

Research Article

Rock Mass Classification for Columnar Jointed Basalt: A Case Study of Baihetan Hydropower Station

Shiyue Zhang,^{1,2,3} Mingjie He,⁴ Jinjian Gu,⁴ Zhihao Cui,^{2,3} Jian Wang,^{2,3} Lin Zhong,⁵ Qingxiang Meng,^{2,3} and Huanling Wang⁶

¹Shanghai Research Institute of Materials, Shanghai 200437, China

²Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, Nanjing 210098, China

³Research Institute of Geotechnical Engineering, Hohai University, Nanjing 210098, China

⁴Huadong Engineering Corporation Limited, Hangzhou 311122, China

⁵Nanjing Yangtze River Management Office, Nanjing 210011, China

⁶Key Laboratory of Coastal Disaster and Defense, Ministry of Education, Hohai University, Nanjing 210098, China

Correspondence should be addressed to Huanling Wang; wanghuanling@hhu.edu.cn

Received 19 October 2020; Revised 18 November 2020; Accepted 25 November 2020; Published 29 December 2020

Academic Editor: Chun Zhu

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Rock mass classification is important in preliminary design of geotechnical engineering projects. Using the columnar jointed basalt at the foundation of Baihetan Hydropower Station as an example, this paper presents a classification scheme of the columnar jointed rock. Unlike many common rock masses, an obvious characteristic of columnar jointed rock is that it is discontinuous in geometry while continuous in mechanics. Due to the inapplicability of existing rock mass classification systems, a classification scheme, combined with rock mass integrity, weak plane tightness, and permeability, is proposed. The new classification system has five grades with quantitative factors, which takes into account the features of columnar joints. As an easy-to-use scheme and case study, it would be helpful as a reference in the rock mass classification of similar problems.

1. Introduction

Columnar jointing is a typical fracture pattern (shown in Figure 1), best known from such locations as the Giant's Causeway or Fingal's Cave, in which cracks self-organize into a nearly hexagonal arrangement, forming an ordered colonnade [1, 2]. As a miraculous natural phenomenon, there is a long research history since the Giant's Causeway was first reported in the 17th century [3]. Nowadays, the formation of columnar joints is reasonably understood as a result of cracks propagating into cooling lava flows [4–7]. As a kind of adverse geologic condition, a reasonable and suitable rock mass classification is extremely important for engineering projects.

Developing the hydropower energy to the west is a trend in China [8–10]. With the booming development of the water conservancy and hydropower projects, more and more com-

plicated engineering geological conditions, such as columnar jointed rock, are encountered. At the foundation of Baihetan Hydropower Station, columnar jointed rock mass is widely distributed. A large number of laboratory and in situ tests give a clear illustration of the characteristics of columnar joints and similar jointed rock mass [11–16]. Unlike other traditional types of rock mass, the geologic structure of columnar jointed basalt is very complex [17, 18]. Due to the cuts of joints, the value of rock quality designation (RQD) is quite low, and it will be identified as fragmented rock mass using existing rock classification methods [19, 20]. However, the seismic velocities V_p are high and the rock strengths are high in certain stress states. It has typical characteristics of discontinuity in geometry and continuity in mechanical properties. The rock quality will be substantially underestimated, and traditional rock classification system is not suitable for such type of rock mass.

