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Experimental and numerical investigations on mechanical property and reinforcement effect of bolted jointed rock mass

Yong Li [a,b,*], Hao Zhou [a,d], Lei Zhang [c], Weishen Zhu [a], Shucai Li [a], Jian Liu [b]

[a] Geotechnical & Structural Engineering Research Center, Shandong University, 250061 Jinan, Shandong, PR China
[b] School of Civil Engineering, Shandong University, 250061 Jinan, Shandong, PR China
[c] School of Civil Engineering and Mechanics, Huazhong University of Science and Technology, 430074 Wuhan, Hubei, PR China
[d] Jinan Rail Transit Group Co., Ltd, 250101 Jinan, Shandong, PR China

HIGHLIGHTS

- An optimized DDARF is proposed to simulate failure process and anchorage effect of jointed rock mass.
- This numerical method is verified through an experimental similarity test.
- The one-joint specimen with one rock bolt under 11 schemes are simulated and the optimal reinforcing position is obtained.
- The one-joint specimen with 2 rock bolts under 3 schemes are also simulated.
- To effectively restrain crack propagation using rock bolt will improve surrounding rock mass stability.

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ABSTRACT

The reinforcement for jointed rock mass using rock bolts has always been one of the most effective and economical geo-structural reinforcing technologies widely used in practical civil engineer projects for a long time. In the field of rock mass engineering, the reinforcement effect of the rock bolt(s) on rock mass is much more obvious due to a large number of natural fractures in rock masses. In this paper, an optimized method using Discontinuous Deformation Analysis for Rock Failure (DDARF) is presented to perform numerical investigations on mechanical property and reinforcement effect of bolted jointed rock mass. In order to verify the effectiveness of the proposed optimized DDARF, laboratory experiments using analog material have also been performed. Experimental results are very favorable with those obtained by the optimized DDARF. Moreover, this numerical method has also been employed to study mechanical property and reinforcement effect of rock specimen with single joint and single rock bolt when the joint and rock bolt have different locations in the specimens. The optimal reinforced location for the rock bolt in the specimen has been obtained through the comparative analysis of reinforcement effects under different conditions. The single jointed rock specimens with two rock bolts have also been numerically simulated and the optimal reinforcing location for the rock bolts has also been obtained. It is concluded that this optimized DDARF would provide an alternative effective tool to investigate the mechanical property and reinforcement effect for bolted jointed rock mass.

1. Introduction

A rock mass is a geological entity which contains different types of structural discontinuities such as fault, joint, fracture and so forth. The physico-mechanical properties are significantly influenced by these natural discontinuities, which leads to the obvious reduction of deformation modulus, strengths, anisotropy of the rock mass, and even the instability of the rock mass [1–6]. Under the disturbances of in-situ excavations, these discontinuities may result in the cracking, propagation, coalescence of the original cracks and even integral instability of the surrounding rock mass [7–10]. A large number of practical underground projects have proved that the instability and integral failure of the surrounding rock mass have great correlations with extensions and propagations of weak discontinuities [11–18]. Therefore, the reinforcement

* Corresponding author at: Geotechnical & Structural Engineering Research Center, Shandong University, 250061 Jinan, Shandong, PR China.

E-mail addresses: yongli@sdu.edu.cn (Y. Li), 845124545@qq.com (H. Zhou), zhangleigeo@hust.edu.cn (L. Zhang), zhuw@sdu.edu.cn (W. Zhu), lishucai@sdu.edu.cn (S. Li), lj75@sdu.edu.cn (J. Liu).

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for jointed rock mass using rock bolts has always been one of the most effective and economical geo-structural reinforcing technologies widely used in practical civil engineer projects for more than 100 years since 1913 in Germany [19–24]. In numerous practical projects, rock bolts are frequently used and the reinforcement effects are most obvious, as they can result in a compressive stress area in the rock bolting area which has apparent reinforcement actions. Meanwhile, the reinforcement actions can remarkably increase the bearing strength and improve the mechanical property of the rock bolting area. The jointed rock mass and rock bolts are finally combined and working together under the actions of both axial force and shear force. The rock bolts can share the internal and external loads of the jointed rock mass to restrain the extension and propagation of original and secondary cracks [25–29]. However, the mechanism of the rock-bolt reinforcement for jointed rock mass is still not totally clear [30,31]. Therefore, the investigations on mechanical property and reinforcement effect of bolted jointed rock mass have a significant theoretical value and practical importance to assure the security and stability of a jointed rock mass under complex geological conditions.

