Nondestructive testing of grouted bolts system
锚固体系无损检测的研究

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Abstract: This paper presents a new technique based on acoustic frequency stress wave (AFSW) technology and nondestructive pullout test (NDPT) that can be used for non-destructive quality testing of bolting systems. In the light of the dynamics of grouted bolt system (GBS) and kinematics of AFSW, the relationship between reflective character phase and grouted condition, as well as the relationship between wave energetic attenuation and anchored length is analyzed. The reflection features and the attenuation laws of the AFSW are further investigated through laboratory experiments, from which an express inspection method using the AFSW is proposed. Also describes curve characteristics of pullout test and the development of testing instrument that can auto-plot pullout curve and autoalarm when the GBS approaches to failure. At the same time, grading standards for anchoring quality inspection are suggested. Their results are confirmed by field tests at first coal mine of Panji. Results show that this new technique and method is practical and effective to conduct large-scale quality testing, valuable to ensure the reliable safety for bolting.
Key words: nondestructive testing; rock bolt; acoustic frequency stress wave; pullout test
CLC number: U 455.7　**Document code**: A　**Article ID**: 1000-4548(2001)01-0109-05
Biography: WANG Ming-wu, born in 1972, male, awarded Ph. D. by Nanjing University. Major and research topics: urban environmental geotechnical engineering, engineering geophysical method, and computer application.
摘　要: 基于锚固体系中的声频应力波的动力学和衰减特征的室内和现场试验研究与分析,提出了快速无损检测锚固体系锚固状态的声频应力波法和无损测定拉拔力的新方法,建立了锚固质量检测的分级标准,并实际应用于潘一矿锚杆支护施工质量检测,结果表明此检测方法是可行的和有效的。
关键词: 无损检测; 锚杆; 声频应力波; 拉拔

1 Introduction*

Anchoring techniques have been widely used in the large-scale constructions in the mining industry and civil engineering, such as railway tunnel support, rock road bolting, underground support, slope reinforcement, dam foundation improvement, deep foundation pit reinforcement, and so on. At the same time, accidents (e. g. roof falls and foundation pit collapse) and unnecessary economy cost result from construction problems and shortage of advanced testing instruments. Therefore, research into new nondestructive testing techniques for anchoring quality is urgent and necessary to ensure safe and efficient use of bolting.

In the 1980s, by the ultrasonic wave reflection method the density of sand cement grouted bolt[1] was inspected in Sweden. In 1990s, the U. S. Bureau of Mines developed ultrasonic measurement instrumentation capable of measuring strains and elongations on bolting systems of tensioned and untensioned mine roof[2~3], but it could not evaluate the construction quality of bolting. The ultrasonic method has the disadvantage that the attenuation of ultrasonic waves is rapid. It may be impossible to test long bolt types. Besides, its exciting condition is difficult, for the bolt head must be ground smoothly in order to receive good signals with ultrasonic transducer.

Torque-wrench-reading practices on a small statistical sample of testing. The accuracy of this method is low, and it probably disturbs and even destroys the anchorage capacity of rock bolt.

Current practical testing instrument is the convenient jack[4]. Pullout test with the jack is a destructive and sampling testing. Moreover, this method can not accomplish the large-scale testing task.

To solve the problem associated with the determination of anchoring state and anchoring force, the testing theory and method of acoustic frequency stress wave (AFSW) is investigated in this paper, and the nondestructive pullout test (NDPT) is also describeed.

2 General theory

2.1 Testing indices of anchoring quality

Anchoring quality of grouted bolt system (GBS) is mainly dependent on two indexes: anchoring state and anchoring force. Anchoring state is related to the following factors: free anchor length, anchored length, density, construction fault, etc. Anchoring force, also called ultimate pullout resistance, is defined as the value of pullout force applied to the GBS near to the failure in the course of pull-test. For the intact and strong rock formation, the adhesion force between grouted medium and bolt dominates the value of anchoring force. However, for the soft rock or weathering rock zone as well as coal bed, the value for force is at the mercy of the friction force of bolthole wall. In addition, geological conditions and construction procedure (e. g. the diameter of bolthole and the quality of installation, etc.) and other factors should be counted in.