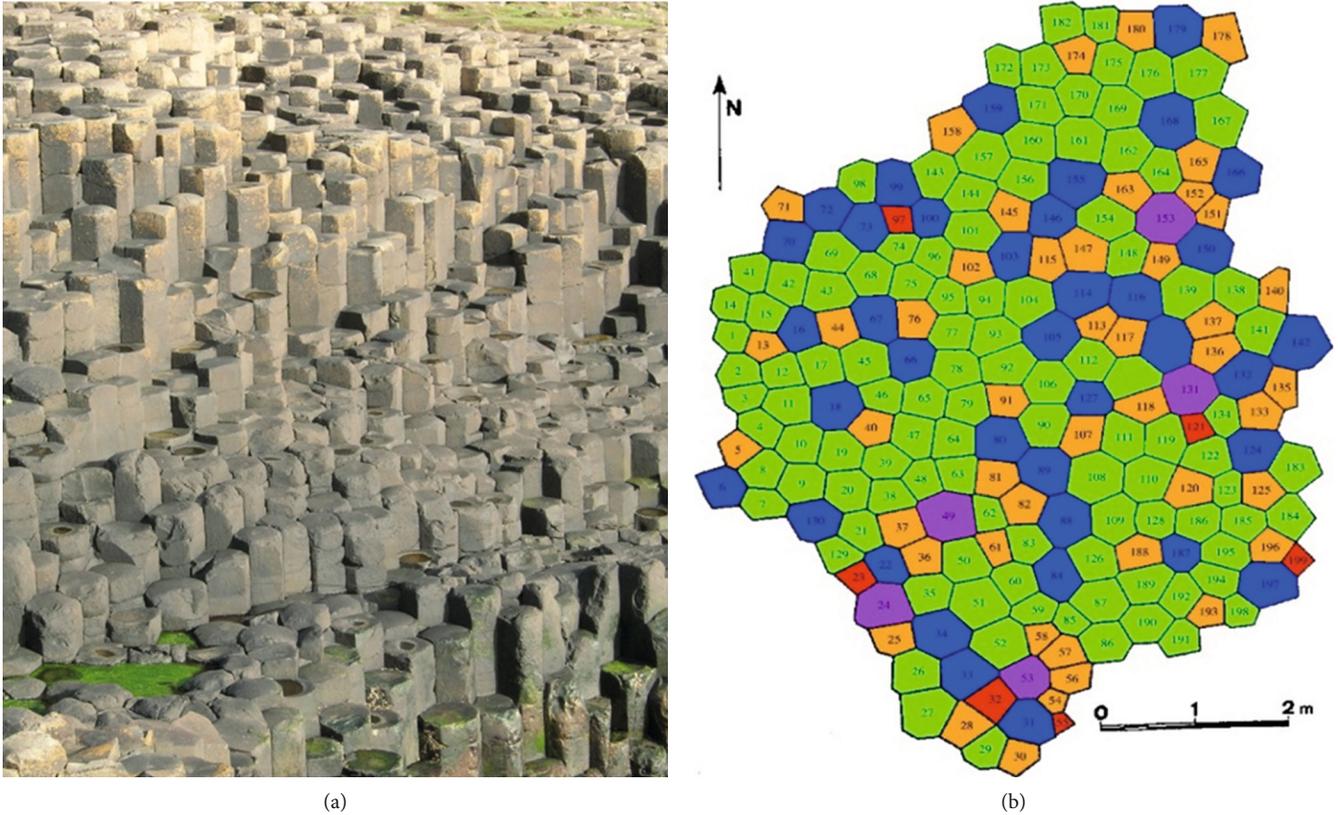


FIGURE 1: Typical columnar jointed rock masses: (a) Giant's Causeway, Antrim in Northern Ireland and (b) colored map of about 200 columns [1].

Considering the exact measurement of mechanical property is very difficult [21–27], rock mass classification methods are commonly used at the preliminary design stage of a construction project. Considering the inapplicability of existing rock classification systems, a rock classification system, integrating a set of key factors controlling the rock quality such as weathering, degree of stress release, degree of integrity of rock mass, and permeability, is proposed. A case study on columnar jointed basalt is conducted; the results may be extended to other similar cases or used as reference for other engineering projects.

2. Existing Rock Mass Classification Systems

A proper rock mass classification can give engineers a quick and reliable estimation of the rock mass without complicated calculations of various parameters. It forms the basis for design and estimation of the required amount and the type of rock support in groundwater control measures. A well-known early attempt is Terzaghi's classification system for support of tunnels. Based on the most important inherent and structural parameters, several other classification systems, such as RMR, GSI, and Q, have been proposed and widely used in engineering. A detailed list of rock mass classification systems is presented in Table 1.

From these rock classification systems, the factors involved in the existing empirical classification systems are related mainly to the general information of rock mass, geometric characteristics of discontinuities, and construction method. Over the past several decades, the existing rock mass classifications have been applied successfully in tunneling, underground mining, and slopes. However, it is noted that considerable caution must be exercised in applying a rock mass classification to other rock engineering problems, although the classification scheme is appropriate for its original applications.

Columnar jointed basalt rock, as a kind of special rock mass, is not suitable to be classified with these factors, and sometimes, the results are evidently inconsistent under different classification schemes. Furthermore, many effective factors in rock mass descriptions, such as underground water and seismic velocity, are absent in existing classification schemes. The objective of this paper is to propose a classification scheme for columnar jointed basalt based on a comprehensive understanding of its properties.

3. Geological Conditions

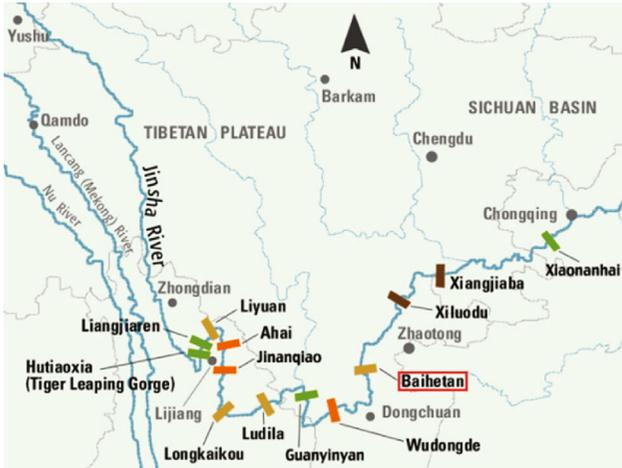
Baihetan Hydropower Station is located on the downstream reaches of the Jinsha River, at the border of Ningnan County of Sichuan Province and Qiaojia County of Yunnan Province

TABLE 1: Existing rock mass classification systems.

