Estimation of REV for Danba schist based on 3D synthetic rock mass technique

CUI Zhen1,2, CHEN Ping-zhi2, SHENG Qian1

1. State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan 430071, China;
2. PowerChina Huadong Engineering Corporation, Limited, Hangzhou 310014, China.

E-mail: zcui@whrsm.ac.cn; chen_pz@ecidi.com; shengqian@whrsm.ac.cn

Abstract. This paper aims to provide a case study of determining the structure and mechanical properties of Representative Elementary Volume (REV) simultaneously for a specific jointed rock mass. The schist of Danba HPP project is taken as the study case here. A Synthetic Rock Mass model (SRM) is firstly constructed based on sophisticated geological loggings. With which the number of joint centers per unit volume (P30), the area of joint per unit volume (P32), and the Young’s modulus (E) are examined for various sample sizes. It is found that the SRM is a powerful tool to address those problems. The P30 reduces gradually with the increase of rock mass scale. As for P32 and E, maximum and minimum value and the variance decrease rapidly with the increase of rock mass size. A comprehensive REV size of 50~60m is then estimated based on the above 3 indexes. According to the SRM simulation, young’s modulus of the REV scale is around 6.8GPa, which is a little bit higher than the recommended value by geologists. This difference is believed to be reasonable as the recommended value usually been significantly undervalued. The procedures and findings of this paper may provide a certain reference for further studies on rock mass scale effects.

1. Introduction
Currently a great number of large-scale energy-related projects, such as ultra-long and deep tunnels, giant hydropower plants, and underground nuclear waste disposal facilities have been continuously planned and constructed in China. And most of these projects are located in rock masses, particularly in jointed rock masses with the frequent presence of geological defects. Hence the proper determination of rock mass properties is the prerequisite and guarantee for engineering design and stability assessment works.

Distinct from other engineering materials, rock masses are known for its discontinuous and heterogeneous. And the parameters obtained by laboratory tests can hardly represent the mechanical properties of rock masses in tens or hundreds of meters [1, 2]. In general, methods of determination of rock mass mechanical parameters and be sorted in to four categories, viz. theoretical approaches, empirical approaches, insitu testing and numerical prediction. Theoretical approaches are often based on sophisticated simplifications and deriving the mathematical formulas for the rock mass size and mechanical parameters. However, often being oversimplified, theoretical approaches may be short of engineering practicability. Empirical approaches, on the other hand, they are easy to use in engineering application and therefore become widely accepted. It is worth mentioning that rock mass classification...
which adopted in many regulation and code are indeed one branch of empirical approach. The defect of empirical approach is whether one or a few indexes used in these systems can represent the behavior of the complex rock mass. Theoretically, insitu testing may be the credible way to determine rock mass mechanical parameters. However their applications are quite limited by the difficulty of large scale sampling and testing. Moreover, the huge cost of purchase and maintain the large scale testers are economical unfriendly. Numerical prediction the lasted emerged one among all four methods. And, this requires the thoroughly understanding of both the geometric pattern and mechanical behavior of the joints and rock matrix that compose the jointed rock mass.

The existence of random structural planes in rock masses leads to scale-dependent properties of rock masses, known as the scale effect of rock mass. Previous studies indicated that when the rock mass scale of interest is larger than a critical value, the equivalent parameters of rock mass tend to be stable[3]. This critical size is defined as the Representative Elementary Volume (REV) of rock mass. And only if the rock mass scale is greater than REV, continuum methods may be applicable. Therefore, determination of REV is one of the important objectives of studies on scale effects of rock mass.

