Longitudinal wave velocity (m/s) | 4088 | 3362 |
| | 4062 | 3288 |
| | 4040 | 3176 |
| | 3438 | 3132 |
| Average wave velocity (m/s) | 3895 | 3208 |
| | 4191 | 3430 |
| | 3685 | 3142 |
Figure 6: Typical dynamic stress balance diagram.

Figure 7: The dynamic strength at different loading rates.

Figure 8: Typical CT scan images. (a) Main powerhouse. (b) Main transformer room.
Figure 9: Cross-sectional image of main powerhouse at different loading rates. (a) 950 GPa/s. (b) 1582 GPa/s. (c) 2029 GPa/s.

Figure 10: Cross-sectional image of main transformer room at different loading rates. (a) 821 GPa/s. (b) 996 GPa/s. (c) 1176 GPa/s.

Figure 11: Three-dimensional image of main powerhouse at different loading rates. (a) 950 GPa/s. (b) 1582 GPa/s. (c) 2029 GPa/s.
displacement distribution of the main powerhouse and the main transformer room after the excavation in the pilot tunnel is shown in Figure 17. The overall displacement of the main powerhouse is between 0 and 0.7 mm. The displacement of the upstream side in middle guide hole of main transformer room is also between 0 and 0.7 mm, whereas the maximum displacement of the downstream can reach 4.5 mm, mainly distributed in the exposed area of the fault SPD9-f1.

To further investigate the influence of the fault SPD9-f1 on the stability of the excavation process of main transformer room, a numerical model without the fault SPD9-f1 is established (other conditions are the same as the model with the fault SPD9-f1). The displacement distribution after the completion of the pilot tunnel excavation is shown in Figure 18. With the absence of the fault SPD9-f1, the displacement distributions of the main powerhouse and the main transformer room are relatively consistent. It can be demonstrated that the abnormal displacement of the downstream side of main transformer room is mainly caused by the fault SPD9-f1. It is worth noting that in the numerical model, the deformation of each measuring section is larger than the field measured value because the support is not considered in the modeling.

The comparison chart of the displacement considering and ignoring the fault SPD9-f1 is shown in Figure 19. It is found that the fault SPD9-f1 has significant influence on the deformation of surrounding rocks, the deformation value reaches 4.5 mm, which is consistent with the measurement results. Although the deformation is 0.75 mm without considering the SPD9-f1, it shows that the fault SPD9-f1 is the key factor to control the deformation. Relatively, the mechanical parameters of the surrounding rock have little effect on the deformation of the surrounding rock itself, and all the remaining deformation values are between 0.4 and 0.75 mm.

Table 5: Basic mechanical parameters of the surrounding rock mass around the fault SPD9-f1.

| Normal stiffness (GPa/m) | Tangential stiffness (GPa/m) | Cohesion (MPa) | Friction angle (°) | Tensile strength (MPa) |
|------------------------|----------------------------|----------------|--------------------|-----------------------|
| 10                     | 1                          | 0.1            | 25                 | 0                     |
The displacement diagram after the subsequent three-level excavation is shown in Figure 20. The deformation of surrounding rock where the fault SPD9-f1 exists is the largest, and as the excavation moves forward, the deformation of the surrounding rock mass around the fault keeps larger than other locations.

Through comparative numerical analysis of the two models, it can be conducted that fault SPD9-f1 is the main reason for the abnormal displacement of the main transformer room. As the excavation progresses, the deformation of surrounding rock becomes larger.

5. Results and Discussions

Comparing the original damage of the surrounding rock of the main powerhouse with the main transformer room, it was found that both caverns were affected by blasting excavation, whereas the damage degree of the main powerhouse is relatively smaller than that of the main transformer room. The strength of rocks from both tunnels shows typical characteristics of rate dependency. With the increase in loading rate, the dynamic compressive strength increases gradually. However, the dynamic compressive strength of rock specimens from the main powerhouse is higher than that from the main transformer room. In addition, there are fewer internal cracks in the rock specimens of main powerhouse at similar loading rates. The dynamic test results provide references for the subsequent excavation of the project, such as blasthole charge, noncoupling coefficient, blasthole number, and blasthole distance. Laboratory tests show that the difference in dynamic compressive strength is one of the reasons for surrounding rock deformation; however, the cause of abnormal deformation of some sections in main transformer room have not been explained.

