Structure effects on seismic response of underground cavern in joint network rock mass

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Abstract. In this paper, structure control effect of joint network rock mass on seismic response of underground cavern is investigated. With discussion of the generating principle of 2-d joint network, five characterizing parameters, i.e. as joint density, joint orientation & its discretization, joint trace length & its discretization are identified. The machine hall cavern of Dagangshan hydropower plant is taken as a study case here. The results indicate that in the precondition of a same seismic level, seismic displacement increases with the joint density. Seismic displacement also increases with the joint inclination increase at the range of 0°-80°. If the discretization of joint inclination is considerable, the seismic displacement is of positive correlation with joint inclination discretization, yet if the discretization of joint inclination is comparatively small, this correlation is ignorable. Seismic displacement increases with the joint trace length increase. At last, little relationship between joint trace length discretization and seismic displacement has been found. Those findings may provide certain reference for the aseismic design of the underground caverns.

Introduction

Abundant hydropower resources are available in southwest China, where a number of large-scale hydropower plants are currently either under construction or at design stage. Owing to the mountainous topography in this region, most of these giant hydropower plants choose to put their powerhouse underground.

For these underground works, falling or sliding of rock mass blocks or wedges defined by intersecting structural discontinuities is the most common type of failure, known as the structure effect of the jointed rock mass. Meanwhile, southwest China is a highly active seismic region with intensive tectonic movements and seismic events, resulting in stringent requirements for seismic design for these hydropower projects. Hence, the influences of the structure effect on the seismic stability of these underground works would be a major geotechnical issue to be addressed during design and construction of these giant hydropower plants.

Traditionally, numerical simulation is the popular way to investigate this very problem. Despite there are many numerical simulation methods, but they may be categorized into two major subgroups. One is the continuous approach in which the joints are seldom considered and the entire rock mass is simplified to an equivalent continues material[2－4]. The other is the discontinuous approach. In this approach the intermittent discontinuity are treated as complete penetrated contact surface and solved as separate discrete blocks[5－6].

With the development of calculation methods and computer efficiency. It becomes possible to conduct directly analyses on the jointed rock mass without simplifying. Jointed finite element method (JFEM) is one of these advanced technique [7]. It refers to an improved finite element method with explicit representation of a joint network system, and been considered as a highly credible alternative

for a class of blocky or jointed rock problems. In JFEM, the rock mass matrix is simulated with solid elements and the joints are simulated with interface elements.

As for the above mentioned joint network system, it is a mathematical representations of joint geometry which can be used in the conceptual development of approaches to the solutions of rock mass problems. Traditional works of joint network system have been focused on the hydraulic conductivity and equivalent mechanical parameters [8, 9], yet less attention has been paid on directly application of static / dynamic stability analysis of rock engineering.

In this paper, the structure effect of random joints on the seismic response of the underground cavern excavation has been systematically investigated. The principle of joint network generation was discussed in the first place, and the characteristic parameters of structure effect was given. The underground machine hall of Dagangshan Hydropower plant was taken as a background study case. The differences of its seismic response under various structure effect characteristic parameters is examined and some insights of the influence of structure effect are discussed.

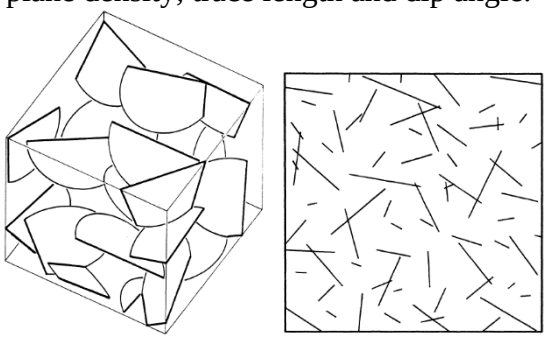
Theoretical background

Establishment of the 2d joint network system. Reconstruction of rock mass structures based on the logging data is much like a reverse process of the field investigation. In field investigation, distribution functions of structural plane's geometric parameter can be estimated based logging data. While reconstruction of joint network system is to build a geometric model which can satisfy the aforementioned probability distribution function.

It is of vital importance to assume a proper joint shape during reconstruction of rock mass structures. As the formation of joint is an extremely complex geological process, leads to a considerable diversification of the joint shape. Hence, for sake of simplicity, it is practical to assume the joint shape as disc or ellipse.