A significant number of researches have been conducted on scale effects and determination of REV size. A representative example was performed by Zhou [3]. Integrating rock mechanics test, engineering rock mass classification, computer simulation and back analysis, a relationship between rock mass deformation moduli and rock size was established and a 10m REV size was suggested for the Three Gorges hydropower project, China. Rajmeny et al [4] proposed an empirical model to estimate rock mass strength encompassing the scale effect based on field observations. However due to technical limitations, pioneer works conducted for rock mechanical scale effect have seldom considered individual joints embedded in the rock mass. Recent developments of computer technology allows one to perform investigation on the influences of joint system to the rock mass scale effect. Kulatilake [5], Min and Jing [6] used a 2d discrete element model and suggested the rock mass mechanical REV. Kulatilake and Wu [7, 8] managed to extend this approach into 3D condition and validated in a real engineering case. It is notable in those works considerable simplification measures were taken. For example Kulatilake [7] limit the number of joints in a 3D model to merely 16. These early works still suffered from the huge computational cost. Hence majority usage of 3D joint network was focused on 3D visualization of rock mass structures and statistics of relevant structural indexes REV [9-12]. Insufficient effort has to be applied in mechanical analysis of rock masses. Furthermore, the previous studies generally dealt with the rock masses with persistent joints or 2D planar problems [5, 6], or non-persistent jointed models with quadrangular structural planes [7, 8]. 3D disc-shaped non-persistent joints were seldom considered.

In addition, various REV indexes were studied separately in different research fields. For instance, geologists are usually concerned with REV for rock mass structures (or Structural REV, SREV) [9-12], while researchers in rock mechanics are more concerned with REV for mechanical parameters [3, 4, 5-8, 13]. Meanwhile, the aforementioned studies are lack of comparison with various REV indexes.

The introduction of the Synthetic Rock Mass (SRM) [13] technique provides a possible breakthrough to overcome these drawbacks. Disc shape joints are considered in this technique with acceptable computing cost. Another advantage would be the feasibility to investigate multiple REV indexes simultaneously.

In this paper the $S_{mx}^{4-2}$ stratum of Danba Hydropower Project, China, is taken as the application engineering. Based on sophisticated geological loggings, the mathematical model of rock mass structural parameters is obtained by regression analysis. Then a 3D disc-shaped joint network system model is constructed. The scale effects on geometrical and mechanical properties of rock masses are analyzed simultaneously using the discrete element method based synthetic rock mass technique, so as to find a comprehensive REV size for the jointed rock mass and to determine the mechanical macro-mechanics parameter for the rock mass.

2. Establishment of joint network system

2.1. Collecting information of rock mass structures
Prior to construction of a 3D joint network system for rock masses, the predominant orientation, trace length, spacing and other basic structural data are obtained by a sophisticated field logging campaign at Danba project.

The Danba hydropower plant is located at the east edge of the Songpan-Ganzi orogenic belt, southwest China. The hydropower plant will rely on a 16 km long headrace tunnel. The main geological structures along its headrace tunnels are folds and faults of various scales, which have been obviously affected by tectonic movements and intense metamorphism in multiple periods and directions. The bedrock is metamorphic rock of the fifth and forth sets ($S_{m5}^{\text{5}}, S_{m4}^{4}$) of Maoxian Group of Silurian System with high degree of metamorphism. The structural data of rock masses adopted in this study was collected from a long exploratory adit CPD-1 in the $S_{m4}^{4-2}$ stratum.

The rock structures in the exploratory adit are shown in Fig 1. Geological loggings indicated that joints are generally moderately developed and locally developed in the $S_{m4}^{4-2}$ stratum. The joint surfaces are mainly filled by ferromanganese and argillaceous materials. Slightly weathered joints are usually covered by calcium film.