2.2 Propagation and attenuation of AFSW

The AFSW is excited at the bolthead and propagates in the GBS (bolt, grouted medium, and mine rock). The wave energy redistributes on the interfaces of generalized wave impedance. The portion of wave energy reserves in

* Received date: 2000-03-16

the form of reflected wave; other portion spreads to the enclosing rock and dissipates. In addition, internal friction among particles results in the loss of AFSW energy. Our research results have shown that the phase characteristic is closely bounded up with the anchoring state and the distribution of side resistance. The AFSW reflects totally at the bottom end interface of ungrouted bolts, and the neighbor frequency difference is similar. The phenomenon of multiple reflection appears clearly in the bolt of bad anchoring state, but for the bolt of excellent anchoring state, reflected phase is hardly observed. The relationship between the amplitude and the propagated distance is given by

$$A_{i+1} = A_i e^{-2\alpha x}$$

i. e.

$$\alpha = \frac{1}{2x} \ln \frac{A_i}{A_{i+1}} \quad (1)$$

where α is absorption coefficient, Napier/ m; x is propagated distance, m; A_i and A_{i+1} are reflected amplitude No. i, $i+1$; and i is subscript.

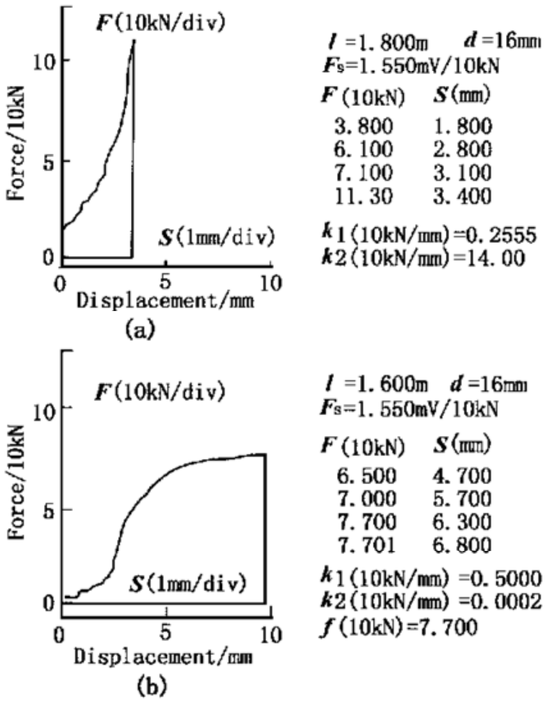


Fig. 1 Measured curve of pullout-test

2.3 Nondestructive measurement of anchoring force

Many field pullout tests have shown that the pullout curve and the pullout factor(defined as pullout force to produce unit deformation displacement) demonstrate some relations with the increment of pullout force applied. Especially it obviously fluctuates when the GBS appoaches the failure. The afterbody of pullout curve increases in a near linear relation when the anchoring force is more than the ultimate strength of steel bolt, and the pullout factor increases sharply(Fig. 1(a)) . Whereas, when the anchoring force is less than the ultimate strength of steel bolt, the curve afterbody rises slowly and the growth rate tends to decrease (Fig. 1(b)) . So the variation law can be utilized to judge whether the GBS approaches to the failure. The value of anchoring force is determined through the interaction value of two secant lines, plotted on both sides of inflection point of curve drawn automatically by the testing system. Likewise, the proper value of ultimate pullout-coefficient is designed to autotrack the curve before stopping the pullout test and then the method is capable of measuring accurately the anchoring force without disturbing the anchorage capacity of bolt.