Through numerical modeling, it is found that the fault is the main cause of abnormal deformation of the surrounding rock. According to the distribution map of the plastic zone shown in Figure 21, the plastic area of the top arch and the bottom wall rock is relatively small. In the middle guide tunnel, the plastic area at the side wall downstream is the largest compared with other places, mainly distributed near the fault SPD9-f1 and as the fault developed. It indicates that the fault SPD9-f1 is the cause of the failure of the surrounding rock and induces the rock damage. The results of field investigation, monitoring measurement, laboratory test, and numerical model show that the deformation of surrounding rock of Shuangjiangkou hydropower station is mainly controlled by faults. Figure 22 is the vector diagram of the surrounding rock displacement in the main transformer room, and the deformation of the pilot hole in the main transformer room points to the excavation-free surface in the radial direction. At the same time, due to the existence of the fault SPD9-f1, the maximum downstream deformation occurs where the fault exposed and developed towards the fault. This is consistent with the on-site monitoring result.

The excavation and unloading process induce the surrounding rock deformation, which is influenced by both the rock strength and the fault. The specific damage mechanism of the Shuangjiangkou hydropower station is illustrated in Figure 23. Excavation causes in-site stress redistribution, and in-site stress redistribution leads to rock burst [32]. In addition, the surrounding rock forms a broken rock zone, causing rock to deform greatly. The fault determines the size of the deformation, accompanied with fissures. The fissures play a role in the distribution and the depth of broken rock zone, indirectly influencing the surrounding rock deformation process. In addition, different in-site stress and distributions cause different types of damage, and in-site stress is greatly affected by fault [33]. At the beginning of blasting excavation, the redistribution of in-site stress leads to rock bursts, collapse, and other types of failure with the progress of tunneling, whereas the deformation of surrounding rock far from the tunnel face deformed gradually.
Figure 15: The first principal stress distribution diagram.

Figure 16: The third principal stress distribution diagram.

Figure 17: Displacement distribution diagram.
Figure 18: Displacement distribution map after excavation of the pilot tunnel without fault SPD9-f1. (a) Numerical model. (b) Displacement distribution diagram.

Figure 19: Displacement comparison diagram. MP = Main powerhouse, MTR = Main transformer room.

Figure 20: Displacement distribution diagrams of three-level excavation.
Figure 21: Distribution map of plastic zone in main transformer room.

Figure 22: Displacement vector diagram in main transformer room.
6. Conclusions

This study examined the surrounding rock deformation of Shuangjiangkou hydropower station. Combined with dynamic tests and field monitoring, the numerical method UDEC is adopted to study the deformation mechanism of surrounding rock and to reveal the influence of the fault. It is determined that the fault SPD9-f1 is the key factor affecting the surrounding rock deformation. The laboratory tests show that the rock specimen of the main powerhouse has stronger resistance to dynamic load than the main transformer room. On-site measurement data show that the deformation where the fault SPD9-f1 exists is largest compared with other sections. By comparison of the of two proposed models, it is found that the deformation value of the model with the fault is about 6 times as that of the model without the fault. Through the analysis of the results from the three methods, it is concluded that the fault SPD9-f1 has the controlling effect on the abnormal deformation of surrounding rock in the main transformer room. The following conclusions are drawn:

(1) The strength of the specimens in both the main powerhouse and the transformer room shows a strong rate dependency.

(2) The dynamic compressive stress of the surrounding rock in the main powerhouse is higher than that of main transformer room at similar loading rate.

(3) Due to the existence of the fault SPD9-f1, the deformation of the transformer room increases sharply. It shows that the fault is one of the key factors that causes the abnormal deformation of surrounding rock in Shuangjiangkou hydropower station.

(4) For underground tunnels with faults, the results of this study can be useful to the design of necessary supports at different locations.

Data Availability

The data used to support the findings of this study are available from the corresponding authors upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The research was funded by the National Natural Science Foundation of China (Grant No.51709200), the Natural Science Foundation of Tianjin (Grant No.18JCQNJC08100) and supported by State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology (Grant no. SKLGDU2K2014).

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