![Figure 1. Typical samples of massive schist rock mass in the exploratory adit CPD-1. (a) Tunnel crown. (b) South side wall.](image)

Fig 2 presents the stereonet plot of 379 structural planes logged in the CPD-1 exploratory tunnel. By intuitive observation and fuzzy cluster analysis (based on DIPS software [14]), four predominant joint sets can be identified in the area of interest:

1) Set 1: 30~71º/115~165º, downslope fractures, extending long, flat and filled with ferromanganese or calcium materials;
2) Set 2: 45~80º/20~50º, surface fractures, frequently changing orientation, relatively flat, extending long, developing parallel;

![Figure 2. Stereonet plot of structural planes in the exploratory adit CPD-1(Lower-hemisphere, equal-angle)](image)

![Figure 3. Diagram of the Fisher distribution](image)
3) Set 3: 40°–75°/225°–265°, flat, extending long and parallel, spacing 1–2 m, locally 1–3 mm, argillaceous filling;
4) Set 4: 25°–60°/290°–330°, flat and rough, trace length greater than 15 m, spacing generally greater than 2 m, locally 20–50 cm.

Among these joint sets, Joint set 1 is better developed, compared to the other three joint sets. The four predominant joint sets are indicated by the red boxes and the predominant orientation of each joint set is indicated by the red lines in Fig 2.

The data are further analyzed by statistical regression. The rock mass structures can then be described by a mathematical function, which is applied for the subsequent joint reconstruction.

2.2. Parameters for structural parameters
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 [15], 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.

| Table 1. Definitions of joint density proposed by Dershowitz and Herda [16] |
|-----------------|-----------------|-----------------|-----------------|
| Dimension of feature | 0 No. of joints | 1 Joint trace length | 2 Joint area | 3 Joint volume |
| 0 Point | P00 (-) | / | / | / |
| 1 Line (Borehole) | P10 (1/m) | P11 (-) | / | / |
| 2 Plane (Trace plane) | P20 (1/m²) | P21 (1/m) | P22 (-) | / |
| 3 Volume | P30 (1/m³) | P32 (1/m) | P33 (-) | Total volume of joints per unit volume |

2.2.1. Center point of joints (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 can be defined by a few ways. Dershowitz and Herda [15, 16] proposed a description system for joint density, as shown in Table 1. In this paper, the joint density data were obtained in an approximately 1d exploratory adit, and the basic conditions are consistent with the P10 index (the number of joints per unit length) in Table 1. Hence, P10 is taken to define the joint density in this study.
The P10 index can be converted based on joint spacing. However, as the joint spacing theoretically ranges between 0 and ∞, the scanline has to be infinitely long in order to measure various joint spacing. In engineering practices, the scanline always has a limited length L. Causing the joints with spacing d>L cannot be measured. In this manner, the joint spacing is underestimated and the linear intensity is overestimated. Therefore, correction has to be made for this estimated joint spacing.

In this paper, the joint spacing is corrected with Sen and Kazi’s method [17]. Thus, assuming the probability distribution function for joint spacing satisfies a negative exponential distribution, the distribution function of joints with spacing d less than the scanline length L is:

\[
i(d) = \frac{\lambda_d e^{-\lambda_d d}}{1 - e^{-\lambda_d L}} \quad (0 < d < L)
\]

where \(\lambda_d\) is the linear density. The average joint spacing \(\bar{d}\) is:

\[
\bar{d} = \frac{1}{\lambda_d} \left(1 - \frac{\lambda_d L e^{-\lambda_d L}}{e^{\lambda_d L} - 1}\right)
\]

Obviously, as \(L \to \infty\), \(\bar{d} \to 1/\lambda_d = d\). Since the scanline for sampling cannot be infinitely long, by substituting the real scanline length \(L\) and the corresponding measured average joint spacing \(\bar{d}\) into Equation (2), the corrected linear intensity \(\lambda_d\) can be obtained. The P10 calculated for the interested region are listed in Table 2.

| Joint set | P10/(m\(^{-1}\)) |
|-----------|------------------|
| 1         | 0.14025          |
| 2         | 0.0434           |
| 3         | 0.0520           |
| 4         | 0.0434           |

2.2.2. Orientation of rock mass structures. In a 3D problem, orientation of a joint is determined by two parameters, i.e. dip, and dip direction. But those two parameters are not independent. It is much more convenient to discuss the joint orientation as a normal vector (pole) in the spherical coordinate system, as shown in Fig 3.

