Experimental investigation of the mechanical properties of basalt in the Baihetan hydropower station region in China

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Abstract. The Baihetan hydropower station is mainly situated in the basalt formations of Mount Emei (Sichuan Province, China). During the excavation process, basalt has shown some special mechanical characteristics. In this study, the deformation and failure characteristics of basalt are investigated via laboratory tests (uniaxial and triaxial compression tests on blocky basalt samples) and field deformation tests (rigid bearing plates applied in situ to columnar jointed basalt). The information gathered is then analyzed to reveal the mechanisms responsible for the failure of basalt. Results show that (1) the stress–strain curves of cryptocrystalline basalt are essentially linear in the pre-peak region and the stress drops rapidly in the post-peak region. The failure mode of the rock changes from being fragmentation-dominated under low–medium confining pressure to fragmentation–shear composite failure under high confining pressure. (2) In the post-peak region, amygdaloidal basalt exhibits brittle mechanical behavior under low confining pressure and ductile behavior under high confining pressure. In terms of failure mode, the basalt transforms from splitting failure under low confining pressure to shear failure under medium–high confining pressure. (3) The deformation moduli measured during field tests with rigid bearing plates are spread over a large range and are influenced by various factors (including column nature, lumpiness, loading direction, unloading-induced relaxation, and stress state). (4) The deformation moduli of the rock masses of Classes II, III₁, and III₂ successively decrease and exhibit significant anisotropy.

Keywords: Baihetan hydropower station, blocky basalt, columnar jointed basalt, mechanical properties, experimental study

1. Introduction

As nonrenewable energy resources gradually become depleted, the efficient use of (renewable) water resources in southwest China is becoming increasingly important. As a result, numerous conservancy and hydropower projects have been constructed successively in China. Among these, the construction of the Baihetan hydropower station (located in Sichuan Province, China) has led to a remarkably diverse and complex range of crucial rock mechanics problems [1–2]. Due to the large-scale underground cavern groups, high geo-stresses, and complex geological conditions, some typical rock mechanics problems have occurred frequently during the excavation process (e.g., stress-induced failure of brittle basalt rock and fracturing and relaxation of jointed basalt columns) [3–5].
Research on the failure of hard-brittle rocks started some time ago in other countries. In Canada, for example, numerous laboratory tests, computer simulations, and field tests have been conducted on the mechanical properties of granite and the fracture mechanisms occurring therein at the Underground Research Laboratory (a test site intended for storing high-level radioactive nuclear waste) [4-5]. In China, scholars have performed numerous tests on fracturing of marble in deeply-buried diversion tunnels, for example, the Jinping II hydropower station [6-7]. Meng et al. [8] studied the mechanical responses of hard-brittle basalt in the vicinity of the Baihetan hydropower station. These researchers analyzed the three mechanisms responsible for the deformation and failure of the rocks surrounding the underground cavern groups of the hydropower station by combining the results obtained from rock mechanics tests and geological field investigations, including monitoring results and numerical simulations. Dai et al. [9] investigated the deformation and failure mechanisms of surrounding rocks caused by excavation-induced disturbances. Here, real-time microseismic monitoring was performed during the excavation and unloading of the underground powerhouses. Jiang et al. [10] conducted a series of borehole camera observations on engineering rock masses in underground caverns and used their results to reveal the unloading-induced cracking behavior of surface basalt layers, the discontinuous spatial distributions of cracking that occurs in the surrounding rocks, and the time-dependent evolution of the structure of cracked rock masses subject to high geo-stress. The abovementioned research has certain significance with respect to the macroscopic exploration of the fracturing and failure of the hard-brittle basalt rocks surrounding the underground powerhouses of the Baihetan hydropower station.