At present, field monitoring, laboratory similarity test, theoretical analysis and numerical simulation are four typical approaches to study mechanical property and reinforcement effect of bolted jointed rock mass. The previous works on field monitoring [32–37] are relatively limited but they have proved that the jointed rock mass applies a load on the pick-up section of the rock bolt and the load drags the anchoring section of the rock bolt towards the underground openings. As for the laboratory similarity test, numerous researchers have studied the mechanical properties of bolted jointed rock mass using original jointed rock or analog materials [38–43]. The above experiments have also considered some influencing factors on the mechanical property of bolted jointed rock mass, such as properties of rock mass and grouting materials, strength, dimension, structure and installation angle of rock bolt, and so on [41]. As for the development of theoretical analysis on bolted jointed rock mass, it makes very slow progress owing to the complicated working mechanism between rock bolt and jointed rock mass, but some practical analytical models have also been established for some special rock bolts [44–50]. Due to the high cost and difficult implementation in field monitoring and laboratory experiments, numerical modelling has become increasingly important to study the mechanical property and reinforcement effect of bolted jointed rock mass. The numerical methods can be divided into two categories: continuum-based methods (CBM) and discontinuum-based methods (DBM). As for CBM, a few researchers [51–54] have considered the bolted jointed rock mass as a homogenized anisotropic media and employed finite element method (FEM) to simulate reinforcement performance of bolted jointed rock mass. The finite difference method (FDM) is also used to numerically simulate the interaction between rock bolt and rock mass [55–57], and different rock bolt elements are adopted in the numerical simulations. These numerical methods using CBM focus mainly on the interaction between rock bolt and rock mass, but do not consider the failure process (crack initiation, extension and propagation) of the bolted jointed rock mass. As opposed to CBM, DBM can simulate the mechanical behaviors and geometrical features of jointed rock mass. For example, Nie et al. [58] coupled a rock bolt element into the two-dimensional discontinuous deformation analysis (DDA^{2D}) program to study impacts of rock bolt intersecting joints in rock masses. Jiao et al. [59,60] proposed an extended Discontinuous Deformation Analysis (DDA) called Discontinuous Deformation Analysis for Rock Failure (DDARF). The unique advantages of DDARF are that it can numerically simulate the whole failure process of jointed rock mass, including the crack initiation, propagation and coalescence and failure mode.

In this paper, an optimized method using DDARF is presented to perform numerical investigations on mechanical property and reinforcement effect of bolted jointed rock mass. Compared with the uniform-mesh numerical model, the numerical model in the optimized DDARF can simultaneously guarantee the calculation accuracy and reduce the computation time. Meanwhile, the calculation accuracy of some specified areas can be greatly improved. Some laboratory similarity tests are also conducted to verify the optimized DDARF. And this optimized DDARF can be employed to study the optimal relative location and reinforcement effect for the rock bolt(s) in jointed rock mass. The related research results have significance to reveal the reinforcement effect of bolted jointed rock mass, and they could provide practical guidance to actual slope and underground engineering projects associated with rock mechanics.

2. Methodology of the optimized DDARF

The DDA method, firstly proposed by Shi [61] is widely used to perform the stability analysis of jointed rock mass projects. It strictly obeys the fundamental theories of elasticity and the FEM, and can also solve the large deformation problems in jointed rock mass as the discrete element method (DEM) does. However, owing that the rock blocks are entirely discrete, sometimes it cannot numerically simulate the whole failure process of jointed rock mass. Therefore, a developed numerical method named DDARF is further proposed [59,60] to analyze the failure problems of jointed rock mass, and it can even simulate the whole failure process of crack initiation, propagation, coalescence and crushing. However, this DDARF can only establish a numerical model whose grids are uniformly distributed, and the numerical calculation cannot be completed if the number of grids is larger than several thousand. Therefore, in this paper, an optimized DDARF associated with Auto CAD is proposed to overcome the disadvantages in DDARF.

2.1. Generation of random joint network

It is known that the joints distribution in natural rock mass always obeys macroscopic statistical laws. And the corresponding geometrical parameters of rock joints (including trace length, dip angle and dip strike) are often presumed to conform to a mathematical model, such as lognormal distribution, normal distribution, uniform distribution and negative exponential distribution, etc. Former researchers have verified that the Monte-Carlo method [62] can successfully describe the corresponding geometrical parameters.

The detailed steps on generating a random joint network are demonstrated as following [63]:

(1) As for each joint set, repeat the following steps.
(2) Evaluate the number of the random joints (N) in the simulated area by the following formula:

$$N = \frac{S}{d \cdot l} \tag{1}$$

here S denotes the area of the numerical model, d denotes the average value of joint spacings and l represents the average value of joint trace lengths.
(3) A sequence of N random numbers of uniform distribution will be expressed by an equation using linear congruent method.
(4) Following the same way as step (3), the direction angles of N joints and joint trace length with normal distribution will be determined.