Name	Abbrev.	Authors	Application	Comments
—	—	Ritter [28]	Tunnels	The first attempt for the formalization of an empirical approach to tunnel design.
Rock load	—	Terzaghi [29]	Tunnels	The earliest reference to the use of rock mass classification for the design of tunnel support.
Stand-up time	—	Lauffer [30]	Tunnels	Related to the stand-up time of an unsupported tunnel excavation.
Rock quality designation	RQD	Deere [31]	General	Component factor of many classification systems.
Rock structure rating	RSR	Wickham et al. [32]	Tunnels	First rating system for rock masses.
Rock tunneling quality index	Q	Barton et al. [33]	Tunnels	The most commonly used classification systems for tunnels.
Rock mass rating	RMR	Bieniawski [34]	Tunnels and cuttings	Widely used for both tunnels and slopes.
Rock mass index	RMi	Palmstrom [35]	Tunnels	An approximate value for the compressive strength.
New Austrian tunneling method	NATM	Rabcewicz [36]	Tunnels	Used in the determination of support measures.
Mining rock mass rating	MRMR	Laubscher [37]	Mines	Based on RMR (1973).
Rock mass strength	RMS	Selby [38]	Cuttings	Based on natural slope database.
Slope mass rating	SMR	Romana [39]	Cuttings	Based on RMR (1979). The most commonly used classification system for slopes.
Slope rock mass rating	SRMR	Robertson [40]	Cuttings	Based on RMR. The classification is provided for of weak altered rock mass materials from drill hole cores.
Chinese slope mass rating	CSMR	Chen [41]	Cuttings	Adjustment factors have been applied to the SMR system for the discontinuity condition and slope height.
Geological strength index	GSI	Hoek et al. [42]	General	Based on RMR (1976). For nonstructurally controlled failures.
Modified rock mass rating	M-RMR	Unal [43]	Mines	For weak, stratified, anisotropic, and clay-bearing rock masses.
Basic quality	BD	Ministry of Water Resources, PRC [44]	General	Engineering quality classification of rock mass in China.
Rock slope deterioration assessment	RDA	Nicholson and Hencher [45]	Cuttings	For shallow, weathering-related breakdown of excavated rock slopes.
Slope stability probability classification	SSPC	Hack et al. [46]	Cuttings	Probabilistic assessment of independently different failure mechanics.
Volcanic rock face safety rating	VRFSR	Singh and Connolly [47]	Cuttings (temporary excavations)	For volcanic rock slopes to determine the excavation safety on construction sites.
Falling rock hazard index	FRHI	Singh [48]	Cuttings (temporary excavations)	Developed for stable excavations to determine the degree of danger to workers.
Basic geotechnical description	BGD	ISRM [49]	General	Established in 1981 by ISRM.
Size strength classification	SSC	Franklin [50]	Tunneling	Based on the strength of intact rock and the spacing of discontinuities.
Simplified rock mass rating	SRMR	Brook and Dharmaratne [51]	General	Three major components: the intact rock strength, joint spacing, and joint type.

(Figure 2). It is one of the cascade hydropower stations on the Jinsha River, with the Wudongde Hydropower Station on the upstream side and Xiluodu Hydropower Station 195 km

away on the downstream side. As the second level of the cascade hydropower stations on Jinsha River, Baihetan Hydropower Station is a concrete double-curvature arch dam with

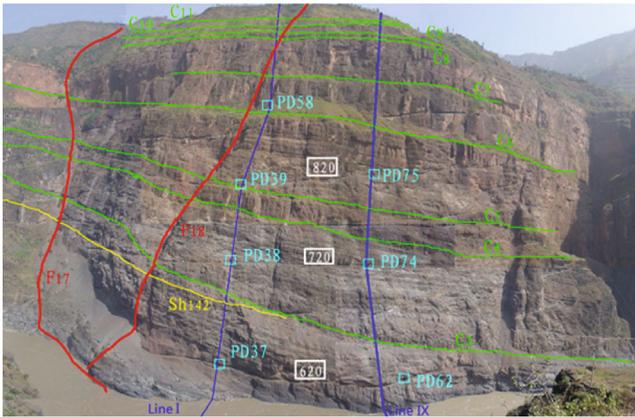


(a)

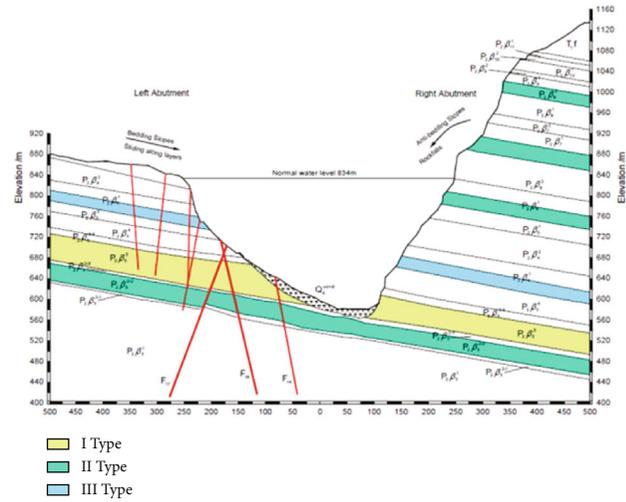


(b)

FIGURE 2: Baihetan Hydropower Station: (a) location of the hydropower station and (b) construction site.



(a)



(b)

FIGURE 3: Profile distribution of columnar basalt at Baihetan dam site: (a) left bank of dam site and (b) profile information of Line I.

a height of 289 m and installed plant capacity of 14,004 MW. The dam site is about 260 km from Kunming and about 400 km from Chongqing, Chengdu, or Guiyang, respectively. The straight distance between the dam site and Shanghai of the East China Region is around 1850 km. The site is located to the east of Zemuhe and Sikai-Jiaojihe fracture zones and to the north of Xiaojiang fracture zone. Although active fault zones exist in this region and the regional seismic activities are intense, no intense earthquake has been recorded in a 40 km range around the dam site.

3.1. Geomorphology and Topography. The river valley at the dam site is asymmetrical and is of a V shape, with massive mountains on both sides. On the left bank, the landform above El. 850 m is wide and flat at No. 1 Exploration Line, while the landform below alternates with gentle and steep slopes or cliffs. On the right bank, the landform above El.

1170 m consists of gentle slopes, whereas cliffs and steep slopes cover the land below El. 1170 m. The outcrops at the dam site are mainly Emei basalt formed in the late Permian Period, with underlying Maokou limestone formed in the early Permian Period. The river alluvial, about 5 to 25 m in thickness, is composed of Holocene boulders with sand. The Q4 unconsolidated deposits distribute mainly on riverbed, terraces, and sloping mesas. An illustration of the distribution of columnar joints is presented in Figure 3.