3 Laboratory experiments

3.1 Instrument

The testing system consists of ejected acceleration mini-transducer, cored force sensor, grid-condenser displacement detector, pocket omnibearing jack, portable and essentially safe MJ-1 mainframe. The mainframe with the ejected acceleration transducer practices express inspection. With the displacement detector, the cored force sensor, and the pocket jack, the MJ-1 measurement device also can be used to make nondestructive pull-test.

3.2 Testing procedure

At the beginning of express inspection using the AFSW instrument, the acceleration transducer itself excites and receives signal at the bolthead, and collected data is transmitted to the mainframe for analysis. Then anchoring state is evaluated quickly by the analysis of time domain, spectrum and energy attenuation. Also assesses roughly the anchoring force.

The steps of NDPT introduce as follows: the omnibearing jack and the cored force sensor are mounted to the bolthead before the omnibearing jack applies force to the GBS. The force transducer determines the value of pullout force and the displacement is measured synchronously by the displacement sensor, the testing system simultaneously auto-plots and auto-tracks the pullout curve. The system autoalarms when the pullout factor is more than the ultimate pullout-coefficient then stops validly the pullout test.

Data obtained from the express inspection and the NDPT can be stored in memory of instrument to be analyzed indoors.

3.3 Tests of free-state bolt

(1) Determination of acoustic parameter

If bolts of some same size and type come from same production lot, their acoustic properties(e. g. wave velocity and absorption coefficient) are stable. For this reason, the acoustic parameters of free-state bolt are valuable to field test. The determination was done with bolts same as the laboratory model. Table 1 indicates that the velocity along with the absorption coefficient varies in a low and focused range, which is advantageous to the field testing of bolting.

(2) Attenuation ratio for free-state bolt grouted

The attenuation ratio of the AFSW was explored by a series of experiments, which employed resin(compressive strength > 60 MPa, adhesive strength = 7.5~ 11 MPa) and sanded cement(grade 525) to adhere and wrap free-state bolt(1.6~ 1.8 m in length, 16~ 18 mm in diameter) with a increment of cemented length. Through the experiments, we have arrived at the following conclusions:

Table 1 Acoustic parameter determination of free-state bolts

Bolt material	Diameter/ mm	Length/ m	Velocity/ ($m \cdot s^{-1}$)	Average absorption factor/ ($dB \cdot m^{-1}$)
16Mn spiral steel	16	1.55~ 1.80	5050 ±100	0.30~ 0.50
A_3 round steel	16	1.50~ 1.65	5150 ±50	0.25~ 0.40

a) The bottom end reflection is obvious for free-state bolt grouted (anchored length < 0.5 m) . The reflection weakens with the increment of the anchored length (between 0.5 m and 1.0 m) , and the reflective wave energy gradually becomes faint when the anchored segment is beyond 1.0 m.

b) The ratio of the initial amplitude, A_0 , to the bottom end amplitude, A , is in exponential relation to the anchored length, l , as described the following formula:

$$\frac{A_0}{A} = e^{2\alpha l} + b \qquad (2)$$

where α is anchored absorption coefficient; and b is a constant, which is related to length and absorption coefficient of bolt. Table 2 shows the absorption coefficient of different grouted type.

Table 2 Absorption coefficient of free-state bolt grouted

Grouted type		Average absorption coefficient / ($dB \cdot m^{-1}$)
Medium	Way	
Resin	Full	6.451
Resin	Partial	6.990
Sanded cement	Full	8.132
Sanded cement	Partial	9.031

3.4 Experiments of laboratory model

The model block is constructed of thin concrete layer plates cemented together one by one. The mixing proportions for cement, water and sand is 0.5∶1∶2 by weight. The length , the width and the thickness of each plate constructed by cement # 525 are 0.8 m, 0.8 m and 0.15 m respectively. The dimension of model is 0.8 m × 0.8 m × 2 m. Bolthole had a diameter of 42~ 48 mm. The population strength approximated to 24 MPa by the method of ultrasonic-rebound-strength. The average ultrasonic wave velocity is about 3700 m/ s. Design parameters of GBS is listed in table 3. The bolt types are in common use for coal industry.