Columnar joints are tensile rupture structures that are primarily formed during the condensation and contraction of basaltic lava. They consist of multiple groups of joint planes involving inter-columnar joint planes, intra-columnar vertical blind joint planes, and intra-columnar horizontal joint planes. Given the special mosaic structures formed, columnar jointed basalt shows various complex mechanical characteristics, such as discontinuities, nonuniformity, and anisotropy [11]. Some valuable research on the structural characteristics and mechanical properties of the columnar jointed basalt in the Baihetan hydropower station region has been conducted to date. The research performed by PowerChina Huadong Engineering Corporation Limited is, perhaps, the most representative of this research [12-13]. Furthermore, Hu et al. [14] and Hao et al. [15] have also conducted important work. Basalt differs from other hard-brittle rocks in terms of its failure characteristics and mechanisms. Specifically, those of columnar jointed basalt are extremely complex due to its special structural characteristics. Therefore, in this work, we conduct a detailed experimental investigation of the basalt in the region of the Baihetan hydropower station. Laboratory tests (uniaxial and triaxial compression tests) were performed for the blocky basalt samples of good integrity. In addition, field tests are conducted using rigid bearing plates to derive information about the highly jointed columnar basalt present in the region. The deformation and failure characteristics of the blocky basalt samples and columnar jointed basalt are discussed in detail, and their failure mechanisms are analyzed. The results form a solid foundation for the accurate exploration of the mechanical responses and evolutionary characteristics of the rocks surrounding the underground powerhouses of the Baihetan hydropower station. They also provide a valuable reference to help us understand why disasters may occur when excavating hard-brittle rock masses under high stress and help us develop control methods for averting such disasters.

2. Project profile

2.1. Background

The Baihetan hydropower station is the largest hydropower project currently under construction in the world. It is located on the lower reaches of the Jinsha River between Sichuan and Yunnan Province in the southwest of China. The installed gross capacity of the Baihetan hydropower station is 16,000 MW (Figure 1). The water diversion and power generation systems of the station are symmetrically distributed on the left and right banks of the river. The main and auxiliary powerhouses in the left and
right banks have tunnels that are 438 m in length, and their heights and widths extend up to 88.7 and 31–34 m, respectively. The tailrace surge tanks have diameters measuring 43–48 m and vertical walls of height 77–92 m. The total height of the excavation is of the order of a hectometer. Thus, the scale of its underground cavern groups puts the Baihetan power station among the top projects in the world, including those that have been constructed, are still under construction, and are planned for future construction.

Figure 1. Details of the Baihetan hydropower station, showing: (a) its location in China, (b) its basic layout on the Jinsha River, (c) the rib spalling of the blocky basalt in the underground powerhouses, and (d) the relaxation and fracturing of the columnar jointed basalt in the diversion tunnels

2.2. Geological conditions
The left and right bank powerhouses of the Baihetan hydropower station are embedded inside the mountains that form the two sides of the valley of the Jinsha River. The powerhouse in the left bank has a horizontal burial depth of 600–1000 m and a vertical burial depth of 260–330 m; the corresponding depths of the right bank powerhouse are 420–800 m and 420–540 m. The geo-stress in the region mainly comes from the tectonic stress acting on the river valley. The maximum principal stress in the left bank powerhouse region is in the range 19–23 MPa (the maximum horizontal principal stress is measured to be 33.39 MPa); the corresponding principal stress in the right bank powerhouse region is 22–26 MPa (with a maximum measured horizontal principal stress of 30.99 MPa).
The basalt formed in the Permian period mainly outcrops in the Mount Emei region in which the Baihetan hydropower station project is located (and includes cryptocrystalline, amygdaloidal, and oblique basalts). The cryptocrystalline basalt with developed columnar joints is referred to as columnar jointed basalt. The rock masses are slightly weathered or fresh, with high strength and brittleness. The underground powerhouses and main transformer chambers are located in formations made of blocky basalt, whereas the foundations of the dam, surge tanks, and diversion tunnels are situated in columnar jointed basalt. Numerous unfavorable structures (e.g., stochastic fractures, dense columnar joints, and blind joints) have developed in the rock masses on different scales. Due to the large scale of the project, complex geological conditions, and the presence of medium–high geostress, the rocks surrounding the underground cavern groups are characterized by their susceptibility to rupture. Various failure modes frequently appear in brittle rock masses (rib spalling, cracking, and fracturing and relaxation), as illustrated in Figs. 1c and 1d. These images demonstrate the brittle failure of the basalt under high stress and the fracturing and relaxation of columnar jointed rock masses under the effect of unloading. They thus highlight the conflict between the ultrahigh strength of the rock and low initiation and damage strength of the rock masses at the site. The mechanical properties of the basalt are therefore different from those of the marble found at the Jinping site.