It can be seen that the middle dam site is mainly composed of $P_2\beta_2 \sim P_2\beta_6$ basalts, basically including microlitic-aphanitic basalt, amygdaloidal basalt, and varied basaltic brecciated lava (Figure 4). The rocks are hard but developed with some columnar joints, especially in the middle portion of $P_2\beta_3$ stratum where the diameters of columns range from 5 cm to 10 cm; the columnar joints in other strata range from 20 cm to 30 cm. Weak basalt or brecciated tuff interlayers in

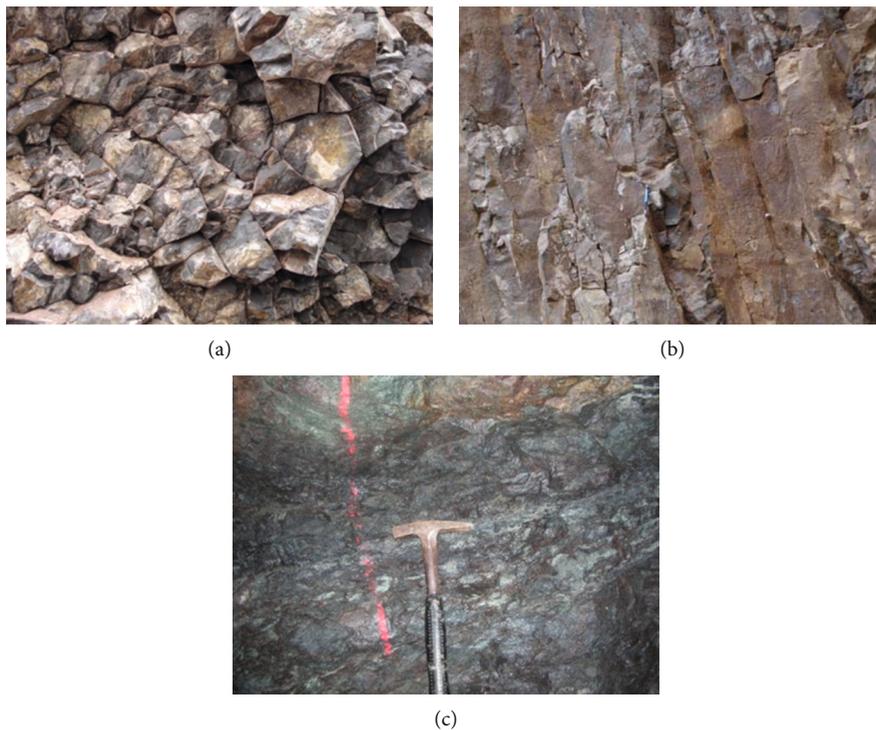


FIGURE 4: Typical columnar jointed rock at Baihetan dam site: (a) strongly weathered, (b) slightly weathered, and (c) fresh.

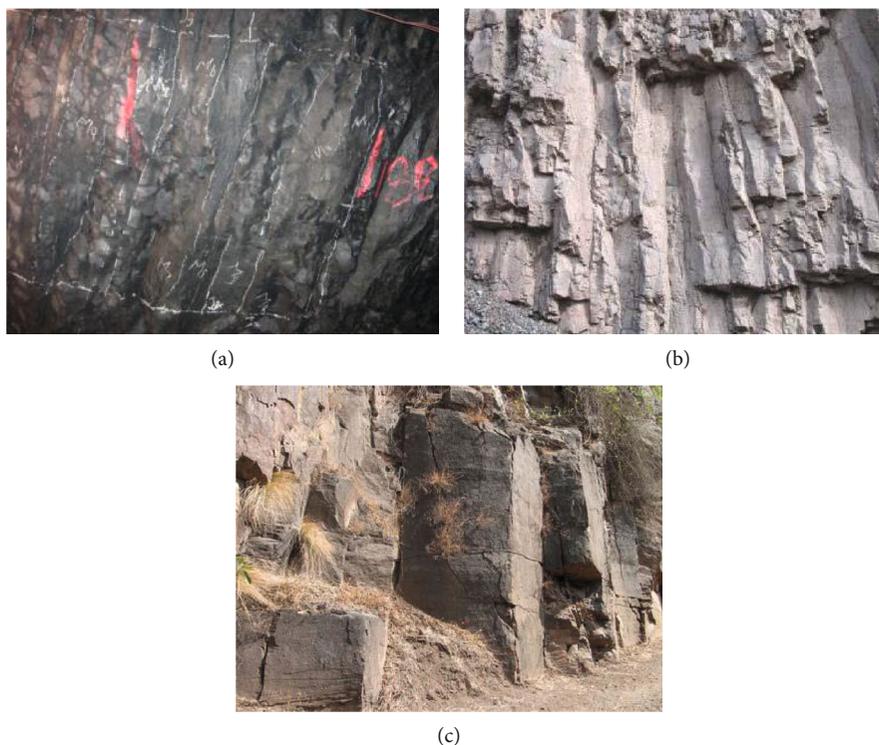


FIGURE 5: Typical columnar jointed rock mass: (a) Type I, (b) Type II, and (c) Type III.

different thicknesses are distributed at top of basalt strata, with thickness of 0.3 m to 1.7 m for lower strata and 0.3 m to 9 m for upper strata ($P_2\beta_9$ to $P_2\beta_{11}$) [52].