The Baecher model is a typical disc shape joint model [8, 9], in which the joint size is finite, and each joint is defined by three parameters, i.e., the center point, orientation and diameter. The center points are uniformly distributed in 3D space; the diameter and orientation are constants or can be defined by a probability distribution function.

As the 3D space degraded to 2D surface (trace plane), the above three parameters are correspondingly degraded to plane density, trace length and dip angle.



(a) 3d case (b) 2d case

Fig.1 Sketches of 3D & 2D joint network of Baechar model[9]

Representative indexes of structure effect in jointed rock. In terms of experience, the characteristic parameters of structure effect obeys some certain mathematic distributions. In the following investigation, joint network systems with various characteristic parameters are established and used in the seismic analysis of the Dagangshan Hydropower plant underground cavern. In this way the influence of the structure effect of jointed rock mass on the cavern's seismic behavior is addressed.

(1) Joint density

In the Baecher model, joints are considered as discs positioned in 3D space. The distribution of disc's center point follows the 3D homogeneous Poisson process. Result in the number or the

intensity of joints also satisfies the Poisson stochastic process, i.e., the center points of joints are evenly distributed in the region of interest. The joint intensity on trace plane can be defined by a few ways. Such as P1: number of the joint traces on per unit area (1/m2), P2: sum of the joint trace lengths per unit area (1/m2), P3: sum of the joint trace lengths per (unit area^0.5), et al. Note the P3 index is dimensionless and is free from the effect of rock mass size. So it is chosen as the characteristic parameter for joint density.

(2) Joint dip angle

Apart from the dip angle, its discretization is also an important characteristic parameter of structure effect. The distribution of joint orientation usually satisfies the Fisher distribution [11]. In Fisher distribution, only one parameter is required to describe the discretization of dip angle. This makes it very easy to examine the influence of the dip angle discretization. Meanwhile, the Fisher distribution function is an integrable function, which is convenient for generation of random numbers.

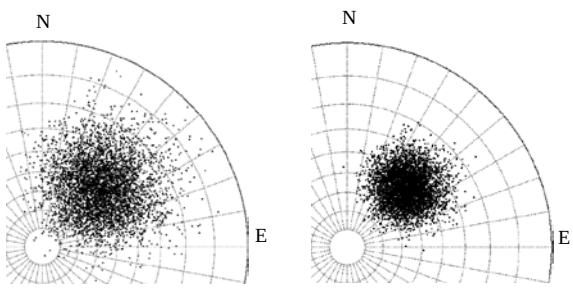
It is assumed in the Fisher distribution that, for one joint set, the joints in the direction of maximum probability have the following probability density function:

$$f(\theta)=\begin{cases} 0, & (\theta<0) \\ \dfrac{k\sin\theta \mathrm{e}^{k\cos\theta}}{\mathrm{e}^{k}-1}, & (0\leqslant\theta\leqslant\pi/2) \\ 0, & (\theta>\pi/2) \end{cases} \tag{1}$$

The corresponding probability cumulative function is:

$$F(\theta)=\begin{cases} 0, & \theta<0 \\ \dfrac{1-\mathrm{e}^{-k(1-\cos\theta)}}{1-\mathrm{e}^{-k}}, & 0\leqslant\theta\leqslant\pi/2 \\ 0, & \theta>\pi/2 \end{cases} \tag{2}$$

Where the Fisher constant k reflects the dispersion of the orientation data respect to the mean value. The greater the constant k is, the more intense the pole distribution is. In another word, the data points are more concentrated toward the average orientation. is the angle between the joint pole the most possible orientation. Figure 2 shows the stereonet plots of joint orientation for different Fisher constants.



(a) k=20 (b) k=50

Fig.2 Stereonet plots with different Fisher constant k

(2) Joint trace length

Much alike the joint dip angle, the Joint trace length and its discretization are both important characteristic parameters for structure effect.

A variety of distribution assumptions were proposed for the joint trace length. Such as Negative exponential distribution, normal distribution, lognormal distribution, and Γ distribution [12].

$$f(x)=\frac{1}{\sqrt{2\pi}\sigma}\exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^{2}\right] \tag{3}$$

The discretization of the trace length is expressed by the standard deviation σ in eq. (3)

So far, five characteristic parameters for structure effect were proposed, and will be discussed in the following work. They are joint density, joint dip angle, discretization of joint dip angle, joint trace length, and discretization of joint trace length, respectively.

