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Optimization of the load transfer mechanism of fully grouted rock bolts by using numerical modeling, genetic and PSO algorithms

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ABSTRACT

Many parameters such as hole diameter, thickness and bonding properties, mechanical properties of the rock mass, grout and rock bolts, profile bolt properties and pre-tension influence the load transfer mechanism of the grouted rock bolt. The author has been studying and reviewing the field of fully grouted rock bolts for more than 17 years and has published several articles in this field. Therefore, one of the most important goals of the author is to use statistical software and algorithms in the field of his previous studies. The purpose of this research was to optimize the load transfer mechanism of fully grouted rock bolts by using numerical modeling and genetic and PSO algorithms. For this purpose, ANSYS, SPSS and MATLAB software have been used in this research. Five types of rock bolts are used with different profiles. The rock bolts are modeled by ANSYS software, and then the results are defined by SPSS software using multiple regression as a linear relationship. Finally, using genetic and PSO algorithms, the load transfer mechanism of bolts has been investigated. The results showed that with the increase in profile down width, the load transfer mechanism was increased and with the increase in thickness of the grout, the load transfer mechanism was increased accordingly.

KEYWORDS

Load Transfer Mechanism, Numerical modeling, Genetic, PSO

I. Introduction

Rock bolting has advanced rapidly during the past decades 5 due to a better understanding of load transfer mechanisms and advances made in the bolt system technology (Ghadimi et al., 2015). A rock bolt consists of a bar inserted in a borehole that is drilled into the surrounding soil or rock mass and anchored to it by means of a fixture. A rock bolt reinforcement system has four principal components: the rock or soil, the reinforcing bar, the internal fixture to the borehole wall and external fixture to the excavation surface (Ghadimi, 2016a& Bastami, 2017).Such system is very efficient if used in one or several of following applications: stabilization of blocky rock masses, provided the far end of the bolt is anchored to a stable zone; rock confinement, contributing to the use of the broken rock bolt to confine the stable rock mass; improvement of the mechanical properties of the rock mass (Ghadimi et al., 2015). Investigations of load transfer between the bolt and grout indicate that the bolt profile shape and spacing play an important role in improving the shear strength between the bolt and the surrounding strata. The short encapsulation pullout tests of rock bolt indicate significant variance of shear resistance for various boltprofile spacing, angle, shape and size. Empirical studies can match the graphs of physical tests; however, these methods cannot describe the exact reasoning why such behavior occurs. Numerical modeling techniques are much better as they can mimic the physical tests in great detail, however, these methods depend on an accurate knowledge of the physical properties that must be incorporated or added into the model. The power of the numerical model rests on its ability to compare several models and to establish the optimum solution to the problem. The laboratory testing has its challenges as fabrication of minute differences in bolt profile in the workshop is difficult. Nevertheless, the laboratory tests are important to calibrate all the empirical work and the numerical models. At present mathematical description of the bolt profile and its behavior during the bolt pull out test is under development to provide better understanding of the physical process that influences the shear strength of the loaded bolt. The in-situ pullout tests are commonly used to examine the shear capacity of rock bolts. Only a few researchers have conducted laboratory tests to study various bolt profile parameters and their influence on the bolt anchorage (Ghadimi et al.,

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2014). Blumel et al. 1997, was the first to report the influence of profile spacing on load transfer capacity of the bolt. They are carried out numerical simulation of the bolt load transfer characteristics, the main aspect of the analysis being investigation of the difference in the bolt behaviour vs. the rib geometry and in particular the spacing between the ribs. The numerical simulation was based on using finite element mesh to study the load transfer mechanisms which were aimed to be incorporated in future interface modelling (Blumel et al. ,1997). In 2010, Cao et al. presented advanced numerical modeling methods of rock bolt performance in underground mines. This study showed how the numerical modeling methods could be successfully used to optimize the load transfer between the bolt and the surrounding strata. The study indicated that the standard rock bolt reinforcing elements, which are commonly used in the numerical simulation of the supported underground excavations, cannot be used to optimize the load transfer capabilities of the bolt. A detailed model of the bolt profile must be constructed, loaded to failure, and compared with other profiles to find the optimum bolt profile with maximum load transfer capabilities between the bolt and host strata (Cao et al., 2010). In 2020, Jianhang et al. presented an analytical model to calculate the load transfer mechanism. The mentioned model is in good agreement with field tests (Jianhang et al., 2020).

