Research of rigid bearing plate test on irregular columnar jointed basaltic mass

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ABSTRACT: The columnar jointed basaltic mass which includes primary irregular columnar morphological tensile fractures has led to new problems in hydraulic and hydropower engineering. The geometric features of irregular columnar joints present unique challenges in the simulation of columnar jointed basaltic mass behavior at the Baihetan hydropower station. Stress-strain curves from rigid bearing plate tests were analyzed by a conceptual model of columnar jointed basaltic mass. The results of rigid bearing plate tests are also compared with the ones of numerical tests by discrete element method on typical irregular columnar jointed basaltic rock mass. The results show that: the cyclic loading and unloading process could be decomposed into four stages: initial compression phase, loading phase, initial unloading rebound deformation phase and subsequent unloading slipping phase. Numerical simulations using Voronoi-shaped blocks and discrete element method could well simulate the loading and unloading mechanic characteristics of irregular columnar jointed basaltic mass.

1 INTRODUCTION

Widespread continental basalt lava flows often generate significant quantities of regular or irregular columnar joints. The special jointed basalt has been called columnar jointed basaltic mass in the field of engineering geology and rock mechanics. It is seen in many famous geological landscapes such as Giant's Causeway in Northern Ireland and Devils Postpile in U.S.A., and leads to some crucial problems in rock mechanics engineering in China. Current hydropower stations are generally located in blocky structural rock mass or thick-bedded bedrock. The thick-bedded blocky basaltic mass provides a good foundation for hydropower station, but a majority of high dams avoid the undesirable dambase with large amount of joints. So far hydropower stations built on columnar jointed basaltic rock mass are few. Besides, whether the columnar jointed basaltic rock mass is suitable to be the foundation of high dams still needs further exploration and study. Presently, as shown in Figure 1, a 298 m high arch dam will be founded on the columnar jointed basaltic rock mass at Baihetan power station on the downstream of Jinshajiang River in Southwest China. The anisotropic mechanical characteristics caused by columnar joints have significant effects on the mechanical indexes of dam foundation such as bearing capacity, strength parameters and so on (Zheng 2008). Some problems of rock mechanics and engineering on columnar jointed basaltic mass have presented a new challenge to the development of hydraulic and hydroelectric engineering in China.

Although domestic scholars have been aware of the importance of studying the columnar jointed basaltic mass, existing research results and in situ tests are rare. There is a description of the hysteresis loop effect of columnar jointed basaltic mass from Nuclear Waste Isolation Project (BWIP) at Hanford by Hart et al. (1985). They analyzed the test data of rigid bearing plate test and simulated the numerical experiment of regular hexagon columnar jointed basaltic mass. The conclusion was summarized as follows: (1) the columnar jointed basaltic mass exhibited hysteresis, non-uniform strain distribution and stress-dependent stiffness. The orientation and
position of joints is such that local stress concentrations are sufficient to allow slip during loading. (2) Individual joints exhibit continuous yielding and hysteretic behavior at all stress levels. (3) In-situ stress concentrations existed in the block before cutting. Hart & Cundall found that the columnar joint’s rotation and sliding led to its nonlinear behavior. They adopted hexagonal numerical models with different orientations for columnar jointed basaltic mass in BWIP at Hanford. The distinct element method was used to simulate the rigid bearing plate test, and the behavior of columnar jointed basaltic mass associated with rotation and slip was studied to help understand its anisotropic mechanical properties.

![Figure 1. Irregular columnar jointed basaltic mass at Baihetan hydropower station in Southwest China.](image)

However, due to different geological environment of columnar jointed basaltic mass, the type of cylindrical surface is not always hexagonal. A large quantity of studies revealed that the percentage of hexagon of basaltic mass with well-developed hexagonal cylindrical columnar joints such as Irish Giant’s Causeway is less than 51%. The geometries of cylindrical surface at Baihetan hydropower station in Southwest China are mainly quadrangle and pentagon, while the percentage of hexagon is less than 10% (East China Investigation and Design Institute 2006). Therefore, the basaltic mass at Baihetan hydropower station is a typical irregular columnar jointed basaltic mass which is distinctly different to the hexagonal one in BWIP at Hanford.

