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Topological and dynamic complexity of rock masses based on GIS and complex networks

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HIGHLIGHTS

- The relation between rock masses indicates power-law property.
- The interaction between rock masses shows remarkable heavy tail phenomenon.
- The interaction between rock masses is related to the structural characteristics.

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ABSTRACT

Lithosphere is composed of a great number of rock masses. Crustal movement may cause the fracture of rock masses and stimulate tremendous energy. The interaction between rock masses may affect deep geological processes, especially earthquakes. This paper studies the spatial distribution of rock masses and proposes a network analysis method for mining the topological and functional characteristics of rock masses from complex networks and geographical information science (GIS) perspectives. Geological survey data covering Sichuan Province and Chongqing Municipality is used for experiments. Results show that if we do not consider the rock type or strength, the degree distribution of rock mass network satisfies power-law distribution; for nine types of rock masses and five levels of strengths, their topological relationships all follow power-law distributions. Moreover, the power-law exponents are greatly different for different rock types and strengths that may affect the interactions between rock masses.

1. Introduction

The circulating interaction between rock masses may lead to some geological hazards, especially earthquakes [1–3]. Crustal movement may lead to the fracture of rock masses, stimulate tremendous energy, and trigger seismic waves.

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Seismic waves can spread in a large region through different types or strengths of rock masses. Therefore, seismologists and geologists try their best to obtain the spatial data of rock masses, and mine the interaction between them or other dynamical characteristics. The interaction between rock masses is a very complicated dynamical phenomenon which is not determined by single rock. A great number of rock masses contribute to lithosphere, which can be regarded as a complex dynamic system. In this real system, each rock mass is one component of the system and may affect the stability and other dynamics of the whole system. Therefore, it will be helpful to study the interaction or relationships between rock masses from the complexity science perspective.

In recent years, scientists have begun to study geographical problems by using GIS and complex network theory, and have discovered some significant phenomenon [4,5], such as the network analysis of earthquake seismic data [6–10], scaling property of the earth's surface [11], structural analysis of landslides [12], complex network modeling of ice shelf channels [13], and so on. With using GIS technology, we can easily obtain the topological relationships between two geographic objects. Most of GIS platforms provide topology tools for computing the topological relationships between different objects, for instance, the most popular GIS software—ArcGIS. Complex network theory is a very useful and active theory which has been playing an increasingly important role in many kinds of research fields. A great number of scholars use complex network to study the structural properties and dynamical behaviors of real systems, such as transportation networks, communication networks, pipe networks, social networks and so on [14–19].

In geological field, rock is a type of natural body that is composed of mineral or rock debris collected according to certain rules under geological process. However, in engineering geology, rock mass is defined as synthetic geological mass which has a certain rock composition, structural characteristics and is lied in definite geologic surrounding. Different rock masses are divided by structural planes which are various kinds of structural trace and cracks. The type and strength of rock masses and the topological relationships all may affect the interactions between them and propagation of seismic waves.

On the basis of this, we aims to study the topological complexity of rock masses considering rock type and strength based on GIS and complex network theory. We believe that some important phenomenon may be revealed through network modeling and analysis of rock masses. Especially, rock masses which cover a large region contribute to a dynamic system with containing many complex mechanisms. It is significant to analyze the inherent properties of the lithosphere in overall. In system science, it is widely believed that the structure of a system determines its function. Any real system is not composed of single component, but a lot of components with different patterns of interactions. Therefore, the purpose of the paper is to realize the network modeling of rock masses and mine the structural characteristics of rock masses.

The remainder of this paper is organized as follows. In Section 2, we study the topological representations of lithosphere, and introduce the concept of rock mass network and the specific modeling approach. Section 3 discusses some important experiments and results on Sichuan Province and discovers the topological characteristics of rock mass system and the interaction between them. Section 4 concludes this paper.

2. Topological representation of relationships between rock masses

2.1. Dual topological modeling of relationships between rock masses

Rock masses are separated by each other's structural plane. There exists a kind of spatial relationships between adjacent rock masses, called adjacent topological relationship. Rock masses maybe adjoin with several, tens or even hundreds of other rock masses. The more the number of adjacent rock masses, maybe the greater the impact of this rock mass on other rock masses and the stronger the interaction between them. Therefore, extracting and describing the topological relationships between rock masses is meaningful to study the interaction and movement mechanism of rock masses.