The purpose of this research was to optimize the load transfer mechanism of fully grouted rock bolts by using numerical modeling and genetic and PSO algorithms. For this purpose, ANSYS, SPSS and MATLAB software have been used in this research. Five different types of bolts are modeled using ANSYS software, and then the results are defined by SPSS software using multiple regression as a linear relationship. Finally, using genetic and PSO algorithms, the load transfer mechanism of bolts has been investigated.

II. NUMERICAL MODELING OF THE LOAD TRANSFER MECHANISM

A three-dimensional finite element model of the reinforced structure subjected to the tension loading was used to examine the behavior of bolted rock joints and validate instrumentation results. Three governing materials (steel, grout and rock) with three interfaces (bolt-grout, grout-rock and joint-joint) were considered for the 3D numerical simulation. A general-purpose finite element program (ANSYS, Version 12), specifically for advanced structural analysis, was used for 3D simulation of elasto-plastic materials and contact interfaces behavior. Due to the symmetry of the problem, only one fourth of the system was considered here. The interface behavior of grout-concreted as a perfect contact was determined from the test results. However, the low value of cohesion (150 kPa) was adopted for grout-steel contact. 3D solid elements (solid 65 and solid 95) that have 8 nodes and 20 nodes were used for concrete, grout and steel respectively, with each node having three translation degrees of freedom. That tolerates shapes without significant loss in accuracy. 3D surface-to-surface contact elements (contact 174) were used to represent the contact between 3D target surface (steel-grout and rock-grout). This element is applicable to 3D structural contact analysis and is located on the surface of 3D solid elements with midsize nodes. The numerical modeling was carried out at several sub steps and the middle block of the model was gradually loaded in the direction of shear (Ghadimi et al., 2014). Fig. 1 shows the three-dimensional model.

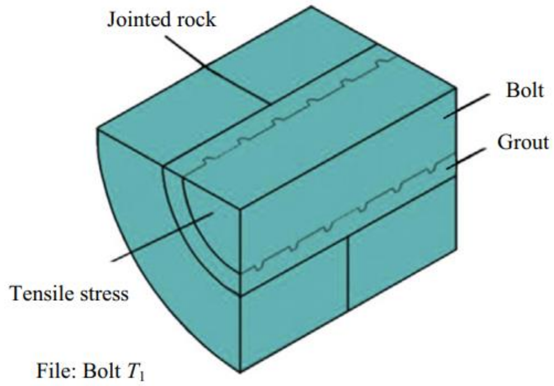

Fig. 1. Three-dimensional image numerical model (Ghadimi et al., 2014).

Bolt profile configuration is an important parameter in load transfer capacity of bolt. To select the optimum bolt profile and its effect on load transfer mechanism, it is necessary to examine the different profiles and check parameters, such as (1) bolt, grout and joint rocks displacement; (2) bolt, grout and joint rocks shear stress; and (3) bolt, grout and joint rocks shear strain. The material properties are shown in Table 1.

The maximum tensile stress in the bolt as load capacity is considered. The maximum tensile stress along the bolt is 330 MPa. This valve is in order of one-half of the elastic yield point strength of 600 MPa. This means the bolt behaves elastically and is unlikely to reach the yield and situation (Ghadimi et al., 2014). So, the only bolt T_4 that is the highest load capacity in this study is presented. Fig. 2 is shown in the displacement contours along bolt, grout and jointed rocks under tensile stress 330 MPa. Table 2 shows the results of different profiles. From Table 2, it can be concluded that: rib height increase causes the load transfer mechanism of the bolt increase; rib spacing increase causes load transfer mechanism of the bolt increase; grout thickness increase causes load transfer mechanism of the bolt increase; rib width reduction reduces load transfer mechanism of the bolt.

Table1. Material properties (Ghadimi et al., 2015 & 2017).