Results from the laboratory model experiment are shown in Table 4. The experiment has shown that the anchored length measured by use of AFSW are almost close to the true length anchored. The reflection is weak in the fully GBS(Fig. 2(a)) , but the phenomenon of reflection is obvious at over and under interface of anchored segment (Fig. 2(a)) . The attenuation of AFSW increases with the increment of anchored length. The value for anchoring force depends on the anchored length. Whereas, type and grouted medium and other factors are following factors. Especially, Comparing the result from the first NDPT with that from the second one of the same bolt, the forms of pullout curves are similar. Their anchoring force values are near, so the anchorage capacity is not disturbed.

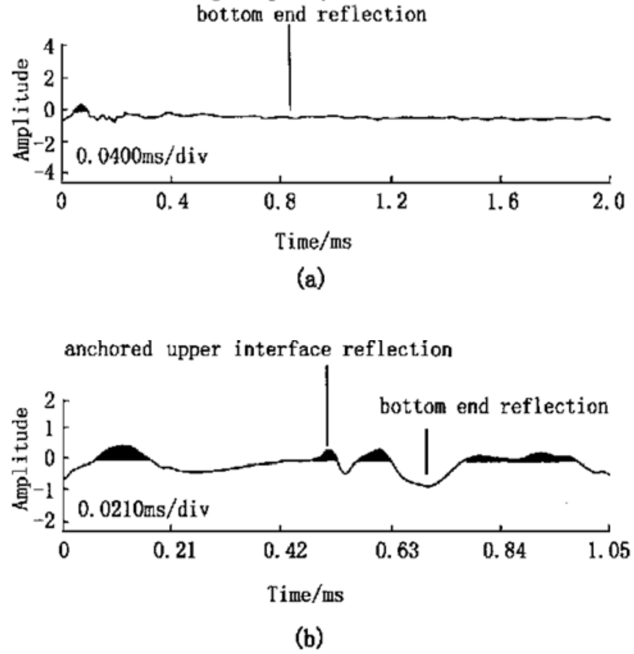


Fig. 2 Waveform records of model test

Table 3 Design parameter of GBS for laboratory model

No.	Bolt material	Grouted medium	Bolt length/ m	True anchoring length/ m
1	16Mn spiral steel	Resin	1.585	1.535
2	16Mn spiral steel	Sanded cement	1.560	1.510
3	A_3 round steel		1.600	0.000
4	A_3 round steel	Resin	1.600	0.297
5	A_3 round steel	Sanded cement	1.570	0.400

Table 4 Results from laboratory experiment

No.	Measured anchored length/ m	Velocity/ ($m \cdot s^{-1}$)	Average absorption factor	Anchoring force ①/ 10kN
1	1.531	5090	7.12	> 12.0
2	1.515	5120	8.85	12.0
3		5170	0.28	
4	0.300	5120	7.61	7.6
5	0.404	5140	9.96	7.2

Note: ①Anchoring force is measured by the nondestructive pullout test

Table 5 Proposed grading standard for anchoring quality of fully resin-grouted bolt

Grade	Reflective phase characteristic		N	R / %	Evaluation of anchoring quality
	In arm	At bottom end			
A	No	No	$N > 6.0$	$R > 80$	Excellent ①
B	Weak	No	$4.0 < N \leqslant 6.0$	$60 < R \leqslant 80$	Good ②
C	Obvious	Weak	$2.5 < N \leqslant 4.0$	$40 < R \leqslant 60$	Up to standard ③
D	Forceful, multiple	Obvious, multiple	$N \leqslant 2.5$	$R \leqslant 40$	Substandard ④