The principle of dual topological modeling of relationships between rock masses is detailed as follows: each rock mass is abstracted by a node that can record some information of this rock mass, such as the rock type, strength, area and so on; an edge can be created and connected to two nodes if the corresponding two rock masses are adjacent to each other; therefore, we can construct a dual graph for describing the relationships between rock masses. As shown in Fig. 1(a), we can see that there are 12 rock masses in the geographical map of rock masses. Fig. 1(b) is the corresponding dual graph that has 12 nodes and 23 edges. The adjacent topological relationships between any rock masses are directly represented. Meanwhile, we can easily obtain the number of adjacent rock masses of each rock mass.

Using ArcGIS platform, we can extract the topological relationship between any pair of rock masses. Then the dual graph for describing all the relationships is generated.

2.2. Topological measures

2.2.1. Degree and degree distribution

In graph theory, degree is the basic and key topological factor for evaluating the properties of nodes, such as node importance [20]. The degree of a node is defined as the number of nodes directly connected to this node, usually represented by k. The average degree means the average of degree of all nodes, represented with $\langle k \rangle$.

Degree distribution is one of the most significant topological measures to studying the structural properties of networks from macroscopic perspective [20]. The pattern of degree distribution is helpful to understand the dynamics and behaviors of real complex systems. For example, the systems with power-law distributions mostly show the robustness for random

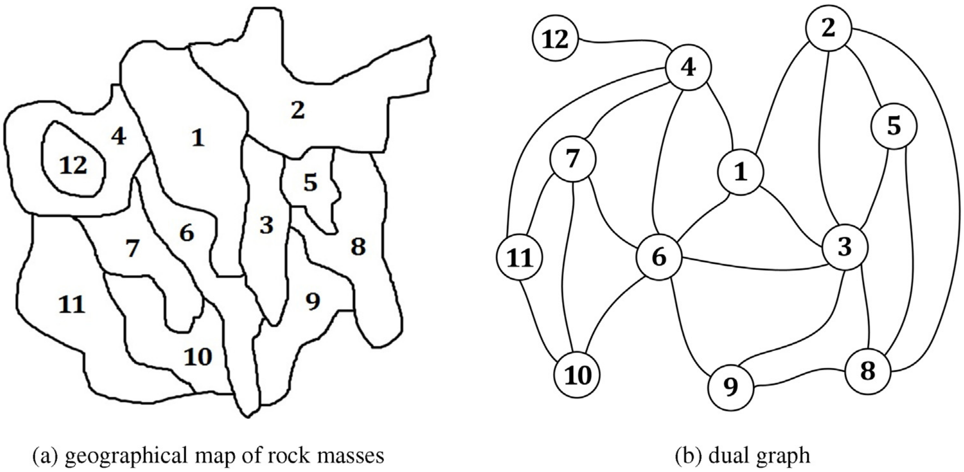

Fig. 1. Dual topological modeling principle of rock masses.

attacks and the frangibility for intentional attacks. The research of degree distribution of real systems can help us discover some inherent properties of real systems, and then control their evolutions and other dynamics. Therefore, we introduce degree distribution to measure the topological characteristics of the rock mass network.

2.2.2. Clustering coefficient

Clustering coefficient is important in the characterization of spatial networks. The clustering coefficient is a measure of the degree to which nodes in a graph tend to cluster together, which is defined as the number of actual connections across the neighbors of a particular node, as a percentage of possible connections, represented with C. The clustering coefficient measures the average probability that two neighbors of a node are themselves neighbors. The average clustering coefficient (represented by $\langle C\rangle$) is defined as the average of clustering coefficient of all nodes, and can reflects the compactness of relationships between nodes from the overall perspective. Therefore, using the average clustering coefficient, we can study the structural compactness of rock masses.