Parameter	Material							
	Steel					Concrete	Grout	joint
	T_1	T_2	T_3	T_4	T_5			
Bond length (mm)	75	75	75	75	75	75	75	37.5
Rock bolt diameter (mm)	22	22	22	22	22			
Grout diameter (mm)	27	27	27	32	27			
Rib height (mm)	1	1.75	1	1	1			
Rib spacing (mm)	12	12	24	12	12			
Profile top width (mm)	1.5	1.5	1.5	1.5	2			
Profile down width (mm)	3	3	3	3	3			
Max tensile load (MPa)	330	330	330	330	330			
Yield stress (MPa)	600	600	600	600	600	68	20	
E (GPa)	200	200	200	200	200	20	12	
Poisson ratio	0.3	0.3	0.3	0.3	0.3	0.25	0.2	
$\varphi(°)$								30
Cohesion (MPa)								0.2

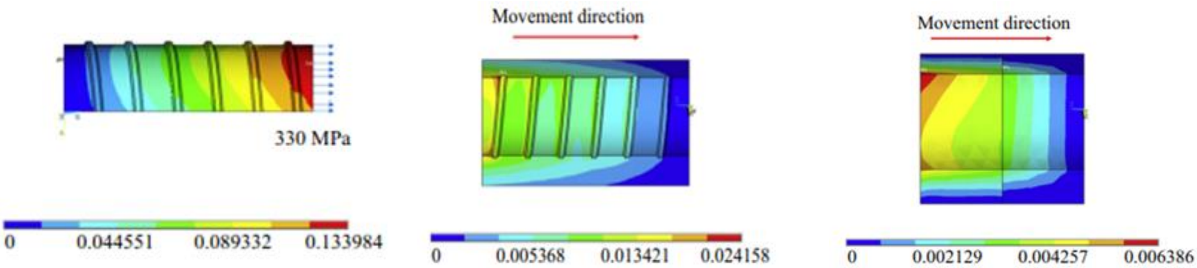

Fig. 2. Displacement along the bolt T_4, grout and jointed rocks

Table 2. Result of displacement, shear stress, shear strain and Load transfer mechanism (Ghadimi et al., 2014).

Element	Parameter	Bolt type				
		T_1	T_2	T_3	T_4	T_5
Bolt	Displacement (mm)	0.1382	0.1256	0.1601	0.13390	0.1254
	Shear stress (MPa)	172.89	183	256.83	149.360	215.21
	Shear strain (MPa)	0.0022	0.0022	0.0003	0.00190	0.0027
Grout	Displacement (mm)	0.0620	0.0391	0.0748	0.02410	0.0542
	Shear stress (MPa)	27.820	9.93	32.218	8.37	11.850
	Shear strain (MPa)	0.0057	0.0020	0.0069	0.00170	0.0024
Joint rock	Displacement (mm)	0.0263	0.0129	0.0332	0.00630	0.0169
	Shear stress (MPa)	7	0.875e-11	9.0810	0.37750	0.8954
	Shear strain (MPa)	0.0008	0.999e-15	0.0010	0.00004	0.0001
Load transfer mechanism (KN)		160	170	180	195	125

III. PREDICTING THE LOAD TRANSFER MECHANISM OF THE FULLY GROUTED WITH MULTIPLE REGRESSION

Statistical methods are used to create predictive models between independent and dependent variables. Therefore, it is possible to obtain the predictive variables and determine the relationship between the criterion variables and the predictive variable. In this research, SPSS software multiple regressions have been used to predict the load transfer mechanism of the fully grouted rock bolts (Table 3).

Table 3. Coefficients (dependent variable) affecting the load transfer mechanism of fully grouted bolt

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	196.667	.000		106480290.228	.000
Thickness of the grout	14.000	.000	.595	109315984.974	.000
Rib height	13.333	.000	.170	31233138.564	.000
Rib Spacing	1.667	.000	.340	62466277.128	.000
Profile down width	-70.000	.000	-.595	-109315984.974	.000

So:

$$F = 196.667 + 13.333b\sin\theta + 1.667S + 14m - 70a \quad (1)$$

F: load transfer mechanism (KN), $b\sin\theta$: rib height (mm), S: rib spacing (mm), m: grout thickness (mm) and a: rib width.