Overcome the randomness problem during the generating process. An important issue in joint network reconstruction is to deal with the randomness problem. It is well known that rock mass structure reconstruction involves a complex stochastic process. For a specified set of characteristic parameter, numerous joint system samples can be generated correspondingly. The properties exhibited by each sample are bound to be stochastic and different.

However, this problem has not been paid enough attention in previous studies. In this paper, for each specified set of characteristic parameter, 10 samples of joint network system were reconstructed. And their average and statistical value are taken as the response under present characteristic parameter.

Structural effects on the seismic response of underground cavern excavation

Model setup. The Dagangshan hydropower plant is located on the Dadu River in southwest China. The underground cavern complex consists of the machine hall, the transformer chamber, the surge chamber, the headrace tunnels, the tailrace tunnels and the auxiliary tunnels. The span of the machine hall is 30.8m. An exhaustive probabilistic seismic hazard analysis by China Earthquake Administration suggest a very high basic ground motion level of 3.36 m/s2. Here, the typical representative cross section of the machine hall was chosen and been analyzed as a 2d numeral model in Phase2 program.

Survey by geologist reports the maximum joint trace length is at a 10 m level. And the respective mechanical parameters of the rock matrix and joints are suggested, as shown in table 1.

The principal components of the in-situ stress field in the vicinity of the cavern complex were recorded approximately as 13MPa, 11MPa and 5MPa, respectively.

For each analysis case, the cavern is excavated with a 10 step excavation sequence. And then followed by a quasi-static seismic analysis [13] in which two seismic wave incident direction were considered, i.e. from left side and right side.

Table 1 Mechanical parameters of rock and joints

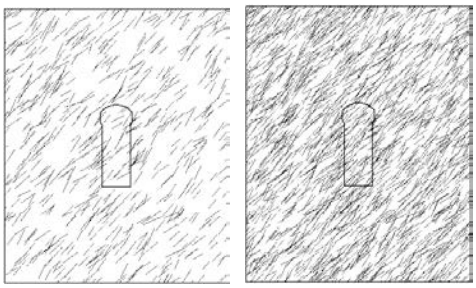
Materials	E / GPa	v	K_n / (MPa/m)	K_s / (MPa/m)	c / MPa	φ / (°)
Rock matrix	25	0.2	--	--	2.50	60
joints	--	--	3000	1000	0.15	31

Joint density. Here the influence of the joint density on the cavern's seismic response is to be discussed. 5 levels of joint density P3 were considered, as 10, 50, 100, 150, and 200. For each level, 10 random joint network system generated and analyzed, and the average seismic displacements and their standard deviation were evaluated.

As for other numerical simulation parameters, the dip angle is fixed as 45 degree and satisfy the Fisher distribution with the Fisher k equals an intermediate values 30; and the trace length satisfy a normal distribution with a mean value of 15m and a standard deviation of 2m, i.e. the interval of trace length is [9, 21]m.

Fig. 3 shown two sample plots of joint network and underground cavern with different joint densities

Fig.4 gives the mean value and standard deviation of excavation displacement under different joint density. While Fig. 5 illustrates the mean value and standard deviation of maximum seismic displacement under different joint density. It is obvious that the seismic displacement reaches the larger value once the seismic wave incidents from the opposite direction of the joint dip, i.e. the left side in current study. And it is notable that in this case, excavation displacement and seismic displacement share a same trend.



(a) Joint density P3 = 50 (b) Joint density P3 = 150

Fig.3 Sketches of joint network and underground cavern plot with different joint densities

As the joint density increases from 10 to 200, the cavern's seismic displacement increases from 0.27cm to 3.4cm, correspondingly. Meanwhile, as the joint density increases, the gap between seismic displacements of each wave incident direction is increases as well.