Note: 1. N = ratio of initial amplitude to bottom end amplitude and R = percentage of anchored length to design value; 2. ①Anchored force value more than design value, ②Anchored force value up to design value, ③Anchored force near design value, ④Anchored force less than design value

Table 6 Proposed grading standard for anchoring quality of partially resin-grouted bolt

Grade	Reflective characteristic of bolt bottom end	N	R / %	Evaluation of anchoring quality
A	No	$N > 1.50$	$R > 90$	Excellent
B	Weak	$1.35 < N \leqslant 1.50$	$70 < R \leqslant 90$	Good
C	Obvious	$1.30 < N \leqslant 1.35$	$60 < R \leqslant 70$	Up to standard
D	Multiple and forceful	$N \leqslant 1.30$	$R \leqslant 60$	Substandard

Table 7 Design parameter of GBS for first coal mine of Panji

Enclosing rock type	Grouting way	Rock bolt material	Grouted medium	Design value of anchoring force/ 10kN
Rock	Full	16Mn spiral steel	Resin	7.5
Coal bed	Partial	A_3 round steel	Resin	2.5

3.5 Proposed grading standards for anchoring quality inspection

Based on the reflective characteristic and the amplitude ratio, construction quality and anchoring quality can be evaluated. Table 5 and table 6 show the proposed grading standards of the resin GBS.

Though the attenuation ratio is related to the surrounding rock variety to a certain extent, field tests show that the grading standards revised lightly still are practicable.

4 Field test

To determine if the results from the indoor experiments could be applied to the condition encountered in mine rock, field tests were performed at the first coal mine of Panji, Huainan. Test sites located at the auxiliary rock road, east Ⅰ, and the semi-coal rock road, 11 adit of west Ⅱ. Table 7 shows the design parameters of GBS[5~6].

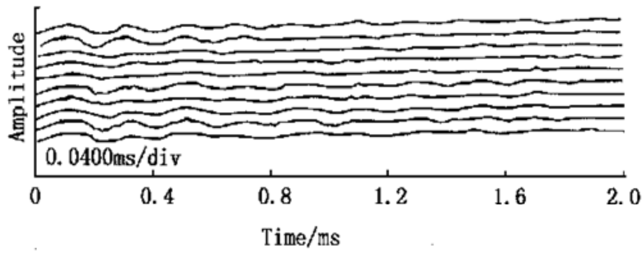
724 partially grouted coal bed bolts and 607 fully grouted rock bolts were tested by the express inspection method. To verify the reliability of quality grading along with the determination of the anchoring force, 20 partially grouted coal bed bolts and 23 fully grouted rock bolts were sampled to conduct the NDPT.

The testing technique was also performed successfully in the quality inspection of soil bolt (length > 3 m), used for the deep foundation pit reinforcement engineering of Yiren building and Jinshan building, Xiamen.

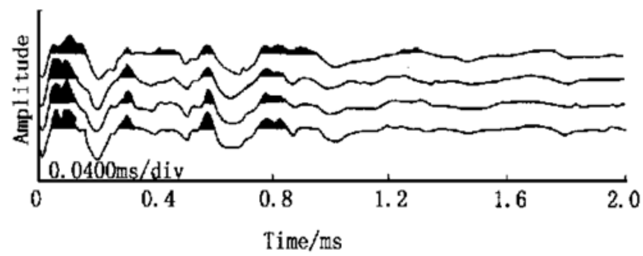
The evaluation of anchoring quality in the light of the proposed grading standards is shown in table 8. It is found from the express inspection that the reflected phase characteristic of good anchoring state bolt is distinct from that of bad one. It is easy to specify (Fig. 3). The test performs well only by two operators within two minutes.