The faults in the dam site are small in scale, and there is no regional fault. Most faults are of strike-slip type, and a few of them are thrust faults. Geological structures are

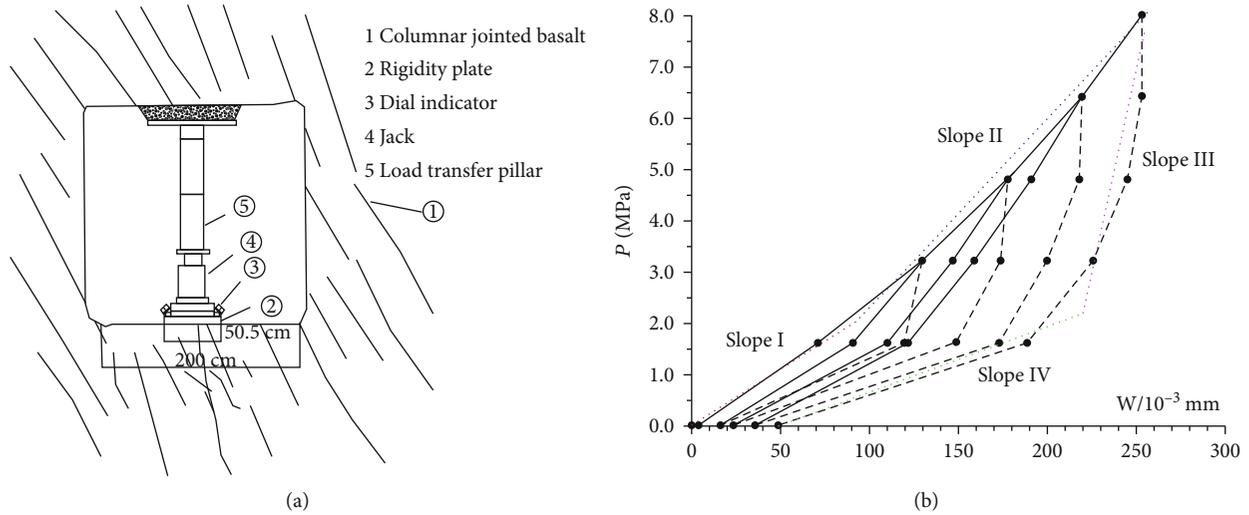


FIGURE 6: Deformation of columnar jointed basalt: (a) illustration of equipment system and (b) typical loading-unloading curve of columnar jointed rock.

composed of mainly faults with thickness less than 1.0 m, fracture zones, and joints, mostly striking NW with a few striking NE, and most of them are dipping at high angles. Outcrop rocks in both banks are weakly weathered, and the underlying rocks are slightly weathered and relatively intact. The load release effect influences rocks on both banks to various depths and deeper in the left bank. The underground water level and relatively impermeable layer are comparatively deep.

3.2. Hydrometeorology. The main source of runoff in the Jinsha River is from precipitation and replenished by the melt snow from the upstream area. The annual runoff is concentrated mainly in June to November, accounting to around 80 percent of the total. An analysis on runoff data of 61 years from June 1939 to December 2000 indicates that the average annual discharge at the Baihetan dam site is $4110 \text{ m}^3/\text{s}$. Floods in the Jinsha River originate mainly from rainstorms. The maximum peak floods of the Jinsha River occur mainly in July to September (over 95 percent of the total numbers), and the remaining 5 percent of floods occur in the last ten days of June or the first twenty days of October.

The annual average temperature at the Baihetan dam site is 21.7°C , with the highest and lowest recorded temperatures being 42.2°C and 2.1°C , respectively. The annual average water temperature is 17.4°C . The mean annual rainfall at the dam site is 715.9 mm , and there are about 100 precipitation days in a year. The annual average wind velocity is 2.1 m/s at the dam site, with the maximum being 13 m/s in south direction.

4. Columnar Jointed Basalt in Baihetan

The development of joint fissures in columnar jointed rock mass is heterogeneous. The columnar jointed basalt can be

TABLE 2: UCS classification for columnar jointed rock mass.

Level	Good	Relative good	Moderate good	Relatively bad	Bad
UCS	>200	50~200	10~50	3~10	<3

classified into three categories based on the columnar size and length.

Type I rock masses have columnar mosaic structures with high fractural densities, and the joint planes are undulating and rough (Figure 5). The columns have a length of 2 to 3 m and a diameter of 13 to 25 cm, and microfractures develop to cut the columns into small blocks with 5 different diameters. Type I columnar basalt distributes in mainly two sublayers: $P_2\beta_2$ and $P_2\beta_3$. Type II columnar jointed masses, distributed in mainly $P_2\beta_3^2$, $P_2\beta_6^1$, $P_2\beta_7^1$, and $P_2\beta_8^2$, have a height of 0.5 to 20 m and a diameter of 25 to 50 cm. They are irregular, and the columns are not cut off completely. There are microcracks cutting the columns into 10 cm diameter blocks. The growth of Type III columnar joints is poorly developed, and the rock can be treated as intact basalt.

The rock block shown in Figure 6 is compact cryptocrystal basalt. The rigid bearing plate method is used to estimate the strength, and a mean deformation modulus about 51.6 GPa is obtained. It indicates that rock blocks have good stiffness and strength properties and the weak planes are the key factor affecting the mechanical properties of columnar basalt. The weak planes in columnar jointed basalt are mainly columnar joints, microfissures, and low-angle structural planes (including shearing band and fractures). Columnar joints and microfissures have typical distribution features like Voronoi diagram. They are closed without disturbance and open after perturbation. Low-angle shearing band is gently cutting the columns transversely.

TABLE 3: The main factors in the classification of columnar jointed rock mass.

Factor	Integrity index of rock mass K_v	Volumetric joint number J_v	Rock block size D (%)	Transverse hidden joint development degree S (m)	Intraformational faulted zones development degree SL (m)
Description	$K_v = V_{pm}^2 / V_{pr}^2$ V_{pm} and V_{pr} are wave velocities of rock mass and intact rock.	Sum of the linear density of rock joint in different directions.	The percentage of surface area for the column with a diameter over 10 cm.	The mean distance between two adjacent transverse hidden joints.	The mean distance between two adjacent intraformational faulted zones.