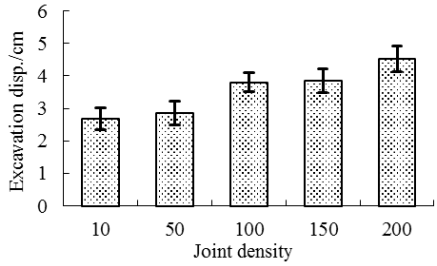


Fig.4 Relationship between excavation displacement and joint density

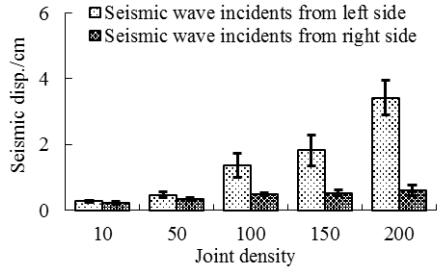
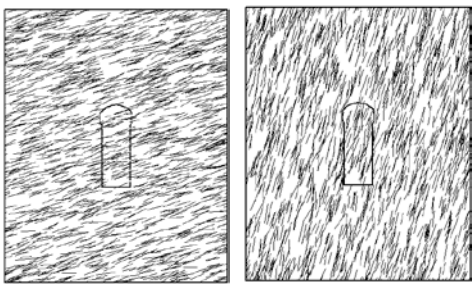


Fig.5 Relationship between seismic displacement and joint density

Joint dip angle. Here the influence of the joint dip angle on the cavern's seismic response is to be discussed. To minimum the disturbance brought upon by the dip angle discretization. A high value of Fisher k was assumed. And 6 levels of average joint dip angle were considered, as 0°、15°, 30°, 45°, 60°, 75°, and 90°. For each level, 10 random joint network system generated and analyzed, and the average seismic displacements and their standard deviation were evaluated.

As for other numerical simulation parameters, the trace length satisfy a normal distribution with a mean value of 15m and a standard deviation of 2m, i.e. the interval of trace length is [9, 21]m; the joint density P3 is assumed as an intermediate values 100

Fig. 6 shows two sample plots of joint network and underground cavern with different joint average dip angle.



(a) average dip angle =30° (b) average dip angle =60°

Fig.6 Sketches of joint network and underground cavern plot of different joint dip angle

Fig.7 gives the mean value and standard deviation of excavation displacement under different average dip angle. While Fig. 8 illustrates the mean value and standard deviation of maximum seismic displacement under different average dip angle. It is obvious that the seismic displacement reaches the larger value once the seismic wave incidents from the opposite direction of the joint dip, i.e. the left side in current study. And it is notable that in this case, excavation displacement and seismic displacement share a same trend.

As the joint average dip angle increases from 0° to 80°, the cavern's seismic displacement increases from 0.6cm to 2.3cm, correspondingly. However, as the average dip angle is 90°, the corresponding seismic displacement would be less than the case of 80°. This phenomenon indicates that the joints with a steep dip angle would be much unfavorable then a vertical joint in a seismic event. Meanwhile, as the joint average dip angle increases, the gap between seismic displacements of each wave incident direction is increases as well.

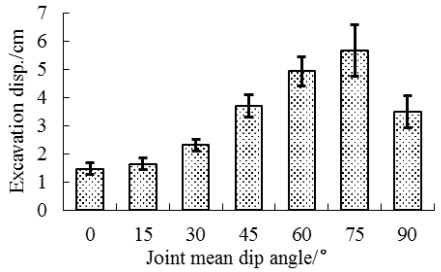


Fig.7 Relationship between excavation displacement and joint density in cavern

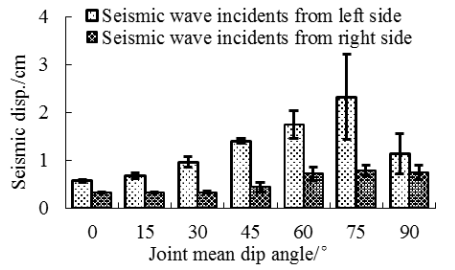
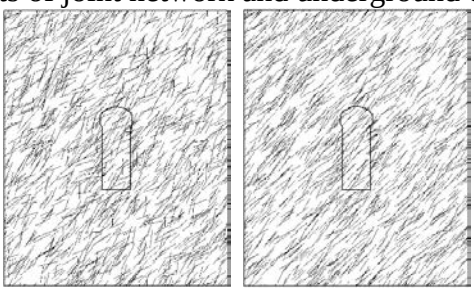


Fig.8 Relationship between seismic displacement and joint orientation

Discretization of Joint dip angle. To investigate the influence of the discretization of joint dip angle on the cavern's seismic response. 6 levels of Fisher k was considered with a fix dip angle of 45°, as 50, 10, 20, 30, 40, and 50. For each level, 10 random joint network system generated and analyzed, and the average seismic displacements and their standard deviation were evaluated.