This paper firstly analyzes the stress-strain curve of rigid bearing plate test on irregular columnar jointed basaltic mass at Baihetan hydropower station in Southwest China. Then, four phase characteristics are demonstrated by a single columnar joint conceptual model. Finally, hysteresis loop effect of irregular columnar jointed basaltic mass is simulated by discrete element method and the comparison between theoretical model and numerical results is studied.

## 2 ANALYSIS OF STRESS-STRAIN CURVE FROM RIGID BEARING PLATE TEST

The results of horizontal and vertical rigid bearing plate tests at Baihetan hydropower station in Southwest China are illustrated by graphs (Shi et al. 2008) in Figure 2. In the horizontal rigid bearing plate test, the curve of stress-strain (P-W) increases linearly. The deformation properties of irregular columnar jointed basaltic mass are similar to homogeneous rock mass in the range of the pressure. There are 24 tests which have similar curves showing a mean deformation modulus is 11.7 GPa. However, the P-W curve of vertical rigid bearing plate tests is concave with the strain growth slowed gradually as the pressure increases. The loading curve of vertical rigid bearing plate tests may be divided into two stages: compression of fissures and linear deformation, while the one of the horizontal tests has only the linear deformation. There are 7 tests of concave P-W curve with a mean deformation modulus of 7.43 GPa.

Based on the slope characteristics of P-W curves of the typical irregular columnar jointed basaltic mass, we find the loading and unloading curves can be divided into four stages which are two loading deformation stages and two unloading deformation stages. The compaction of irregular columnar joints occurs in the initial loading and deformation stage (Slope I), as shown
in Figure 2(c). The slope of $P$-$W$ curve is low and concave, and the slope increases with a high growth rate. Then the $P$-$W$ curve goes into a linear elastic deformation stage (Slope II). In the second stage, the curve increases linearly due to the contribution of the deformation of rock and the compression and shear deformation of irregular columnar joints. After it reaches the peak, the $P$-$W$ curve in the initial unloading stage (Slope III) shows a non-linear response with a high initial slope. Finally, the $P$-$W$ curve of the subsequent unloading stage (Slope IV) is a lower slope curve to the one of Slope III. After the unloading stage, there has been some unrecoverable permanent deformation in irregular columnar jointed basaltic mass. There is an obvious hysteretic loop effect in repeated rigid bearing plate tests, and the hysteretic loop effect becomes more and more pronounced.

Figure 2. Stress - strain curve of rigid bearing plate test on irregular columnar jointed basaltic mass at Baihetan hydropower station in Southwest China.

Brady et al. (1985) explained the load-deformation behavior of a large basalt block, using conceptual model of a rock specimen containing a single crack. As shown in Figure 3, a conceptual model of basaltic mass with a single irregular columnar joint is adopted for studying the four stages of the $P$-$W$ curves of rigid bearing plate test at Baihetan hydropower station. Under the uniform load of $P$, we assume that the total deformation of rock mass is $u_t$, the deformation of rock block is $u_r$, the deformation along the joint surface of the columnar joint with a dip of $\beta$ is $u_j$, and the stiffness of rock and joint are $k_r$ and $k_j$, respectively. The normal force ($N$), the spring resistance ($T$), and the frictional resistance ($F$) along the irregular columnar joint surface $AB$ are shown in Figure 3(a).

Figure 3. A conceptual mode of irregular columnar jointed basaltic mass.
In the initial loading stage (Slope I), the $P$-$W$ curve shows a soft and convex slope with a high growth rate. For the physical mechanism of such concave curve, Palmstrøm & Singh (2001) gave an explanation when he had studied the P-W curve of rigid bearing plate tests in the tunnel. He postulated that the surface of rock mass was relaxed and broken during the excavating and blasting. Some old cracks and joints were opened, and new cracks and hidden joints developed. Under the pressure of the initial loading stage (Slope I), open cracks and joints were compacted and closed. So he considered the deformation at the initial stage should not be taken into account while calculating the deformation modulus. Test points were always disturbed by excavating and blasting, then rock mass decompressed. Therefore, the cracks and joints were compacted and closed in the initial loading stage and therefore do not represent the actual mechanical behavior. Sharma et al. (1989) also pointed out that the thickness of damage zone in the adit by blasting was still over 0.5 m even if the loose rock mass had been removed carefully before the bearing plate test. They thought that the blasting damage significantly affected the accuracy of rigid bearing plate test, and it was the root cause why the deformation modulus obtained from rigid bearing plate test was less than that from flexible bearing plate test.