2.3. Structural characteristics of columnar jointed basalt

Columnar jointed basalt is widely distributed in the Baihetan hydropower station region, as displayed in Figure 2. The columnar jointed basalt in the Baihetan hydropower station region can be divided into three types according to the geometric shapes of the cross-sections of the columns and the degree of regularity and diameters of the columns of columnar joint rock masses (Figure 2).

Class I: The density of the developed columnar joints is high, but most of them do not cut the basalt into complete columns. Columns are essentially 2–3 m in length and 13–25 cm in diameter. Microfractures are developed in the gray/black rocks that cut the rock masses into blocks with a lumpiness of ~5 cm. This class of joints is mainly distributed in the P2β33 sub-layer.

Class II: Columnar joints are irregularly developed and do not cut the basalt into complete columns. Columns are essentially 0.5–2.0 m long and 25–50 cm in diameter. Microfractures are favorably developed in the columnar joints; however, they are interactively embedded with each other and do not cut the rocks completely with a lumpiness of ~10 cm. This class is mainly found in P2β61, P2β71, P2β82 sub-layers.

Class III: Columnar joints are irregularly developed and therefore do not cut the basalt into complete columns. The columns are bulky, with lengths of 1.5–5 m and diameters of 0.5–2.5 m. The columnar joints do not completely cut the rock and are closely embedded. This class mainly appears in P2β22, P2β23, and P2β1 sub-layers.

The columns in the jointed basalt of type Class I have dip angles of 70–85°. Their cross-sections are mainly in the form of irregular pentagons and quadrangles; they also have straight and rough cylindrical surfaces. The columnar jointed rock masses in the Baihetan hydropower station region are highly jointed. Apart from the development of columnar structural planes, longitudinal and transverse micro-joints are also widely developed in the columns. Therefore, columnar jointed rock masses can be characterized by their most significant features—they are discontinuous, anisotropic, and exhibit high levels of initial damage.
Figure 2. Distribution and classification of the columnar jointed basalt in the Baihetan hydropower station region showing: (a) distribution zones of the different classes of columnar jointed basalt and (b) examples of the different classes in the region

3. Laboratory tests on blocky basalt
Uniaxial compression and conventional triaxial compression tests were conducted on the blocky basalt samples in the laboratory to explore its mechanical behavior and help reveal the mechanisms by which the basalt is likely to fail.

3.1. Test scheme
Rock cores were drilled on the site (at a vertical burial depth of approximately 500 m) to sample the rocks surrounding the underground powerhouses of the Baihetan hydropower station. The cores were 50 mm in diameter. In accordance with the test methods recommended by the International Society for Rock Mechanics, the rock cores were processed to form standard cylindrical samples (ø50 mm and height 100 mm, giving an aspect ratio in the range 2–3), as shown in Figure 3.
Figure 3. Basalt samples used for the laboratory mechanical tests, showing samples made of: (a) cryptocrystalline basalt and (b) amygdaloidal basalt

The loading equipment employed was a rigid press machine for rocks (MTS model 815.03, with an integral framework rigidity of 11.0 × 10^9 N/m). The machine was capable of applying a maximum axial force of 4,600 kN and a maximum confining pressure of 140 MPa. Tests were performed using loading rates of 0.001 mm/s (axial displacement) and 0.1 MPa/s (confining pressure). The axial and lateral strains of the samples were automatically recorded using extensometers. At least five samples were tested at each level of confining pressure. The testing scheme is summarized in Table 1.

### Table 1. Test parameters employed in the mechanical tests

| Type of basalt            | Dimension (mm × mm) | Confining pressure (MPa) | Axial loading rate (mm/s) | Lateral loading rate (MPa/s) |
|---------------------------|---------------------|--------------------------|---------------------------|-----------------------------|
| Cryptocrystalline basalt  | ø50 × 100           | 0, 10, 20, 30, 50, 70    | 0.001                     | 0.1                         |
| Amygdaloidal basalt       | ø50 × 100           | 0, 5, 10, 15, 20, 30     | 0.001                     | 0.1                         |

3.2. Test results and analysis

3.2.1. Stress–strain curves. The deviatoric stress–strain curves measured using different types of basalt are illustrated in Figure 4 for different confining pressures. Figure 4a shows the results for cryptocrystalline basalt. The curves are all essentially linear in the pre-peak stage, with the degree of nonlinearity being insignificant. After peaking, the stress drops sharply as the samples succumb to strong brittle failure. Therefore, post-peak curves are difficult to obtain for most samples. Unlike the brittle–ductile transition that characterizes other types of hard-brittle rocks (e.g., marble), when a high confining pressure is applied, the cryptocrystalline basalt has a brittleness that is not significantly affected by the application of high confining pressure (at least at the pressures used in this study). The case is the same even though its residual strength increases significantly as the confining pressure is increased. No significant yield platforms appear around the peaks when a high confining pressure is used (σ ≥ 50 MPa).