3. Results and discussions

3.1. Rock mass dataset

The research area covers Sichuan Province and Chongqing Municipality, and is about 568,005 square kilometers. The experimental data is derived from State Key Laboratory of Geohazard Prevention and Geoenvironment Protection of China, and contains many kinds of geo-information including the geometrical shape, rock type (e.g., carbonate rock, magmatic rock, sandstone, mudstone, etc.), strength and other properties of each rock mass (see Fig. 2). The whole area is composed of 6130 rock masses that the minimal area is 5598.7 square meters and the maximal area is 44 488.4 square kilometers. The rock mass network contains 6130 nodes and 12 914 edges. The average degree of this network is equal to 4.2.

Without considering the rock type or strength of rock masses, we study the topological properties of the rock mass network. As shown in Fig. 3, the results indicate that we can approximately use a straight line with negative slope to describe the degree distribution. It means that this distribution follows power-law property. Therefore, we conclude that the rock mass network is a scale-free network, and its degree distribution can be described as $P(k) \sim Ak^{-\gamma}$, where γ is the power-law exponent and A is the coefficient. Scientists have discovered that scale-free networks present very robust for random attacks but fragile for deliberate attacks [16]. Generally, geological disasters especially earthquakes do not come from random events. For example, one of the most important reasons of triggering earthquakes is the interaction between rock masses that the interaction can collect enormous energy. Earthquakes can be considered as deliberate attacks to rock masses. Because the topological relationships between rock masses present power-law properties, deliberate attacks can spread to other rock masses and lead to a wide range of hazards. Therefore, it can be concluded that for the rock mass network, it may be very fragile to strong interactions between rock masses.

3.2. Structural properties of different types of rock masses

Seismologists believe that there may be some relations between earthquake and lithology. For example, in seismic data, a reflector might represent a change in lithology. Different types of rock masses are adjacent to each other in space and form rock formations or lithosphere. The interactions between rock masses may be different, because the lithology of rock masses

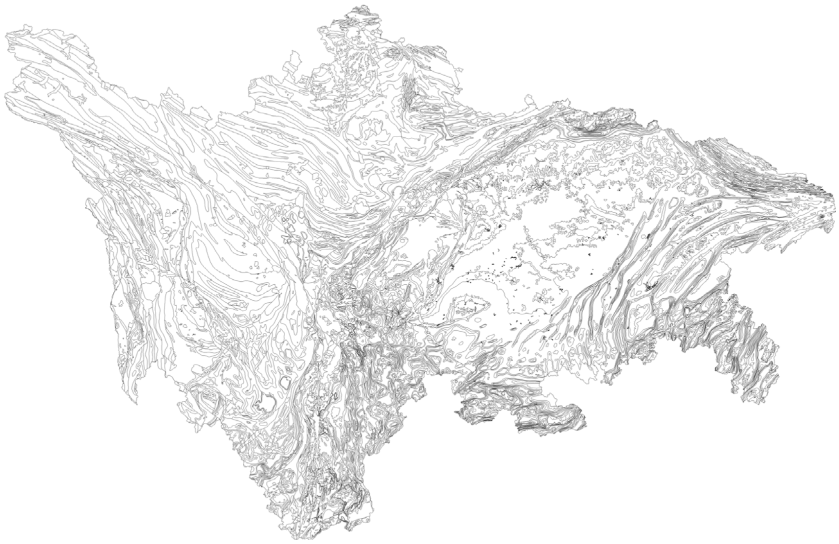

Fig. 2. Geographical map of rock masses in the research area.

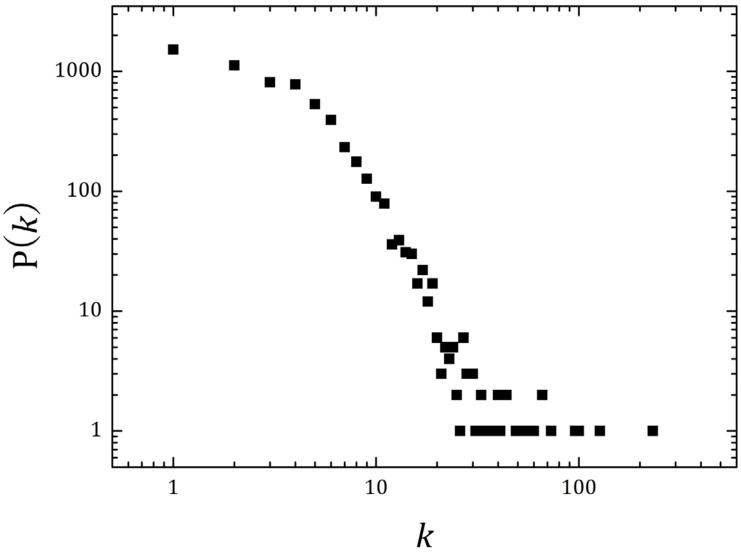

Fig. 3. Degree distribution of rock mass network.