TABLE 4: Rock mass integrity classification.

Rock mass integrity	Intact	Relatively intact	Poor intact	Relatively fractured	Fractured
Integrity index of rock mass K_v	>0.75	0.75~0.55	0.55~0.35	0.35~0.15	<0.15
Volumetric joint number J_v (m^3)	<3	3~10	10~20	20~35	>35
Rock block size D (%)	80~100	50~80	25~50	15~25	<15
Transverse hidden joint development degree S (m)	>20	10~20	5~10	3~5	<3
Intraformational faulted zones development degree SL (m)	>10	3~10	1.5~3	1~1.5	<1

TABLE 5: Weak plane tightness classification.

Weak plane tightness	Tight	Relatively tight	Moderate tight	Relatively loose	Loose
Weak plane opening (mm)	<0.5	0.5~3	3~5	5~10	>10
Columnar joints opening (mm)	0	<0.5	0.5~1	1~3	>3
Geological condition	Unweathering	Slightly weathering~unweathering	Weak weathering~slightly weathering	Weak weathering	Weathering

TABLE 6: Division standard of rock mass permeability.

Permeability	Good	Relative good	Moderate good	Relatively bad	Bad
Lugeon	<1.5	1.5~3.7	3.7~8.1	8.1~12	>12

5. Rock Classification for Columnar Jointed Basalt

5.1. Columnar Basalt Classification. In columnar jointed rock masses, there exist both original and conformation structural planes, including faults, bedding fault zone, joints, and microfissures. For the distribution of weak planes without the consideration of the compact degree of structural planes, the linear density of rock joints is as high as 15 strips per meter. Therefore, the RQD of columnar basalt is low and would be categorized as weak rock mass. However, the mechanical properties, such as strength and seismic velocity (V_p), are quite high so that columnar jointed basalt can be classified as good rock mass in some rock mass classification systems. Due to the special features of columnar jointed basalt and the inconsistency between geometric discontinuity and mechanical properties, conventional classification schemes may be not suitable; special analysis is required in the classification of columnar jointed rock mass.

In the development of a classification scheme of columnar jointed basalt, the following factors are taken

into account. Based on the application environment, the main factors controlling the structure and quality of columnar rock mass are estimated first. In most rock classification schemes, the factor of water is absent. However, columnar jointed rock mass in Baihetan distributes at the dam foundation and will suffer from super high pore water pressure with a height over 200 m. Therefore, water permeability is inevitable in classifying rock mass with underground water. Furthermore, the degree of compact of joints, geometric integrity, structural type, and weathering are also taken into consideration. Adopting the strength parameter from RMR and employing the description and analysis of geometric and geological characteristics, a rock classification scheme for columnar jointed rock is developed in the following.

5.2. The Main Factors and Indexes in Classification System

5.2.1. The Rock Mass Strength. The rock mass strength is the most important parameter in rock classification and almost every scheme takes it as the first parameter. In RMR scheme,

TABLE 7: Columnar jointed rock classification scheme.

Level	Sublevel	UCS (MPa)	Rock mass integrity	Weak plane tightness	Permeability (Lu)	Basic features
I		>200	Intact	Tight	<0.9	Rock mass is hard and intact with blocky structure. It is fresh without unloading effect and has extremely low permeability. Columnar joint is not developed and the rock mass in this level can be used as directly without any treatment.
II		100~200	Relatively intact	Tight	0.9~1.5	Rock mass is hard and relatively intact without or slightly weathered. Column is short and wide with blocky structure. The permeability is slight and rock mass can be used with local treatment.
III	III ₁	50~100	Relatively intact~poor intact	Relatively tight~tight	1.5~2.6	Rock mass in this level is relatively intact and slightly weathered. Columnar joint develops and make the columns have columnar mosaic texture. The weak plane is tight and this level rock can be used under simple engineering treatment.
	III ₂	25~50	Poor intact	Moderate tight~relatively tight	2.6~3.7	Rock mass is poor intact and weak weathered. Columnar joints develop and make the columns have columnar mosaic texture. The weak plane is relatively tight and the permeability is poor. Rock mass can be used under certain treatment.
IV	IV ₁	10~25	Relatively fractured~poor intact	Moderately tight~relatively loose	3.7~8.1	Rock mass is relatively fractured with weak unloading effect. Weak plane is moderately tight and develops in columns, making the rock in block-fracture structure. This kind of rock has relatively strong permeability and cannot be used as dam foundation directly.
	IV ₂	3~10	Fractured~relatively fractured	Relatively loose	8.1~12	Rock mass is relatively fractured with intensive unloading effect. Weak plane develops adequately and the rock has cataclastic structure with strong water permeability. Rock mass in this level cannot be used and needs to be removed.
V		<3	Fractured	Relatively loose~loose	>12	There are large-scale intraformational faulted zones and open weak planes. The rock mass is extremely fractured with fragmental block structure.

uniaxial compressive strength (UCS) of intact rock is employed as the representative strength parameter. Considering RMR has been widely applied in a large number of engineering projects, the classification of Baihetan columnar joints uses the same parameter as RMR classification standard (Table 2).

5.2.2. Rock Mass Integrity. Rock integrity is a key factor affecting the quality of rock mass. For hard rock blocks, the integrity is determined by the development of joints. In the analysis of the degree of integrity of columnar basalt, column sizes and hidden joints are also considered. For a comprehensive analysis of columnar jointed basalt, five quantitative parameters are employed (Table 3).

Columnar jointed rock masses have complex structures, and a single factor cannot describe the integrity of rock masses accurately. In this rock classification system, a quantitative categorization of rock mass integrity is listed in Table 4.