Figure 4b illustrates the results obtained for amygdaloidal basalt. Here, when the confining pressure is low (0 MPa ≤ σ3 ≤ 10 MPa), the stress curve is markedly concave in the initial stages, implying a compaction effect due to the presence of initial defects in the rock (e.g., amygdales). This nonlinear behavior becomes insignificant shortly before the peak stage where the curves are essentially linear. In the vicinity of the peak, multiple stress drops appear and the stress drops rapidly after some fluctuations, indicating the occurrence of remarkable brittle character. As the confining pressure is raised in Figure 4b, the stress–strain curves become much less nonlinear in the initial compaction stage and thus essentially become linear in the pre-peak stage. The curves then gently zigzag in the peak region, and a ductile platform can be discerned whose range constantly increases as the confining pressure increases. The stress slowly declines in the post-peak stage, which indicates the gradual exhibition of a brittle–ductile transition. This behavior is similar to the brittle–ductile transition characteristics exhibited by other types of hard-brittle rocks (e.g., marble) under high
confining pressures.

Figure 4. Typical deviatoric stress–strain curves for: (a) cryptocrystalline basalt and (b) amygdaloidal basalt subjected to different confining pressures [16,17]

The presence of amygdales has a significant effect on the deformation and failure characteristics of basalt, especially in the peak and post-peak stages where its mechanical behavior undergoes a gradual brittle–ductile transition. As a result, the brittleness of basalt is reduced. The elastic modulus and strength parameters of amygdaloidal basalt are significantly smaller than those of cryptocrystalline basalt, as presented in Table 2.

### Table 2. Mechanical properties of different types of basalt

| Type of basalt          | $E$ (GPa) | $\nu$ | $c$ (MPa) | $\phi$ (°) | $\sigma_c$ (MPa) |
|-------------------------|-----------|-------|-----------|------------|-----------------|
| Cryptocrystalline basalt| 47.38     | 0.16  | 61.01     | 40.48      | 209.57          |
| Amygdaloidal basalt     | 36.30     | 0.18  | 32.02     | 40.60      | 130.44          |

3.2.2. Failure characteristics. The macroscopic failure characteristics of a rock mass (e.g., intensity, ductile/brittle characteristics, and disintegrated form) can reflect, to some extent, the mechanism responsible for its failure. Thus, a detailed knowledge of such characteristics provides a firm basis for understanding the failure phenomena occurring on site and for devising support and control schemes. Typical failure patterns found in basalt samples subjected to different confining pressures are presented in Figure 5 (note that the sketches clarifying the macroscopic cracks formed in the amygdaloidal basalt samples only show the amygdales adjacent to the cracks).

In Figure 5a, when the cryptocrystalline basalt samples fail, they burst open under uniaxial loading (accompanied by a loud roar and expulsion of rock fragments). The fragmentation level is high and suggests that the samples are extremely brittle. The broken lamellar fragments have clean surfaces with a distinct absence of powder, suggesting that tensile failure occurs. In the low–medium range of confining pressure ($0 \text{ MPa} < \sigma_3 < 50 \text{ MPa}$), the samples fragmented with longitudinal tensile cracks pass through them from the upper end face to the lower end face; many secondary transverse cracks are also apparent. Therefore, the fracture planes are rough; numerous shear-induced scratches, rock fragments, and debris are also generated. Here, the rocks primarily undergo tensile failure, accompanied by some shear failure. When the confining pressure is high ($\sigma_3 \geq 50 \text{ MPa}$), the fractures generated mainly cut obliquely through the whole of the rock sample. The fracture planes are smooth, and fine stone dust appears on the lamellar fragments. Multiple obvious transverse tensile cracks are found and appear to have caused the fragmentation of the rocks. Macroscopically, the rock samples are mainly subjected to shear failure, accompanied by some tensile failure. Figure 5b illustrates the failure patterns generated in the amygdaloidal basalt samples subjected to uniaxial loading. In this type of basalt, the sound generated at the point of failure is crisp and intense, suggesting that the rock has significant brittle characteristics. The rock samples undergo splitting failure: multiple longitudinal tensile cracks run through the rock samples from the upper end face to the lower end face. During the splitting process, debris fall down locally. Most cracks pass through amygdales, but some fractures are located at the interfaces between amygdales and the matrix. The trajectories of the fractures are affected by the amygdales. When the confining pressure is low (i.e., $0–10 \text{ MPa}$), the amygdaloidal basalt samples mainly undergo splitting, and shear cracks are found to form in local zones within the samples.
Macroscopically, the samples undergo tensile–shear composite failure. At high pressures (10 MPa < $\sigma_3$ ≤ 30 MPa), the amygdaloidal basalt samples become globally damaged by oblique shear cracks. Some amygdales along the primary fracture planes are crushed and exfoliated, and a certain number of tensile cracks appear in the vicinity of the fracture planes. The number of tensile cracks formed gradually decrease as the confining pressure increases. Macroscopically, the samples thus primarily undergo shear failure, supplemented by some tensile failure.