may be different. Therefore, it is of important meaning to study the spatial distribution of different types of rock masses and the adjacent relationships between them. The research will help us understand the structural characteristics and dynamics of rock masses. Fig. 4 is the geographical distribution map of different types of rock masses, which contains 9 types: carbonate rock, magmatic rock, meta-sandstone, mudstone, phyllite, sandstone, soil, slate and shale. We can see that, there are a great number of carbonate rock, sandstones, magmatic rocks and meta-sandstones in this area. Moreover, we find that there are a lot of magmatic rocks in Longmenshan Fault Zone, Jinshajiang Fault Zone, Litang Fault Zone and Anninghe–Zemuhe Fault Zone.

Fig. 5 is the statistical results of degree distributions for different rock types. The results indicate that whatever the type of rock mass, the degree distribution approximately follows power-law distribution because the main part of the plot can be represented by a straight line in a log–log coordinate system. We can see that the maximum degree of sandstones is greater than that of other rocks that means the corresponding rock mass can affect many other adjacent rock masses. Moreover, results also indicate that although the degree distributions of rock masses for different rock types are visually similar to each other, the topological measures are quite different. Table 1 show the average degree $\langle k \rangle$, average clustering coefficient $\langle C \rangle$ and power-law exponent γ of each type of rock masses. We can see that phyllites have the maximum average degree,

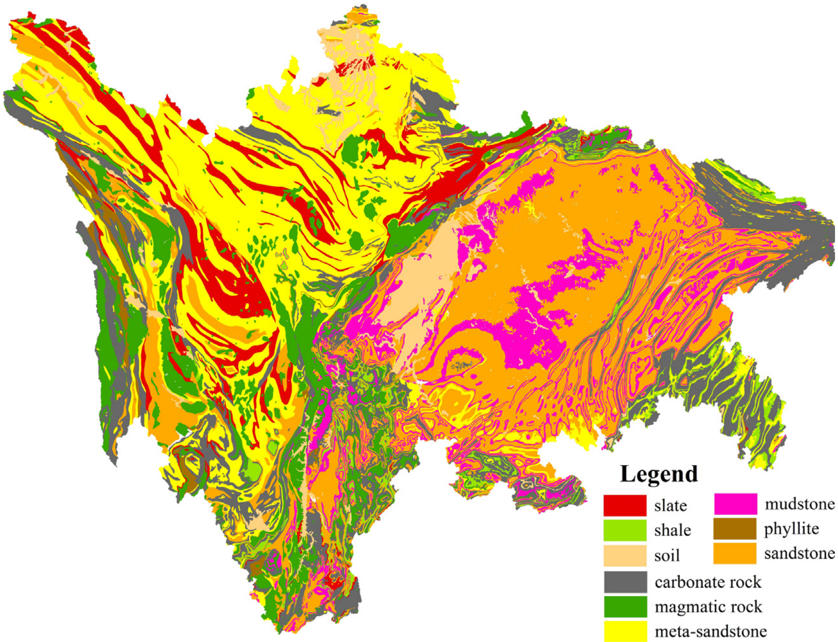

Fig. 4. Geographical distribution map of different types of rock masses.

Table 1
Topological measures of rock mass networks for different rock types.

Rock type	$\langle k \rangle$	$\langle C \rangle$	γ
Carbonate rock	4.364	0.415	2.778
Magmatic rock	3.733	0.475	2.579
Meta-sandstone	4.803	0.483	3.227
Mudstone	3.670	0.403	4.089
Phyllite	5.623	0.549	1.514
Sandstone	4.307	0.407	2.972
Slate	4.881	0.530	3.970
Shale	4.210	0.482	3.498
Soil	5.518	0.506	2.440

maximum average clustering coefficient and minimum power-law exponent; mudstones have the minimum average degree, minimum average clustering coefficient and maximum power-law exponent.