From the analysis of acoustic test results along the adit in different directions at 58 m horizontal distance of adit PD37 at Baihetan hydropower station, we know that there is an excavation damage zone (EDZ) where the acoustic velocity is decreased near the adit surface. It is caused by excavating and blasting. The thickness of EDZ around the side wall of the adit is 0.35 m-0.40 m, while the one at the top arch is 0.6 m-0.8 m, and the maximum thickness is at the bottom which is 0.9 m-1.0 m. Results indicate that the damage caused by blasting is larger at the bottom than the one around the side wall. Irregular columnar jointed basaltic mass damages obviously at the bottom. In the vertical bearing plate test, low surrounding rock pressure gives a larger deformation of basaltic mass. Hoek et al. (2002) introduced the rock mass disturbance factor ($D$) to describe the decrease of the deformation modulus. He thought that poor quality blasting would result in severe damage of hard rock and surrounding rock. The thickness of EDZ would be up to 2.0 m-3.0 m, its $D$ was equal to approximately 0.7. High quality controlled blasting or digging with a tunnel excavator could lead to the minimal disturbance of surrounding rock, and its corresponding $D$ was closer to 0. For the irregular columnar jointed basaltic mass, the joint disturbance parameter ($jdp$) is introduced to describe the effect of excavation and blasting on the stiffness of columnar joints. Analysis shows that $jdp$ is 0.7 in the bottom and $jdp$ is 0.5 around the side wall at Baihetan hydropower station and these values are recommended here.

Under the uniform load of $P$, the frictional resistance ($F$) on the irregular columnar joint surface has the form $F = N \tan \phi$ in the initial loading phase, therefore:

$$u_r = u - u_j \sin \beta$$

(1)

$$P = k_j(u - u_j \sin \beta)$$

(2)

To meet the force balance along the irregular columnar joint surface AB, we obtain the follow expressions:

$$N = P \cos \beta$$

(3)

$$P \sin \beta = T + F = k_j' u_j + F$$

(4)

$$F = N \tan \phi = P \cos \beta \tan \phi$$

(5)

Taking the effect of excavating and blasting on the stiffness of the irregular columnar joints into account, the formula can be written as follows:

$$P \sin \beta = jdp \cdot k_j' u_j + P \cos \beta \tan \phi$$

(6)
Putting \( u_i \) into the Eq. 2 and simplifying the equation, we obtain the following expression:

\[
Slope \ I = \left( \frac{dP}{du} \right)_I = \frac{k_r}{1 + \frac{k_r \sin(\beta - \phi) \sin \beta}{jdp \cdot k_j \cos \phi}}
\]  

(7)

In the subsequent loading stage the curve is linear with increased slope. This stage can be considered as linear elastic deformation stage. The stiffness of columnar joint is small for the compression effect. Similar to the derivation of the initial loading phase, we have the expression:

\[
Slope \ II = \left( \frac{dP}{du} \right)_II = \frac{k_r}{1 + \frac{k_r \sin(\beta - \phi) \sin \beta}{k_j \cos \phi}}
\]  

(8)

Removing the vertical load at a certain rate when the rigid bearing test goes into the initial unloading stage, there would be a rebound deformation in the opposite direction at the irregular columnar joints surface. That is to say, the frictional resistance \( F \) at \( AB \) is then reversed which is down along the joint surface as shown in Figure 3(b). The rebound deformation of the rock \( ur \) is the deformation of rock when \( F \) is large enough to stop joint surface from sliding up. Therefore, the slope of initial unloading phase represents the deformation modulus of complete basaltic mass. This is in accordance with Hart & Cundall’s analysis of the bearing plate test of regular columnar jointed basaltic mass in BWIP at Hanford (Hart et al. 1985). Then, the formula of the slope in \( Slope \ III \) is:

\[
Slope \ III = k_r
\]  

(9)

Finally, the rigid bearing plate test went into the subsequent unloading phase (\( Slope \ IV \)). As the applied load decreased to 0 MPa, the normal force \( N \) on the surface \( AB \) decreased, and the frictional resistance \( F \) is also reduced. When the frictional resistance \( F \) couldn’t prevent the sliding blocks from the upward rebound deformation, it reaches the limit equilibrium state. The basaltic mass would slip up along the plane \( AB \) of irregular columnar joint, therefore:

\[
Ps\sin\beta = T - F
\]