Figure 5. Typical failure modes of samples of: (a) cryptocrystalline basalt and (b) amygdaloidal basalt subjected to different confining pressures [16,17].

Hard-brittle rocks (e.g., marble, granite, and sandstone) succumb to splitting failure under low confining pressures, whereas shear failure dominates under medium–high confining pressure [4-7]. However, the main
fracturing mode of cryptocrystalline basalt changes from being fragmentation-dominated under low–medium confining pressure to fragmentation–shear composite failure under high confining pressure. Thus, the fragmentation failure of cryptocrystalline basalt can be considered the most significant characteristic, which distinguishes its behavior from that typically encountered in other hard rocks. The failure characteristics observed in amygdaloidal basalt are similar to those commonly found in other hard-brittle rocks (splitting failure under low confining pressure; shear failure under medium–high confining pressure). Therefore, the presence of amygdales changes the failure characteristics of basalt.

4. In situ tests of columnar jointed basalt
Columnar jointed basalt has peculiar structural characteristics that are inadequately represented in the samples prepared for laboratory testing (complete inter-columnar joints, intra-columnar joints, and hidden microfractures). Therefore, accurately determining the true character of columnar jointed basalt on the basis of the results of highly discrete laboratory tests is difficult. To remedy this situation, field tests were conducted using rigid bearing plates applied in situ to columnar jointed basalt for further exploring its deformation characteristics.

4.1. Testing scheme
The testing points selected for the field deformation tests were all located in Pβ32 and Pβ33 sub-layers. The tests were performed in the prospecting adits created in the two banks of the river (in the dam area). The points used to investigate the effect of the horizontal loading were distributed along the walls of the lower reaches of the adit or the walls in the mountains; those used to investigate the effect of vertical loading were situated on the floor of the adit, as illustrated in Figure 6. A total of 67 points were tested. During the field deformation tests, the overall deformation, elastic deformation, deformation modulus, and elastic modulus were tested under different loading levels.

![Figure 6. Diagrams showing the typical rigid bearing plate configurations used in the vertical and horizontal field deformation tests; key: ① columnar joint, ② rigid bearing plate, ③ micrometer gauge, ④ jack, ⑤ transfer column](image)

4.2. Test results
The deformation tests with rigid bearing plates yielded the deformation and elastic moduli of the columnar jointed rock masses. The geological conditions at the testing points were analyzed, and nonrepresentative testing points were eliminated. The deformation moduli obtained at other testing points were classified and summarized according to the type of rock mass present and loading direction. The statistical results are shown in Table 3, and a histogram is displayed in Figure 7 to highlight the spread in the values of the deformation moduli.

| Class | Loading direction | Number of tests | Deformation modulus under 0–8 MPa (GPa) | Tangent modulus under 8 MPa (GPa) |
|-------|-------------------|----------------|----------------------------------------|----------------------------------|