Moreover, the power-law exponents are quite different for different rock types that the range of exponents is from 1.514 to 4.089. It is widely believed that power-law exponent is one of the most important factors for measuring the structural properties of a complex system. The power-law exponents are quite different, so the interactions between different types of rock masses may be unstable and unbalanced.

3.3. Structural properties of different strengths of rock masses

In this region, the aggregation effect of earthquakes is remarkable in space to some extent. Most of strong earthquakes occurred in the west and north of Sichuan, such as the Diexi earthquake (7.5M, 1933.8.25), Kangding earthquake (7.5M, 1955.4.14), Luhuo earthquake (7.9M, 1973.2.6), Songpan earthquake (7.2M, 1976.8.16), Wenchuan earthquake (8.0M, 2008.5.12), Lushan earthquake (7.0M, 2013.4.20) and Jiuzhaigou earthquake (7.0M, 2017.8.8). Seismologists believe that the cause of earthquakes and the propagation of earthquake waves are related to the hardness degree of rock masses. For instance, earthquake waves spread faster in hard rock masses rather than soft rock masses. Therefore, to study the spatial distribution and topological properties of different strengths of rock masses may be helpful for revealing in-deep dynamics of earthquakes. In order to further study the topological characteristics of rock masses, we analyze the degree distributions for different strengths of rock masses. Fig. 6 is the geographical thematic map of rock masses with different strengths. We can see that in this area, there are many hard rock masses and relative hard rock masses in the western and northern parts of Sichuan Province where contains several large faults, including the Longmenshan Fault Zone, Xianshuihe Fault Zone, Jinshajiang Fault Zone and Daliangshan Fault Zone.