(10)

\[
Ps\sin\beta = k_r \cdot u_r \cdot P\cos\beta\tan\phi
\]

(11)

Getting the value of \( u_i \) and simplify the equation, we obtain the following expression:

\[
Slope \ IV = \left( \frac{dP}{du} \right)_IV = \frac{k_r}{1 + \frac{k_r \sin(\beta + \phi) \sin \beta}{k_j \cos \phi}}
\]  

(12)

From Eq. 7 and Eq. 8 we know that \( Slope \ I < Slope \ II \). By comparing Eq. 9 with Eq. 12, \( Slope \ III > Slope \ IV \). As the pitching angle \( \beta \) of irregular columnar joints at Baihetan hydropower station is generally around 70º, and \( \beta > \phi \), \( \sin(\beta + \phi) > \sin(\beta - \phi) \), then we have the relation:

\( Slope \ II < Slope \ III \), \( Slope \ IV < Slope \ II \), that is to say, \( Slope \ IV < Slope \ II < Slope \ III \).

The relationship of \( Slope \ I \) and \( Slope \ IV \) can be determined by Eq. 13:

\[
sp = \frac{(1 - jdp) \tan \beta}{(1 + jdp) \tan \phi}
\]

(13)

When \( sp > 1 \), we have the relationship: \( Slope \ I < Slope \ IV < Slope \ II < Slope \ III \).

When \( sp < 1 \), we have the relationship: \( Slope \ IV < Slope \ I < Slope \ II < Slope \ III \).
According to the test report (East China Investigation and Design Institute 2006), the pitching angle $\beta$ of columnar joints at Baihetan hydropower station is $70^\circ$, the friction angle $\varphi$ is $26^\circ$, and the joint disturbed parameter $jdp$ at the bottom of adit is 0.7. Calculations indicate that $\varphi < 1$, so $Slope \ IV < Slope \ I < Slope \ II < Slope \ III$. Comparing the theory result with the vertical rigid bearing plate test, they matched well. It indicates that the conceptual model can explain well the results of in-situ test. As the conceptual model is a single irregular columnar joint, in order to consider multi irregular columnar joints, we further study the additive effect. As shown in Figure 2(c), the initial stage of unloading curve shows a gradually decreasing slope.

According to conceptual model based on the analysis of $P-W$ curves of rigid bearing plate tests on irregular columnar jointed basaltic mass, we obtain the understandings described below. A complete cycle of loading and unloading consists of four stages: the initial pressure consolidation stage in which the irregular columnar joint does not slip, the loading stage in which the deformation is comprised of the intact rock and nonlinear sliding on the irregular columnar joint, the initial unloading rebound deformation stage in which the irregular columnar joint does not slip, the subsequent unloading slipping stage in which there is nonlinear sliding at the irregular columnar joint. The nonlinear slipping at the structural plane will lead to hysteresis effect in the loading and unloading cycle which produces a permanent deformation. For considering the nonlinear characteristic of in-situ test curve comes from the irregular columnar jointed basaltic mass, the hysteresis characteristics under less pressure would be considered to be caused by the nonlinear elastic behavior of irregular columnar joints. In other words, the deformation of irregular columnar jointed basaltic mass can be decomposed into two parts: elastic deformation (including the intact rock and structural plane) and nonlinear elastic deformation (the slip, rotation and separation only occur at the joint plane). Only the unloading stage can inhibit the inelastic deformation and represent the real elastic deformation of the columnar jointed rock mass. Therefore, when accessing the equivalent deformation modulus of the columnar jointed rock mass, the initial stage of unloading curve of the bearing plate in-situ test should be used, and the inelastic deformation could also be evaluate solely at the same time. As the theory can only explain the conceptual model, while the numerical analysis method can take more influencing factors and complex operating conditions and physical processes into consideration, and it can help us understand the nature of the problem. It can be seen that the remarkable compression effect and hysteresis loop effect are the key characters of columnar jointed rock mass. So it is of great significance for understanding the mechanic behavior of columnar jointed rock mass to choose a suitable numerical method to simulate this characteristic.