The distribution of poles for each joint set usually satisfies the Fisher distribution [18]. In Fisher distribution, only one extra parameter is required besides the mean dip and dip direction. This makes it very easy to do data fitting job. 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:

\[
f(\theta) = \begin{cases} 
  0 & \theta < 0 \\
  \frac{k \sin \theta e^{k \cos \theta}}{e^k} & 0 \leq \theta \leq \pi/2 \\
  0 & \theta \geq \pi/2 
\end{cases}
\]

The corresponding probability cumulative function is:

\[
F(\theta) = \begin{cases} 
  0 & \theta < 0 \\
  \frac{1 - e^{k(1 - \cos \theta)}}{1 - e^k} & 0 \leq \theta \leq \pi/2 \\
  0 & \theta \geq \pi/2 
\end{cases}
\]
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. \( \theta \) is the angle between the joint pole the most possible orientation. Fig 4 shows the stereonet plots of joint orientation for different Fisher constants.

As the cluster analysis on predominant structural planes in the DIPS software was based on the assumption of Fisher distribution \(^{[14]}\), the orientation of each joint set in the interested region can be estimated conveniently, as shown in Table 3.

| Joint set | Average dip angle/° | Average dip direction/° | Fisher constant \( k \) |
|-----------|---------------------|-------------------------|-------------------------|
| 1         | 50                  | 139                     | 33.146                  |
| 2         | 62                  | 36                      | 29.934                  |
| 3         | 55                  | 244                     | 34.200                  |
| 4         | 43                  | 311                     | 33.749                  |

2.2.3. Diameter of structural planes (Joint size). The uniform and normal distribution are two probability density functions frequently used to describe the size of structural planes in traditional studies. In fact, smaller joints appear with higher probability. Therefore, the negative exponential distribution and the power-law function may better fit the exact distribution of joint size (disc diameter). The negative exponential function was selected by many researchers as it can be conveniently applied, while the power-law function was less popular due to its difficulties in parameter estimation.

Furthermore, the exponential function is linear only in a logarithmic coordinates system, while the power-law distribution remains linear in a dual-logarithmic coordinates system. Hence, compared to the negative exponential distribution, the power-law distribution has a steeper and long-tailed pattern. Simply speaking, the negative exponential distribution may underestimate the number of small joints, and overestimate the number of large joints. Therefore, the more complex power-law function is adopted to describe the joint size in this study.

Table 4. Estimated parameters for joint size

| Joint set | \( L_0 \)/m | \( D \) |
|-----------|------------|-------|
| 1         | 3          | 1.8   |
| 2         | 4          | 1.2   |
| 3         | 2          | 2.3   |
| 4         | 2          | 1.8   |

With the assumptions of power-law distribution, the distribution of joint size can be expressed as:

\[
N = CL^{-D} 
\]  

(5)

where \( N \) the number of joints with size larger than \( L \), who is the joint size, \( C \) is the proportionality constant and \( D \) is the only distribution parameter. If the joint size is assumed to be a continuous variable, the probability density function for joint size can be written as:

\[
f(L) = \frac{D}{L_0} \left( \frac{L}{L_0} \right)^{-1+D}
\]

(6)

where \( L_0 \) is the threshold of characteristic joint size in rock masses.

In consideration of the complexity of regression for the power-law distribution parameter, the Newman power-law toolbox in MATLAB \(^{[19]}\) was employed to estimate the size parameter for four joint sets. The results for the interested area are listed in Table 4.