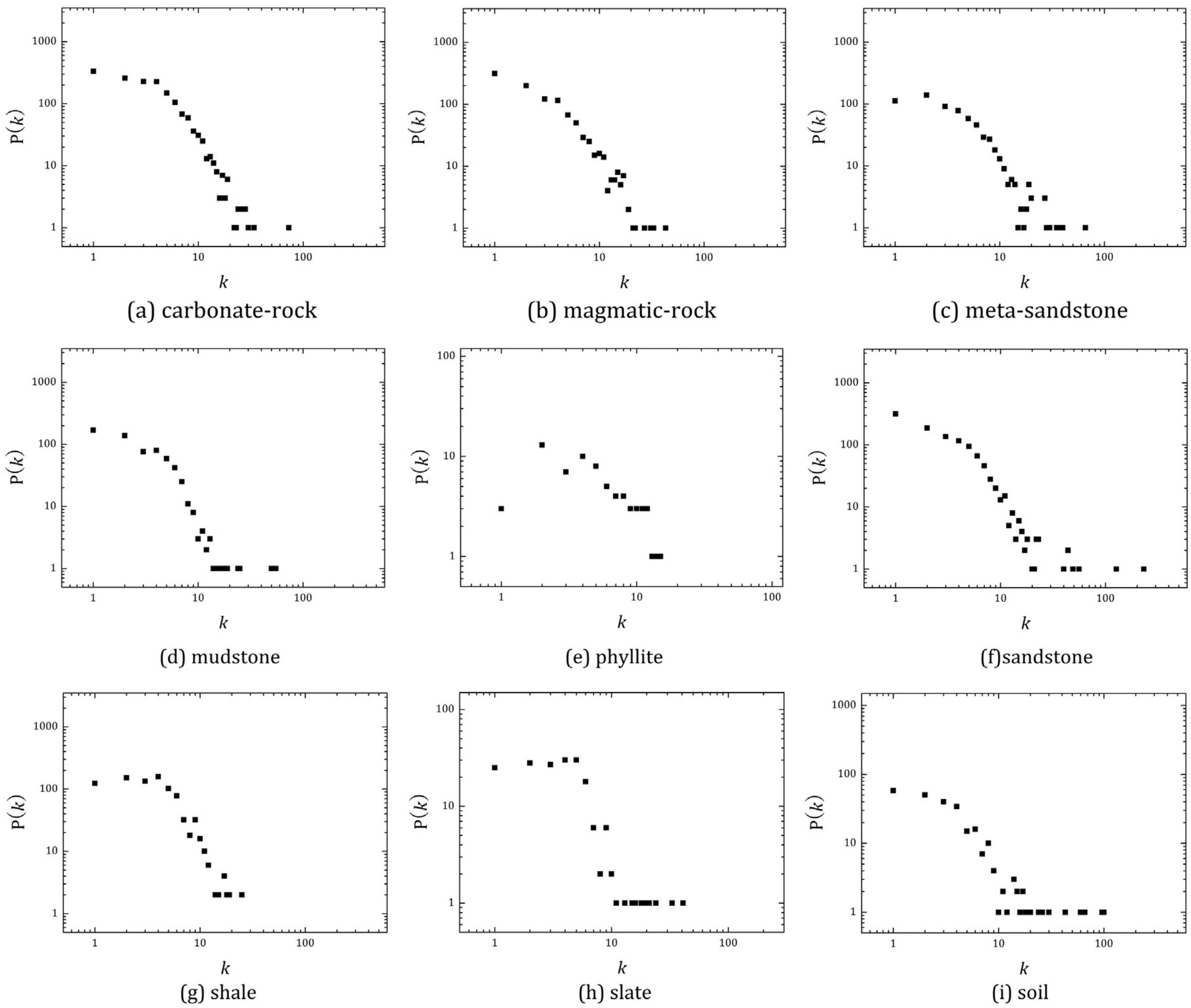

Fig. 5. Degree distributions of different types of rock masses.

Fig. 7 is the degree distributions of different strengths of rock masses. According to the results, we can see that for the five kinds of rock strength, the corresponding degree distributions all satisfy power-law distribution. Moreover, we discover that a great number of hard rock masses or relative hard rock masses are adjacent to each other. Deep crustal movement may lead to the extrusion, disruption and dislocation of rock masses, and then it may motivate seismic waves that contain tremendous amounts of energy. Because there are many hard rock masses in the west of Sichuan that most of these rock masses are adjacent to each other, the propagation of earthquake waves will be faster in this area. Besides, during the transmission process of earthquake waves, it may cause the fracture of hard rock masses that must lead to serious hazards. Therefore, we can see that earthquakes (especially strong events) are more active and the impact of earthquakes is more serious in the west of Sichuan. Table 2 is some of topological measures of rock masses for different strengths. Results indicate that loose rock masses have the maximum average degree, maximum average clustering coefficient and minimum power-law exponent. For the other four kinds of strength, the average clustering coefficient is inversely proportional to the average degree that means the greater the average degree, the smaller the average clustering coefficient. This phenomenon indicates that although the average degree of hard rock masses is the smallest, the average clustering coefficient is greater that means the adjacent rock masses are related to each other more closely.

3.4. Analysis of the interaction between rock masses from geological perspective

In order to further study the geographical significance of the structural characteristics of rock masses, it is necessary to analyze the interaction between rock masses. We believe that it exists interactions between adjacent rock masses. If two adjacent rock masses are both very active, we can consider that the interaction between them is strong. Actually, the mechanism of the interaction among rock masses is very complicated that existing researches still cannot explain it