5.2.3. Weak Plane Tightness. Existing rock classification systems usually neglect the tightness of weak planes. However,

the tightness of columnar joints is extremely important in the rock characteristics. For columnar jointed basalt, the tightness of rock joint is determined based on open distance, filling material, and degree of weathering. A detail description of weak plane tightness is presented in Table 5.

5.2.4. Rock Mass Permeability. Underground water condition is one of the five important parameters in RMR rock classification system. Considering the columnar jointed rock mass is in the foundation of the dam with a height of 289 m, the underground water problem is serious and the columnar jointed rock mass is saturated [53]. Permeability obtained from site packer permeability test is used for the classification of columnar jointed rock mass (Table 6).

5.3. Columnar Jointed Rock Classification System and Application

5.3.1. Classification Scheme. The proposed columnar jointed rock mass classification system is based on three main factors. This scheme categorizes rock mass into five levels and seven sublevels. Related quantitative indices are listed in

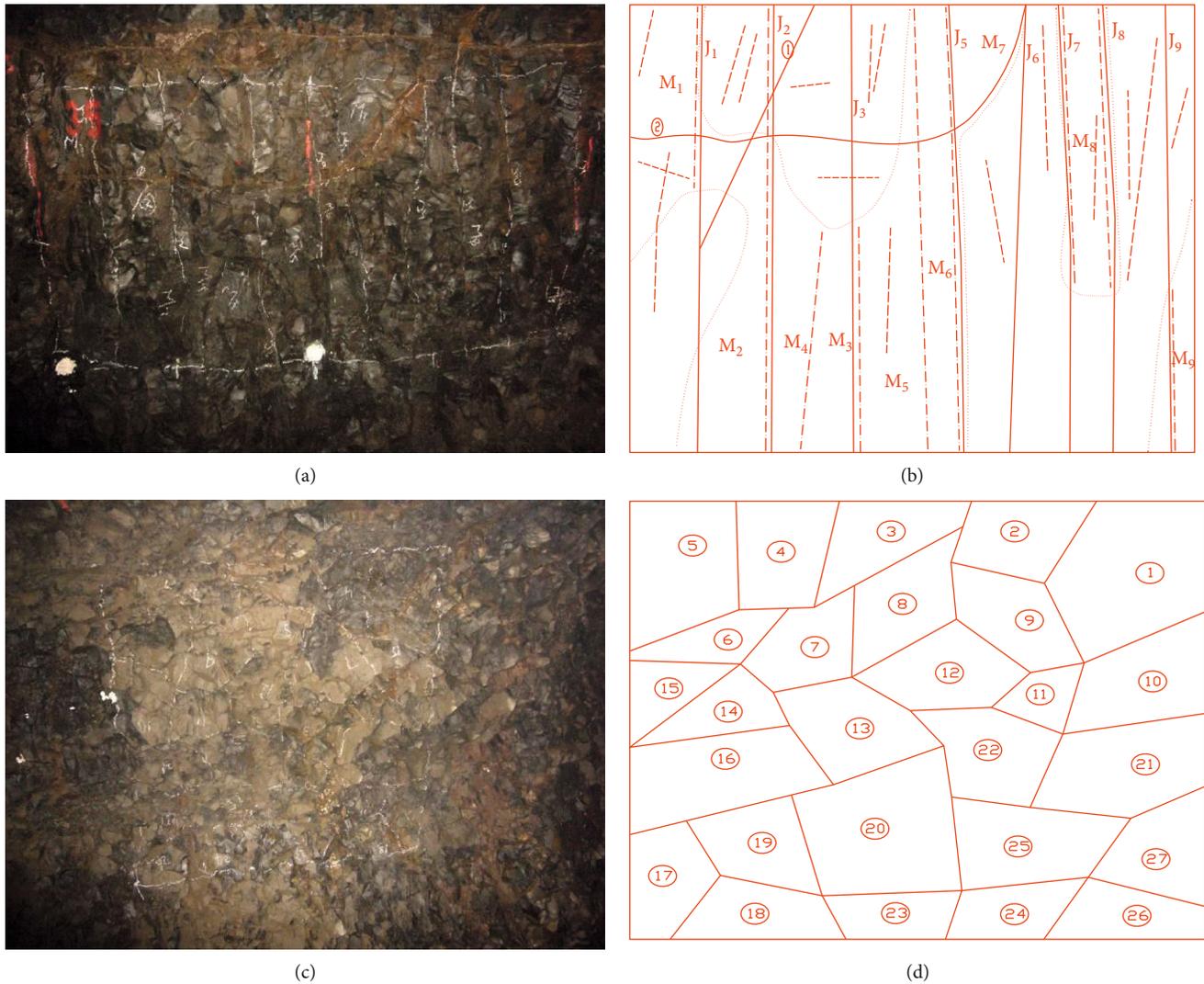


FIGURE 7: Illustration of microcrack in columnar jointed basalt of PD37: (a) the original photo of adit wall, (b) geologic sketch map of adit wall, (c) the original photo of adit top, and (d) geologic sketch map of adit top.

Table 7. Rock mass in levels I to III can be considered in the construction of dam foundation.

5.3.2. *Application.* After the introduction of the proposed classification system, a simple example for rock mass in $P_2 \beta_3^3$ is used to demonstrate the application of this new classification scheme. Take the information in PD37 (shown in Figure 3) as example; this kind of rock mass is distributed at a distance about 20 to 40 m to the entrance. The slightly weathered columnar basalt is shown in Figure 7 and it indicates that this kind of rock has relatively obvious columnar outline.