As for other numerical simulation parameters, the trace length satisfy a normal distribution with a mean value of 15m and a standard deviation of 2m, i.e. the interval of trace length is [9, 21]m; the joint density is assumed as an intermediate values 100

Fig. 9 shows two sample plots of joint network and underground cavern with different Fisher *k*.



(a) Fisher *k* = 10 (b) Fisher *k* = 40

Fig.9 Sketches of random joint network rock and underground cavern plot of different joint dip angle discretization

Fig.10 gives the mean value and standard deviation of excavation displacement under different dip angle discretization. While Fig. 11 illustrates the mean value and standard deviation of maximum seismic displacement under different dip angle discretization. It is obvious that the seismic displacement reaches the larger value once the seismic wave incidents from the opposite direction of the joint dip, i.e. the left side in current study. And it is notable that in this case, excavation displacement and seismic displacement share a same trend.

As shown in Fig. 11 that, while the Fisher k is less than 20, the cavern's seismic displacement decreases with the decrease of dip angle discretization, correspondingly. However this trend is not that notable since the change of seismic displacement is no more than 1cm. As the Fisher k is more than 20, dip angle discretization seems have no impact on cavern's seismic displacement.

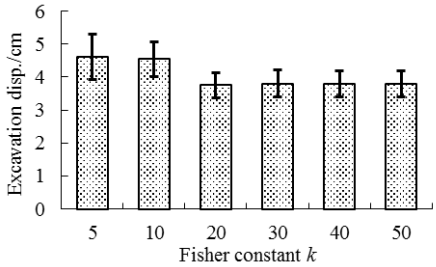


Fig.10 Relationship between excavation displacement and joint density

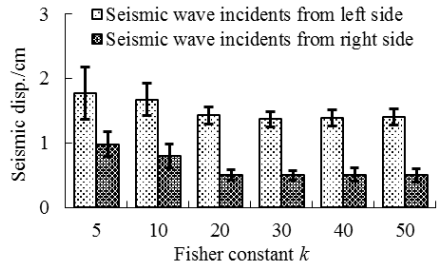
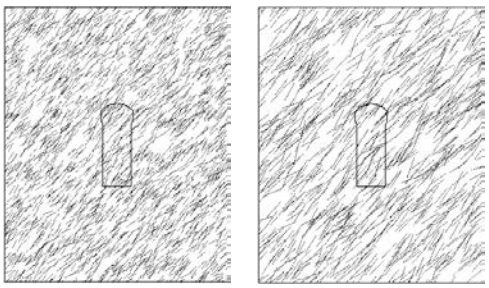


Fig.11 Relationship between seismic displacement and joint orientation discretization

Joint trace length. To investigate the influence of the discretization of joint dip trace length on the cavern's seismic response. 6 levels of fixed joint trace length was considered, as 5, 10, 15, 20, 25m. For each level, 10 random joint network system generated and analyzed, and the average seismic displacements and their standard deviation were evaluated.

The other numerical simulation parameters are as follows, the dip angle is fixed as 45 degree and satisfy the Fisher distribution with the Fisher equals an intermediate values 30; the joint density P3 is assumed as an intermediate values 100.

Fig. 12 shows two sample plots of joint network and underground cavern with different joint trace length.



(a) Fixed joint tarce length = 10 m (b) Fixed joint tarce length 20 m

Fig.12 Sketches of joint network rock and underground cavern plot of different joint trace lengths

Fig.13 gives the mean value and standard deviation of excavation displacement under joint trace length. While Fig. 14 illustrates the mean value and standard deviation of maximum seismic displacement under different joint trace length. It is obvious that the seismic displacement reaches the larger value once the seismic wave incidents from the opposite direction of the joint dip, i.e. the left side in current study. And it is notable that in this case, excavation displacement and seismic displacement share a same trend.

And while the trace length is no more than 25m, cavern's seismic displacement increases with the increase of dip angle discretization, correspondingly. However this trend turns to stationary once the trace length is greater than 25m. Meanwhile, as the joint trace length increases, the gap between seismic displacements of each wave incident direction is increases as well.