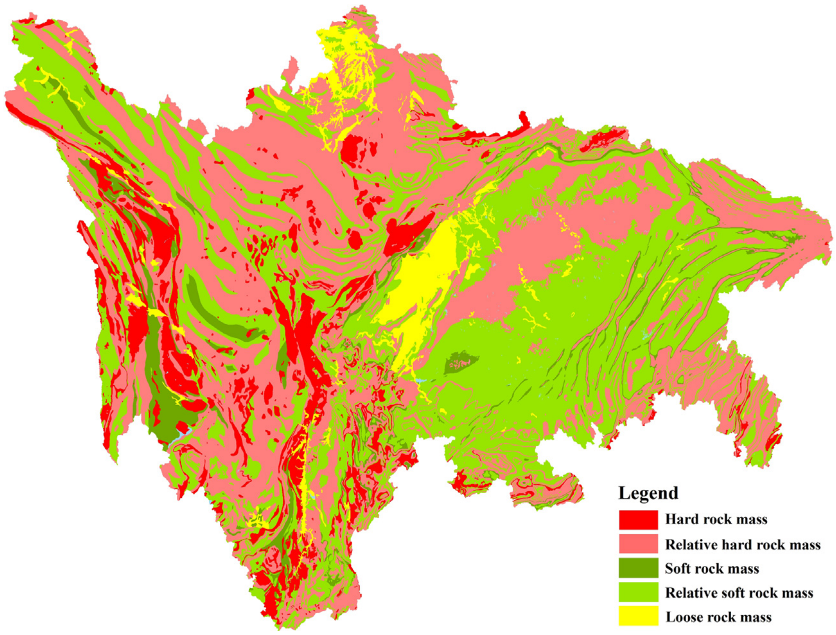

Fig. 6. Geographical distribution map of rock masses with different strengths.

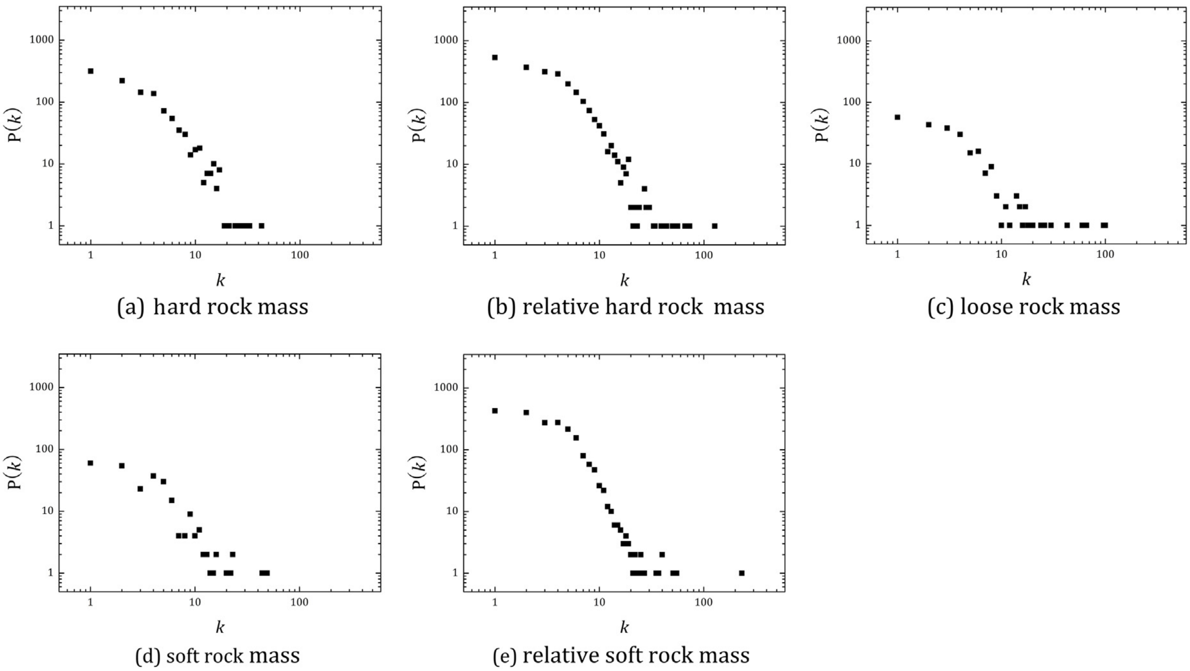

Fig. 7. Degree distributions of rock masses with different strengths.

accurately. Geological research indicates that the tectonic movement may cause different kinds of geological disasters, especially earthquake. Therefore, it is more meaningful to use the earthquake dataset to study the interaction between rock masses. For illustrating the relationships between the interactions and structural properties, here we use the number of earthquakes to describe the activeness of a rock mass. Let i and j be two adjacent rock masses, and N_i, N_j be the number of earthquakes of them respectively. It is widely believed that earthquake is a kind of physical phenomena mainly triggered by the crustal movement. The friction between rock masses can release vast amounts of energy that may cause earthquakes. The more active the mutual interactions between rock masses, the more earthquakes occur. We consider that the interaction

Table 2
Topological measures of rock mass networks for different rock strengths.