The columns are irregular and twisty with a length of 2 to 3 m and a diameter of 13 to 25 cm. The dipping angle is about 70 to 85°, and the shape of section is mainly pentagon or tetragon. Besides the columnar joints, there have developed a certain number of microfissures in the columns, and the per-

centage of microfissures with diameters over 10 cm is about 27%. Microfissures are mainly parallel to the columnar joints with trace lengths from 0.3 to 2 m, and the density is shown in Figure 8(a). The faces of microfissures are tortuous and closed. The mean J_v value is about 8.8 per m^3 . From Figure 8(b), the average seismic wave velocity is 3800 which leads to an integrity factor which is about 0.48 meaning a poor contact condition. Besides, the mean distance between two adjacent transverse hidden joints is less than 8.5 cm. The mean distance between two adjacent intraformational faulted zones is about 5.5 m and can be categorized as “slightly developed.”

The opening widths of columnar joints are about 0.5 to 1.0 mm and those of microfissures are less than 0.5 mm. The weak planes are “relatively tight” based on the categorization scheme. Water pressure test shows that the permeability is about 2.6 to 6.2 Lu. Referring to the classification criteria, the rock integrity is “poor intact,” and the weak

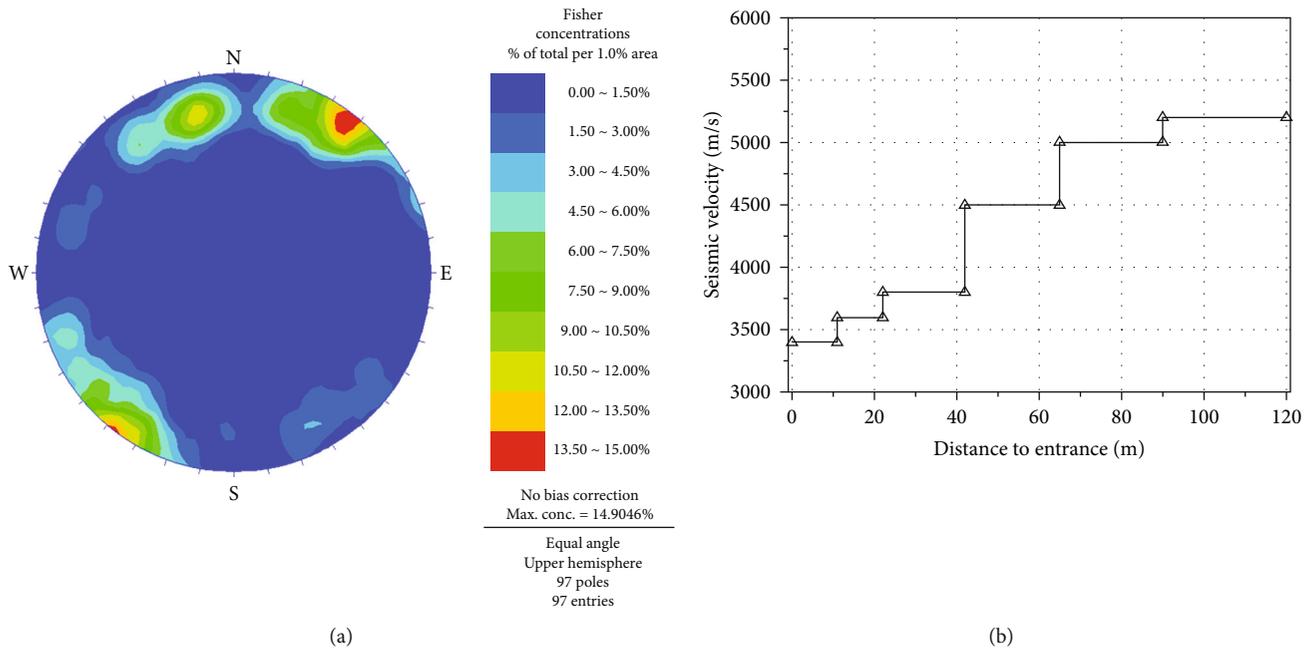


FIGURE 8: Microfissures and seismic velocity in adit PD37: (a) isodensity map and (b) seismic wave velocity.



FIGURE 9: The final excavation of the Baihetan dam foundation.

planes are “relatively tight.” Hence, the level of columnar jointed basalt in this part of the foundation is III₂. Rock mass cannot be employed as dam foundation directly, but can be used under effective reinforcement treatment.

Using the classification for columnar jointed basalt in Baihetan, the excavation scheme is designed for rock mass with different levels. The whole excavation process is very successful, and the final image of the dam foundation is shown in Figure 9. Now, the construction of dam is nearly finished. The result indicates that the rock classification is feasible for the related engineering with columnar jointed rock.

6. Conclusion

Baihetan hydropower station is the first arch dam built on the foundation with columnar jointed rock mass. Columnar jointed rock mass is special in that it is discrete in geometry but is still of high quality like intact blocks. For columnar jointed basalt, the strength and deformability features are mainly governed by rock-to-rock contacts. The tightness of weak planes plays an important role in the rock classification. Since the rock mass is located at the dam foundation, the effect of permeability is important. Existing rock classification schemes cannot give a comprehensive estimation due to the absence of these critical factors.

A rock mass classification scheme for columnar jointed basalt is proposed based on rock integrity, weak plane tightness, and permeability. With the help of a number of measures, such as seismic wave velocity, and geology descriptions, such as microfissures, this work tries to present a more suitable scheme. As an attempt for columnar jointed basalt, this work is also valuable as reference for similar rock masses.

Data Availability

Data are available on request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This research is supported by the National Key R&D Program of China (No. 2018YFC0407004), the Fundamental Research Funds for the Central Universities (B200201059), and the Natural Science Foundation of China (Grant Nos. 51709089, 51939004, 12062026, and 11772116).

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