3. Reconstruction and verification of joint network

3D reconstruction of the joint network was performed with the 3DEC software by Itasca \(^{[20]}\). 3DEC is a widely used commercial 3D discrete element code. A rock mass structure generation module has been equipped in the latest version of 3DEC, which gives 3DEC the full capability of generate, analyze and calculate of complex joint network system.
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 regression 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, based on the experiences of Esmaieli et al [21], the following method was adopted to deal with the randomness in generation of a joint network system model. First, a sample with a distribution satisfying the regression parameter is reconstructed within a very large range. The sample range shall be much more than the expected REV, so as to ensure that sufficient statistical samples are available. Within this large model, specimens with a certain size can be extracted for the following research. When conducting the extraction, different samples are taken at various center points in the large model for a specific specimen size. The scale effect characteristic indexes for these specimens are then examined. And their average or statistical value are taken as the equivalent characteristic value of jointed rock mass under present size.

Based on the regression parameters of the $S_{m6}^{4.2}$ stratum of Danba hydropower project mentioned the previous section, a 3D joint network system model with a total number of approximately 26000 disc joints was generated in a large range of 200m×200m×200m, as shown in Fig 5. In order to verify the 3D joint network system model, a stereonet is plotted for the reconstructed joints, as shown in Fig 6. It can be seen that the reconstructed joint network system agrees very well with the geological logging results shown in Fig 2.

Figs 7 and 8 present the 50m×50m trace planes in the east-west and north-south directions, respectively. The color of trace lines indicates the length of trace lines. It can be observed from Figs 7 and 8 that: Joint set 1 has the most intensive distribution and Joint set 2 has the longest trace length.

In summary, the reconstructed 3D joint network system model can represent the rock mass structure of the $S_{m6}^{4.2}$ stratum of Danba hydropower project and can be used for further analysis.
4. Sampling of joints with finite sizes
In order to illustrate the feasibility of the sampling method mentioned in section 2.3, different samples were drawn with a same center point and different sizes, or with the same size and different center points. These exactation result are to be discussed below.

4.1. Same center point, different sample sizes
Fig 9 shows rock mass specimens drawn from the large-scale joint network system model. These specimens share a same center point (0, 0, 0) but with different sizes. It can be seen that, for rock masses with different sizes, the fundamental difference is caused by the difference in rock mass structures contained in the sample region. This is also believed to be the root cause for scale effect of rock mass properties.

4.2. Same sample size, different center points
Another important factor in rock mass structures, the randomness, can be reflected by Fig 10. Each group of these specimens share respectively same sample size but are drawn from random center points.

It can be seen in Fig. 10 that, for samples with a same size, essential difference may be caused by the random occurrence of rock structure. Therefore, one should consider the randomness when investigating the scale effect of rock mass, which can be described by a statistical method.

Therefore, the two most important problems in 3D joint network system modelling for rock masses can be solved by the sampling methods proposed above.
5. Scale effects of rock mass structural parameters

With increasing scale of jointed rock mass, the number of joints contained also increases, as shown in Fig 11. The reciprocal of the number of joints in sample volume is the volumetric density $P_{30}$. The volumetric density can reflect the density of rock mass structural planes by counting the number of center points for rock mass structural discs within unit volume. Therefore, it is considered as an important REV index [11, 12]. When $P_{30}$ approaches constant with varieties of rock mass scale, the corresponding scale can be considered as the REV size of rock mass.

For each rock mass sample drawn from the joint network system, the number of center points for structural planes can be obtained by the FISH code imbedded in the 3DEC program. $P_{30}$ for the current sample scale is the ratio between the number of center points and the sample volume. In this study, 50 specimens with different center points were taken for each size level. The statistical results are shown in Fig 12. It can be seen that, with increasing sample size, the range, variance and mean value of $P_{30}$ gradually decrease and approach constant. For the $S_{m2}$ stratum under study, $P_{30}$ tends to be stable at a sample size of approximately 50m. When further examined via the T-test and the F-test [11, 21], the corresponding REV sizes are 50m and 60m, respectively. Based on the above analyses, the REV size corresponding to $P_{30}$ is 50~60m.