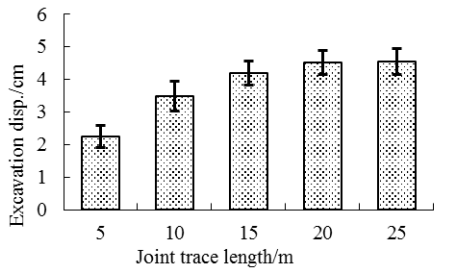


Fig.13 Relationship between excavation displacement and joint density

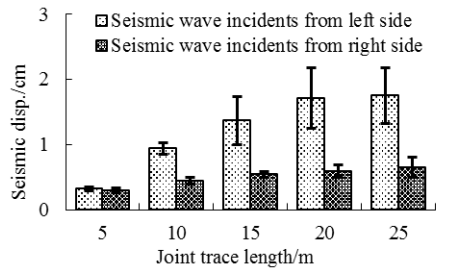
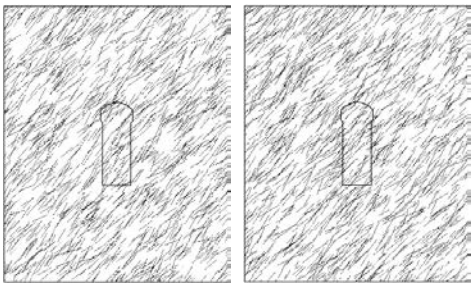


Fig.14 Relationship between seismic displacement and joint trace length

Discreteness of joint trace length. Here the influence of the discretization of joint trace length on the cavern's seismic response is to be discussed. 6 levels of standard deviation was considered with mean joint trace length of 0, 1, 2, 3, 4, and 5m.

As for other numerical simulation parameters, he joint density P3 is assumed as an intermediate values 100; the dip angle is fixed as 45 degree and satisfy the Fisher distribution with the Fisher k equals an intermediate values 30.

Fig. 15 shown two sample plots of joint network and underground cavern with different joint trace length discretization. Fig.16 gives the mean value and standard deviation of excavation displacement under different joint trace length discretization. While Fig. 17 illustrates the mean value and standard deviation of maximum seismic displacement under different joint trace length discretization. Clearly, the changes of the t joint trace length discretization seem as have no impact on the excavation and the seismic displacement.



(a) [9, 21] m, $\sigma = 2$ m (b) [3, 27] m, $\sigma = 4$ m

Fig.15 Sketches of random joint network and underground cavern plot of different joint trace length discretization

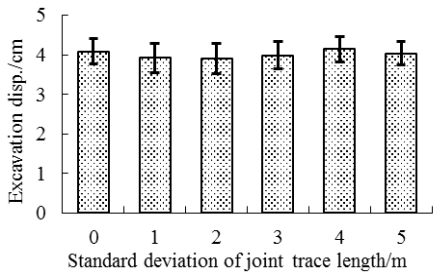


Fig.16 Relationship between excavation displacement and joint density

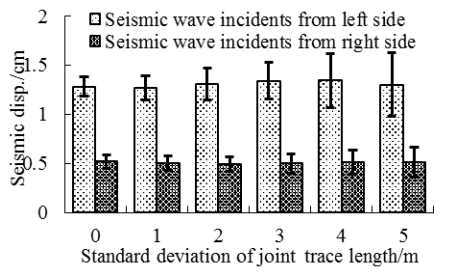


Fig.17 Relationship between seismic displacement and joint trace length discretization

Conclusions

In this paper, characteristic parameters of structure effect was given, and the underground machine hall of Dagangshan Hydropower plant was taken as a background study case. The differences of its seismic response under various structure effect characteristic parameters is examined. The following conclusions can be drawn:

(1) The influence of the joint structure effect can be repented by 5 characteristic parameters, as joint density, joint dip angle, discretization of joint dip angle, joint trace length, and discretization of joint trace length, respectively.

(2) In the precondition of a same seismic level, seismic displacement increases with the joint density. Seismic displacement also increases with the joint inclination increase at the range of 0°-80°. If the discretization of joint inclination is considerable, the seismic displacement is of positive correlation with joint inclination discretization, yet if the discretization of joint inclination is comparatively small, this correlation is ignorable. Seismic displacement increases with the joint trace length increase. At last, little relationship between joint trace length discretization and seismic displacement has been found.

(3) It is found in the quasi-static seismic analysis that seismic displacement always reache the larger value once the seismic wave incidents from the opposite direction of the joint dip, i.e. the left side in current study.

(4) Only one random joint set was considered in current study, and in future, multiple joint set as well as 3d random joint network system are to be investigated.

Acknowledgements

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