Table 8 Inspection of anchoring quality

Grouted bolt system	Percentage of different grade/ %			
	A	B	C	D
Rock fully grouted	26	62	9	3
Coal bed partially grouted	26	58	10	6



(a)



(b)

Fig. 3 Curve of express inspection for fully resin-grouted bolt($\Delta t = 4.0\ \mu s$)

Verification test results have shown that the reliability of partially grouted bolt amounts to 86 percent and that of fully grouted bolt is 90 percent. They both go beyond the reliability standard for field engineering. The ultimate pull-out factor ranging from 0.2 to 0.3 kN/ mm is applicable to the partially grouted coal bed bolt, and the appropriate value ranges from 0.4 to 0.5 kN/mm for the fully grouted bolt. It is also found that optional sampling internal is 4.0 μs or 2.1 μs for the bolts 1.6~ 1.8 m in length, and optional gain is in 30~ 60 dB range.

5 Conclusions and discussions

Several significant findings of the research are highlighted as follows:

(1) The express inspection method and the NDPT allow for the anchoring quality testing without requiring extensive bolt modifications. The AFSW instrumentation along with pullout test equipment enables nondestructive testing of various types of bolts installed in any medium.

(2) The method of AFSW is easy of excitation and reception, simple and convenient to operate, etc. Meanwhile, the method meets requirement and reliability of the large-scale field construction testing.

(3) The attenuation ratio is in exponential relation to the anchored length, which in turn can be estimated by the former.

(4) The NDPT can auto-plot the pullout curve and measure nondestructively the anchoring force. It is a method more reliable and more scientific than the method of using the conventional jack puller for this purpose.

(5) This testing technique provides a new means for geotechnical engineering testing. It is practical and effective to inspect the quality of bolting construction, and has potential and wide prospect of research and practice.

Based on field tests and laboratory experiments, we have reached some considerable conclusions on the characteristic of acoustic frequency in the GBS. However, the anchoring quality is depended on various factors, our research is still required to further investigate into the relationship between acoustic frequency and medium, the reliability of this testing method, and proposed model in the future. The authors believe that the new testing method has wide practical value through improvement and practise.

Acknowledgments:

This study was financially supported by the coal ministry of China under grant number 8520102043. The writers wish to acknowledge the assistance of the first coal mine of Panji during the field test, and the participants from Huainan Institute of Technology and White Cloud Instrument Company.

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Appendix Ⅰ

Notation

The following symbols are used in this paper:

x = propagated distance (m);

A_i, A_{i+1}, A_0, and A = reflected amplitude;

α = absorption coefficient(Napier/m), 1 Napier/m= 8.686 dB/m;

Δt = sampling internal(μs);

N = ratio of initial amplitude to bottom end amplitude;

R = percentage of anchored length to design value, (%);

l = anchored length, (m); and

i = subscript.

新书介绍

由刘允芳等著的《岩体地应力与工程建设》一书, 最近已由湖北科学技术出版社出版。地应力对于岩石工程建设的重要性日益突出, 而地应力测量技术的发展又日新月异, 早已引起国内外普遍重视。该书系统全面论述了当前国内外通用的各种地应力测量方法的理论、测量原理、测量元件和测量仪器以及实测数据处理技术。并论述了根据地应力实测资料和地质条件确定大范围工程区的地应力场的分析方法, 特别是讨论了我国岩石工程在地应力测量和研究方面的主要成就。全书 25 万字, 大 32 开精装本, 定价 36 元/本。本书共分 7 章: 1. 地应力及其测量; 2. 岩体表面应力测量技术; 3. 套钻孔应力解除法地应力测量技术; 4. 水压致裂法地应力测量技术; 5. 其他地应力测量方法的测量技术; 6. 地应力场分析; 7. 地应力测量与研究在水工地下工程中的应用。

该书理论扎实、观点新颖、视野开阔、实例丰富, 可供地质、水工、矿山、隧道、军工、地震以及地面、地下、边坡岩石工程的科研、设计等工程技术人员和大专院校师生、研究生参考。有意购书的单位和个人, 直接与长江科学院岩基研究所联系, 地址: 汉口赵家条九万方, 430010, 电话: 027-82829885, 027-82829791。

(刘允芳 供稿)