The results of the sensitivity analysis of parameters affecting the load transfer mechanism are shown in Fig. 3.

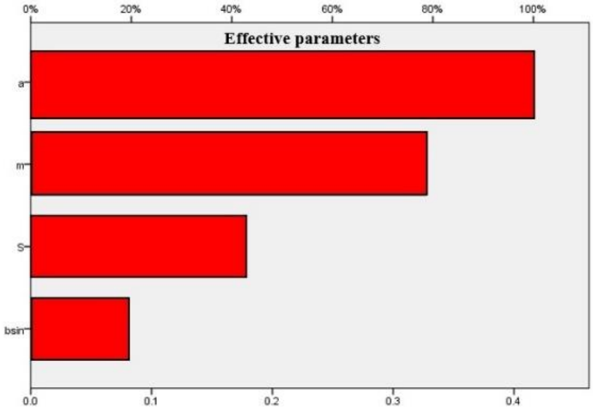

Fig. 3. Sensitivity analysis of parameters affecting load transfer mechanism

IV. GENETIC ALGORITHM

Genetic algorithm is a search-based technique for finding an approximate solution for the optimization and search problems. Genetic algorithm is a particular type of evolution algorithm that uses biology techniques such as inheritance and mutation. This algorithm was originally developed by John Holland in 1967. This method then extended with the efforts of Goldberg in 1989, and nowadays, it is well-positioned among other optimization methods due to its capabilities. MATLAB software was used to optimize the load transfer mechanism of fully grouted bolts by genetic algorithm (GA). The process is started by recalling the objective function, and then, the input parameters with the related lower and upper bounds are given to the algorithm. In order to access the best results by genetic algorithm, it is necessary to accurately determine the options related to the algorithm including the population size, selection functions, reproduction, and determination of the maximum number of generations. The chromosomes are examined based on the options and the fitness function presented in Eq. (1). After having run the program, the chromosome with the least error as the final solution was selected as the proposed pattern (Dehghani et al., 2019). Calculation of load transfer mechanism by using genetic algorithm is shown in Table. 4 and Fig. 4.

Table 4. Calculation of load transfer mechanism by using genetic algorithm

Parameters		$b\sin\theta$	S	m	a
Bounds	Lower (mm)	1	12	2.5	1.5
	Upper (mm)	1.75	24	5	2
Current interaction		400			
Final point		1	12	2.5	2
Load transfer mechanism (KN)		125			

V. OPTIMIZATION WITH THE PARTICLE SWARM OPTIMIZATION ALGORITHM (PSO)

Particle swarm optimization (PSO) is one of the bio-inspired algorithms and it is a simple one to search for an optimal solution in the solution space. The PSO algorithm is one of the optimization algorithms based on the random generation of the initial population. Each member in this group is defined by a velocity vector and a position vector in the search space. Each particle calculates the value of the objective function at any position of the space where it is placed. It then chooses a direction to move using a combination of information about its current location and the best location it has been to before, as well as information from one or more of the best particles in the collection (Bastami et al., 2019). After coding the model with PSO algorithm in MATLAB, and applying cost function in the relevant model, different results were obtained by changing the inertia coefficient and its adjustment factor, personal learning rate, collective learning rate at the output of the model. The optimal results were obtained when these parameters were selected based on Table 5. The proposed model was executed with different repetition numbers including 200, 500, 1000, 2000 and even higher. It was observed that the value of the objective function remained constant after the 50th repetition (Fig. 5).