Rock strength	$\langle k \rangle$	$\langle C \rangle$	γ
Hard rock mass	3.813	0.479	2.310
Relative hard rock mass	4.470	0.413	2.858
Soft rock mass	4.452	0.421	2.205
Relative soft mass	4.173	0.454	3.456
Loose rock mass	5.660	0.513	2.175

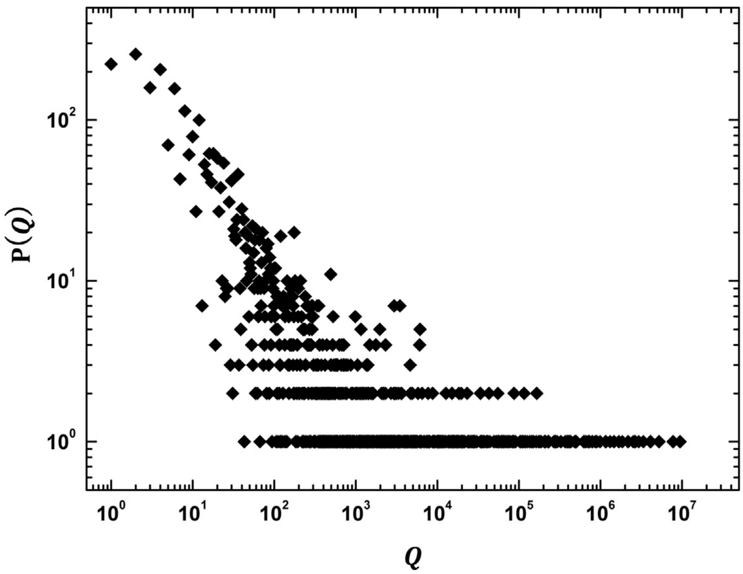

Fig. 8. Distribution of interaction strength among rock masses.

between two adjacent rock masses is great if there are many earthquakes occurred at these two rock masses. Therefore, the interaction between two adjacent rock masses is defined as $Q = N_i \cdot N_j$ in this paper. This equation indicates that, the greater the number of earthquakes occurred in both rock masses, the stronger the interaction between them. Then, the interaction strength Q can be used to define the weight of edges of the dual graph for the rock mass geographical map.

For this, combined with 44 091 earthquakes from January 1, 1990 to December 31, 2008 in this region and the rock mass dataset, we compute the number of earthquakes occurred in each rock mass and then calculate the interaction strength Q between any two adjacent rock masses. The result as shown in Fig. 8 (where $Q = 0$ is not plotted in this figure) indicates that the distribution presents heavy tail phenomenon. Therefore, we can see that strong interaction between rock masses actually occur more frequently compared to e.g. in the normal distribution. We can get a very great value of interaction strength with a non-negligible probability. The results indicate that the number of rock masses with great interaction strength cannot be ignored and there exist some very active rock masses in this region. Therefore, many geological disasters (e.g. earthquakes) occurred in this region.

4. Conclusions

Geological hazards turn very frequent in recent years that result in enormous loss of life and property, especially earthquakes. To understand the underground spatial information is becoming more and more urgent. Lots of rock masses covering a large region contribute to a complex dynamic system that the interaction between rock masses may cause geological hazards.

With using GIS technology and complex network theory, this paper introduces the concept of rock mass network and defines the corresponding network modeling method. Based on this, the geological survey data covering Sichuan Province and Chongqing Municipality is used for experiments. Results indicate that the degree distribution of rock mass network meets power-law distribution that means it is a scale-free network; regardless of rock type, the topological relationships of rock masses of different types all follow power-law distribution; and meanwhile, for different strengths, topological relationships of rock masses also satisfy power-law distribution. However, the power-law exponents are greatly different for different rock types or strengths, which means the interactions between different types or strengths of rock masses may be unstable or unbalanced. Overall, this paper contributes to the following three aspects: (1) This study proposes a spatial network modeling approach for describing the relationships between rock masses; (2) We reveal some important topological characteristics of rock mass networks for different rock types and different strengths, especially scale-free properties; (3) This paper provides a research prototype for intensive research on the interaction between rock masses. In the next work, we will further analyze the dynamics of rock mass networks with using lots of geological hazards dataset.

Acknowledgments

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