Table 3. Classification and statistical information about the measured deformation moduli
|       | Range    | Mean  | Range    | Mean  |
|-------|----------|-------|----------|-------|
| II    | Horizontal | 3 | 22.31–31.99 | 26.18 | 23.02–27.36 | 24.65 |
|       | Vertical  | 3 | 9.83–15.99  | 11.95 | 9.30–14.72  | 11.35 |
| III₁  | Horizontal | 9 | 8.89–31.35  | 18.53 | 9.97–34.12  | 18.58 |
|       | Vertical  | 16 | 3.22–14.72  | 9.02 | 4.32–16.00  | 9.53  |
| III₂  | Horizontal | 9 | 10.02–18.93 | 13.24 | 10.10–18.58 | 12.93 |
|       | Vertical  | 14 | 4.30–13.49  | 7.35 | 4.45–14.73  | 8.42  |

| II, III₁, and III₂ | Horizontal and vertical | 39 | 4.30–31.99 | 12.88 | 4.32–34.12 | 12.26 |

Figure 7. Histogram showing the frequency distribution of the deformation moduli of the rock masses; the continuous curve is a fit to a normal distribution function.

The statistical results suggest the following:

1. The test results obtained for deformation modulus are spread over a large range, 4.30–31.99 GPa, which means that the maximum value measured is nearly eight times larger than the minimum value measured. This indication reflects the fact that the deformation modulus is affected by numerous factors (including column nature, lumpiness, degree of weathering, loading direction, unloading-induced relaxation, and stress state). Fractures developed in different types of rock masses are mainly short, and the lumpiness is low (generally in the range 2–15 cm). Except for some points that are affected by dislocation planes, the deformation moduli of the rock masses are mainly affected by the tightness of the embedded rock blocks, that is, the closeness of short fractures.

2. The deformation moduli of the rock masses in Classes II, III₁, and III₂ decrease successively; the mean horizontal deformation moduli of the classes exceed 13 GPa (being equal to 26.18, 18.53, and 13.24 GPa, respectively). Meanwhile, the mean vertical deformation moduli are all less than 13 GPa (11.95, 9.02, and 7.35 GPa). Considering that a layer subjected to stress relaxation appears at most of the vertical testing points, the test values in the vertical direction are low.

3. The horizontal deformation moduli of different types of rock masses are higher than the vertical deformation moduli that indicate the deformation moduli of the rock masses as highly anisotropic. The vertical deformation modulus is more affected by inter-layer dislocations and low-angle fractures than the presence of columnar joints.

4. In the vertical direction, the tangent moduli of the rock masses in Classes III₁ and III₂ under 8 MPa are 5.7% and 14.6% larger than the deformation moduli under 0–8 MPa, respectively. The corresponding differences in the horizontal direction are small. Similarly, the tangent moduli of the rock masses in Class II are approximately equal to their deformation moduli, indicating that the tangent modulus of a homogenous rock mass is not significantly different from its secant modulus.

5. Conclusions

1. The pre-peak stress–strain curves of cryptocrystalline basalt were essentially linear, whereas the stress dropped rapidly in the post-peak stage. No significant yield platforms were found in the peak region under high confining pressures, suggesting that the basalt shows great brittleness. The presence of amygdales causes
remarkable changes to the characteristics of the basalt (as can be seen from the stress–strain curves). Amygdaloidal basalt exhibits brittle behavior under low confining pressures; under high confining pressures, its brittleness is significantly reduced and ductile behavior is exhibited.

(2) The primary fracture mode of cryptocrystalline basalt changes from being fragmentation-dominated under low–medium confining pressure to fragmentation–shear composite failure under high confining pressure. The propensity of cryptocrystalline basalt to readily undergo fragmentation failure is its most significant characteristic, which distinguishes it from other hard rocks. The failure characteristics of amygdaloidal basalt are similar to those commonly encountered in hard-brittle rocks; that is, it undergoes splitting failure under low confining pressure and shear failure under medium–high confining pressure.

(3) The results obtained in the in situ deformation tests with rigid bearing plates show great variation. The deformation moduli are spread over a large range, 4.30–31.99 GPa, which means that the ratio of the maximum to minimum deformation modulus is approximately eight. This condition reflects the wide variety of factors influencing the deformation moduli of the rock masses (column nature, lumpiness, degree of weathering, loading direction, unloading-induced relaxation, and stress state).

(4) The deformation moduli of the rock masses in Classes II, III1, and III2 successively decrease. The horizontal deformation moduli of the different classes are all higher than their vertical deformation moduli, which is a strong indication that the rock masses have deformation moduli that are highly anisotropic.

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