Table 5. The controllable parameters of the PSO algorithm

Parameter	Value
Maximum number of iterations (MaxIt)	50
Number of particles (Npop)	100
Number of input variables (Nvar)	2
Inertia coefficient (W)	1
Inertia coefficient adjustment factor (Wdamp)	0.99
Personal learning rate (C1)	2
Collective learning rate (C2)	2

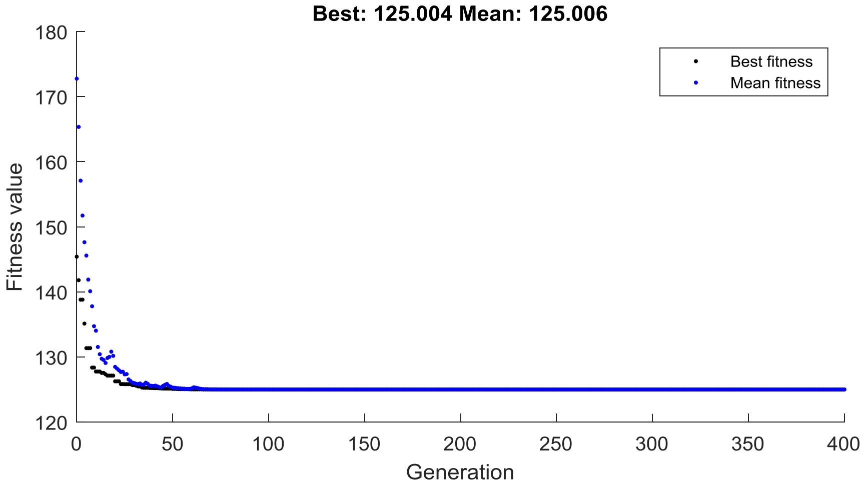

Fig. 4. Minimum amount of load transfer mechanism using genetic algorithm

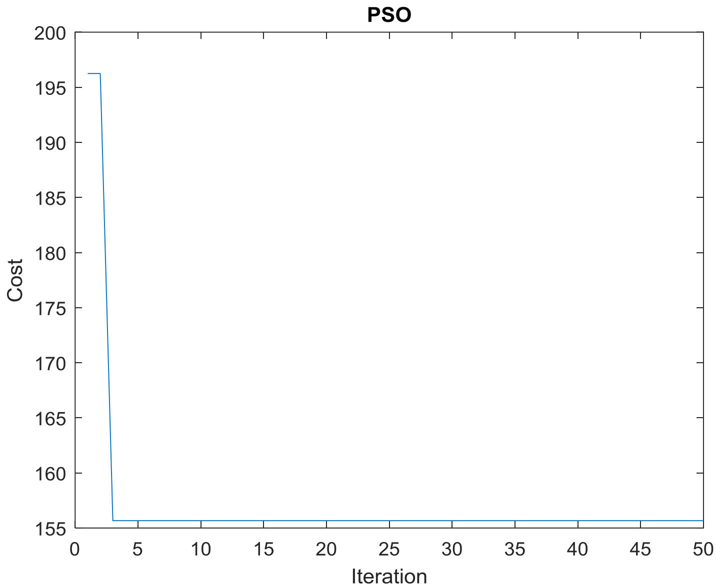

Fig. 5. The maximum and optimal values of the load transfer mechanism obtained from the cost function

Table 6 shows the consistency of results obtained from the PSO algorithm. The obtained results are in good agreement with the numerical modeling.

Table 6. The result of by PSO algorithm.

Parameter	Optimal	Max
Grout diameter (mm)	2.5	5
Rib height (mm)	1	1
Rib spacing (mm)	12	12
Profile top width (mm)	1.5	1.5
Load transfer mechanism (KN)	157	196

VI. CONCLUSIONS

The purpose of this research was to optimize the load transfer mechanism of fully grouted rock bolts by using numerical modeling of genetic and PSO algorithms. For this purpose, ANSYS, SPSS and MATLAB software have been used in this research. Five different types of bolts are modeled using ANSYS software, and then the results are defined by SPSS software using multiple regression as a linear relationship. Finally, using genetic and PSO algorithms, the load transfer mechanism of bolts has been investigated.

The results showed that:

- Profile bolt configuration is an important parameter in load transfer capacity of bolt. So that, load capacity of bolts T_1 to T_5 are 160, 170, 180, 195 and 125 KN, respectively. So, with the increase in profile down width, the load transfer mechanism increased and with the increase in thickness of the grout, the load transfer mechanism increased.
- Numerical modeling has been validated by genetic and PSO algorithms. The comparison of numerical and algorithms shows a good agreement between the results. So, this study showed how the algorithms can be successfully used to optimize fully grouted rock bolt.

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