$P_{32}$, the area of rock mass structures per unit volume, is another index commonly used for density of rock mass structures. This index is believed to be less affected by orientation and distribution of joint sets [8-10]. Similarly, by using the FISH code in 3DEC, 50 specimens with different center points are taken for each size level and the joint area per unit volume is calculated for each sample, as shown in Fig 13. When the disc intersects the sample boundary, only the disc area within the model domain is considered in the calculation.

The results show that, compared to the $P_{30}$ index, the range and variance of $P_{32}$ decrease rapidly with the increasing sampling size, while the average value basically remains unchanged. The size, with which the range and variance of $P_{32}$ tend to be stable, is taken as the REV size. Based on intuitive observations, the T-test and F-test, the REV size corresponding to $P_{32}$ is also 50~60m.

6. Scale effect of mechanical parameters via synthetic rock mass technique
6.1. The discrete element method based synthetic rock mass technique

The Synthetic Rock Mass (SRM) technique is a state-of-art numerical simulation technique based on 3D joint network system. A 3D joint network system model is embedded into a rock matrix model to construct a synthetic rock mass model which can fully reflect both the real spatial distribution of joints and mechanical effects of the matrix. In this way, mechanical and many other properties can then be analyzed simultaneously. In the past few years, the PFC-based synthetic rock mass technique has been studied [13, 21, 22]. However, the synthetic rock mass technique based on conventional discrete element method (DEM) has seldom been reported.

The theory of discrete element method suggests that it can only consider problems involving convex polygons or convex polyhedrons. In simple terms, it can only be applied to persistent joints, but not non-persistent joints. It is generally considered that discrete element method cannot handle the mechanical analyses of disc shape joints.

However, with the enhancement of code execution efficiency, some alternative methods can be adopted for analysis of disc shape joints by conventional discrete element method. For a joint disc, the specimen model is cut through according to the joint orientation. Meshes are then generated for the cut block and contact elements are generated on the cutting surface. Finally, the parameters are reassigned to the contact elements inside or outside the disc according to the disc diameter. Very large mechanical parameters are assigned to the contact elements outside the disc, so that these elements become “virtual joints” which will not fail, slide, or separate [20]. The contact elements within the disc are assigned with normal material parameters so as to form a disc joint plane, as shown in Fig 14.

![Figure 14. Computation principle for disc shape joints in discrete element method](image)

(a) Model cutting based on joint orientation. (b) Reassignment of element parameters according to disc diameter

Fig. 15 gives some examples of specimens after cutting of the disc joints. It is advisable to densify the initial large specimen into smaller specimens and glue them together, using the same “virtual joints” trick. So as to prevent some small joints forming very long cuts. Therefore the amount of contact elements is reduced, so as the computation workload is economized.

![Figure 15 Computation principle for disc shape joints in discrete element method](image)

(a) 5×5×10m. (b) 10×10×20m. (c) 30×30×60m

The above approach for disc joints will undoubtedly be affect by the element sizes on the contact surface. Fig 16 shows discretization of a 50m diameter disc with different mesh sizes. The real normal stiffness of joints inside the disc is 2GPa and the virtual normal stiffness is 30GPa for joints outside the disc. When the mesh size is not smaller than 1/10 of the disc diameter, this approach can reflect the 3D disc-shaped joint network system much realistically during numerical simulations.
6.2. Scale effects of rock mass mechanical parameters

Due to the huge computation demand of synthetic rock mass, only scale effect of the young's modulus $E$, among all the mechanical parameters of rock masses, is analyzed in this paper.

With the synthetic rock mass mentioned in the above section, uniaxial compression tests on rock samples of various sizes are simulated using 3DEC. Due to the large amount of calculation, only elastic calculation was performed. Thus, only the elastic modulus alone was presented as the mechanical parameters. The young's modulus of rock matrix was taken as 12GPa, based on laboratory tests on small specimens. The joint stiffness was taken as 5GPa/m and 2GPa/m in the normal and shear directions, respectively, as recommended by geologists. The loading rate at each end was controlled by the servo system in the 3DEC program. Due to the huge amount of computation workload, loading tests were only conducted on 10 randomly exacted specimens for each size. The simulation results are shown in Fig 17.