3 THE NUMERICAL SIMULATION TEST OF IRREGULAR COLUMNAR JOINTS

As the Voronoi tessellation is very similar to the natural structures of irregular columnar joints, the numerical model of Voronoi joint network can be used to analyze the mechanical behaviors of irregular columnar joints. Due to the great difficulty to build lots of irregular columnar joints by continuum mechanic, and suitable mechanical constitutive of irregular columnar jointed basaltic mass is also difficult. For the past few years, mechanical behavior by simple contact with a large number of micro-element under the surface of the macro-mechanical characteristics emerges to reveal the complex mechanical behavior of new methods such as DDA, discrete element method, particle element and so on.

The discrete element method of discontinuum numerical method relying on its absolute advantages in simulating a large number of joints is becoming the first choice in numerical analysis of irregular columnar jointed basaltic mass. Furthermore its representative commercial software UDEC (Itasca 2011) and 3DEC (Itasca 2007) have been widely used internationally. UDEC has a strong capability of joints fracture network simulation. The built-in Voronoi tessellation generator can generate Voronoi joint network automatically. Its deformable solution of discrete element model not only simulates the embedding, contact, rotation and separation of columnar jointed basalt, but also uses finite difference element to discretize the rigid blocks and calculate the elastic deformation and the internal stress distribution. This paper uses UDEC to simulate the rigid bearing plate test of the irregular columnar jointed basaltic mass. The
parameters of irregular columnar joints are given in Table 1, and the numerical model is showed in Figure 4.

Table 1. Irregular columnar joint parameters at Baihetan hydraulic station in UDEC calculation.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Physical and mechanical parameters of basalt blocks</th>
<th>Geometric and mechanical parameters of columnar joints</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$E_i$ [GPa]  $v_i$  $\text{Density}$ $\text{Diameter}$</td>
<td>$K_n$ [GPa/m] $K_s$ [GPa/m] $jdp$ $\phi$ [°]</td>
</tr>
<tr>
<td>Irregular columnar</td>
<td>76.2  0.23  2900  0.20</td>
<td>335.48  104.09  0.5  26.0</td>
</tr>
</tbody>
</table>

Figure 4. Geologic sketch map and numerical model of irregular columnar joints.

Results of numerical simulations are shown in Figures 5 & 6. The $P$-$W$ curve of Voronoi columnar joints numerical test is in accordance with the one of rigid bearing plate test. The $P$-$W$ curve is comprised of four stages, the slope of the initial pressure consolidation stage is less than of the loading stage, and the slope of the subsequent unloading stage is less than of the initial unloading stage. Comparing the deformation in four stages and permanent strain after unloading of in-situ test and numerical test, the strains are both in the magnitude of $10^{-4}$m. It also can be seen that the initial unloading stage (Slope III) of the numerical test is composed of three multi-line curves with decreasing slope (1 2 3 4 in Fig. 6), and this curve matches the initial unloading curve of in-situ test well.

Figure 5. Stress and displacement diagram of plate loading test of Voronoi-shaped columnar joint.
4 SUMMARY

The mechanical behavior of the irregular columnar jointed basaltic mass at Baihetan hydropower station in Southwest China is studied in this paper. The geometrical features and stress-strain curve of rigid bearing plate test are described in detail. According to conceptual model based on the analysis of P-W curves of rigid bearing plate tests on irregular columnar jointed basaltic mass, the intact loading and unloading cycle curves can be divided into four stages: the initial consolidation phase, loading phase, the initial unloading rebound deformation stage and the subsequent unloading slip stage. Then Voronoi tessellations are used to produce the block geometry and distinct element method are used to do numerical simulation. Numerical test shows the Voronoi joint network can simulate the loading and unloading mechanic characteristics of irregular columnar jointed rock. It explains the significant compaction and hysteresis loop effect in the rigid bearing plate test. Numerical tests also give two suggestions for the next step of study:

1. Restricted by the two-dimensional model, this paper only analyzes the hysteresis loop effect in the vertical load direction. Study of next step can be set from the three-dimensional Voronoi model to research the hysteresis loop effect of columnar joints.

2. The stiffness of joints in numerical bearing plate test except the initial pressure consolidation stage is treated as a constant. It means that joint constitutive is ideal elastic-plastic (Mohr-Coulomb face contact behavior). Therefore, the stress-strain curve of subsequent loading stage is straight line, while it’s a slightly concave curve in the in-situ test. This is caused by the confining pressure influence on the stiffness of columnar joints. Stiffness of joint under high confining pressure has a significant characteristic of strain hardening. As a result, it is probably more suitable to employ continuous yielding joint constitutive model in future studies.

REFERENCES