It can be seen that, with increasing sample size, the average young's modulus $E$ gradually decreases in a narrow range. However, the degree of dispersion is reduced significantly. It indicates that the scale effect of young's modulus $E$ is mainly exhibited by the decreasing degree of dispersion with increasing rock mass size. This is consistent with the scale effect described by Zhang [23] and Pinto [24]. In combination with intuitive observations, the T-test and F-test results, the REV size considering the young's modulus $E$ for the $S_{mx}^{4-2}$ stratum is about 50–60m. The corresponding modulus is about 6.8GPa.

7. Discussions

(1) Both structural and mechanical REV sizes are determined for the Danba schist rock mass. As a compassion, Esmaieli et al [21] suggested that the mechanical REV size is about 50–100% greater than the structural REV, based on their study on Brunswick Mine. For Danba $S_{mx}^{4-2}$ stratum studied in this paper, the structural and mechanical REV sizes are close to each other, being 50–60m. However, it is worth noting that more studies are required before this conclusion can be applied to other rock masses.
(2) By using the DEM-based synthetic rock mass technique, the test results from small-scale specimens can be directly applied to engineering-scale rock mass. The young's modulus $E$ of the $S_{mx}^{4-2}$ stratum is calculated to be about 6.8GPa. Compared to 5~6GPa recommended by geologists, the young's modulus obtained by the synthetic rock mass technique is slightly higher. This in fact reflects the difference which should exist between the true 'calculated value' and the “reduced value” which based on geologists’ experiences from indoor or field experiments, since the “reduced value” is usually affected by the subjective confidence of geologists.

8. Conclusions
A 3D joint network system model was established based on geological logging data. Both the structural and mechanical REV sizes were obtained for the $S_{mx}^{4-2}$ stratum of Danba Hydropower Station, using the DEM-based synthetic rock mass technique. The following conclusions can be drawn:

(1) With the DEM-based synthetic rock mass technique, the 3D joint network system model can be used to study the mechanical properties of rock masses, other than the rock mass structures. In this manner, it is possible to find a comprehensive REV size for structural, mechanical, seepage and other parameters for one joint network system model.

(2) The P30 index, i.e., the number of joints per unit volume, of the Danba $S_{mx}^{4-2}$ stratum gradually decreases with increasing rock mass size. It approaches constant when the rock mass size is 50~60m. The range and variance of the P32 index, i.e., the joint area per unit volume, decrease rapidly with increasing rock mass size, and the mean value remains basically unchanged. The range and variance of P32 tend to be stable when the rock mass size is 50~60m. The structural REV sizes based on P30 and P32 are basically the same, i.e., 50~60m.

(3) The degree of dispersion of the young's modulus $E$ for the Banba $S_{mx}^{4-2}$ stratum decreases with increasing rock mass size. However, the mean value varies in a narrow range. The mechanical REV size corresponding to $E$ is about 50~60m.

(4) The REV sizes, with consideration of both structural and mechanical properties of the $S_{mx}^{4-2}$ stratum, are basically close to each other, being 50~60m. As the expected excavation span (in the order of 10m for the headrace tunnels and 30m for the surge chamber), is smaller than the REV size, the continuum method may not be applicable for excavations in this stratum. Instead, the discontinuum method considering rock joints and fractures shall be adopted.

(5) Under the REV size obtained in current study, the suggested young's modulus of the Danba $S_{mx}^{4-2}$ stratum is 6.8GPa, which is slightly higher than 5~6GPa which recommended by geologists.

(6) The scale effects of strength and seepage parameters of rock mass and the relevant REV size will be investigated in the future research. In addition, the structural and mechanical REV sizes are seldom obtained simultaneously for a same rock mass. The conclusions have not been commonly recognized and further studies are required.

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