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Assessing the effects of insufficient rebar and missing grout in grouted rock bolts using guided ultrasonic waves

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ABSTRACT

One of the challenges in field monitoring of grouted rock bolts, which normally have a short exposed end, is to detect the defects of the bolt or grout. In this paper, grouted rock bolts are studied using guided ultrasonic waves. Numerical modeling for grouted rock bolts is performed to assess the effects of insufficient rebar and missing grout. The numerical results are verified with laboratory tests on rock bolt samples. With introduction of correction factors at the reflection end, the results indicate that it is practically possible to identify insufficient rebar and grout defects with guided ultrasonic signals received at the exposed end. It also indicates that with the attenuation and wave velocity of guided waves, defective rock bolts with insufficient rebar length or missing grout in the ground can be detected with reasonable accuracy.

1. Introduction

Grouted rock bolts are widely used in mining and geotechnical engineering as a ground reinforcement and stabilization system. It is often required to monitor the rock bolts for their performance. Of particular interests are the defects of grouted rock bolts. Traditional rock bolt test methods such as pull-out test are usually destructive, expensive and time consuming. Guided ultrasonic waves as a new research initiative in non-destructive rock bolt test have attracted much interest over the past two decades (Beard and Lowe, 2003; Cui and Zou, 2006; Madenga, 2004; Thurner, 1988; Zou and Cui, 2011; Zou et al., 2007). Parameters of wave frequency, group velocity and attenuation of guided waves received particular attention. Zhang et al. (2006) and Zou et al. (2007) found that the group velocity of the guided wave is dependent on the material properties and the wave frequency. Madenga et al. (2006) demonstrated that the behavior of the guided waves in grouted rock bolts strongly depends on the wave frequency. Cui and Zou (2006), Klimentos and McCann (1990), O'connell and Budiansky (1974), and Tavakoli and Evans (1992) indicated that the wave attenuation is inversely proportional to the travel distance and it is directly related to the amplitude ratio in the following format:

$$\ln\frac{A_b}{A_a} = \ln(R) = -\alpha L \tag{1}$$

where A_a and A_b are the amplitudes at locations a and b respectively, R is the amplitude ratio, α is the attenuation coefficient and L is the distance from locations a to b.

Cui and Zou (2006) conducted further experiments, which led to the understanding of the effects of the frequency and grout length on the wave attenuation. They reported that the attenuation in a short (less than 2 m) free bolt is negligible and that the boundary effect on attenuation is significant for the grouted portion of a rock bolt. Eq. (1) is thus modified for attenuation calculation along the axis of a rock bolt by introducing a boundary correction factor, K_b.

$$-\alpha L = \ln(R) - \ln(K_b) = \ln(R/K_b). \tag{2}$$

Zou et al. (2007) observed a fixed energy loss at the contact interfaces between the transducers and bolts. The transducer-recorded amplitude ratio during a test is typically lower than the amplitude ratio (R) indicated in Eq. (2). This part of energy loss is attributed to test equipment setup.

Han et al. (2009) installed full scale rock bolts in a rock mass and performed tests using ultrasonic guided waves with the input transmitter installed at the exposed end and the output transducer embedded in the ground on the other end of the bolt. They recorded clear and analyzable waveforms, indicating the potential of using the guided waves for rock bolt monitoring in the field. However during routine operation, it is not practical to install a transducer in the ground because the only direct access to the installed bolt is the short exposed end.

Recent research by Zou and Cui (2011) indicated that the output transducer may be installed on the grouting surface near the exposed end as shown in Fig. 1. They also reported that with this

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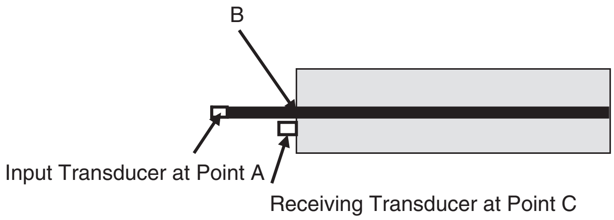

Fig. 1. Fully grouted rock bolt.

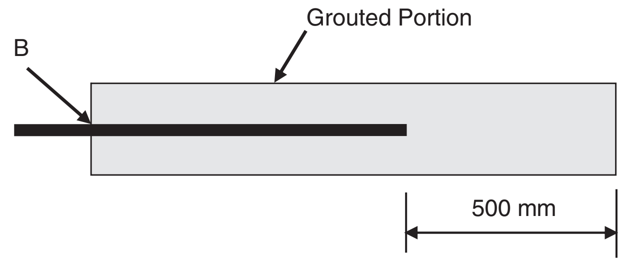

Fig. 2. Rock bolt with insufficient rebar length.

method it was practically possible to receive meaningful signals. Furthermore, the attenuation and group wave velocity in the grouted rock bolts could be determined with reasonable accuracy in this setup. With consideration of the receiving transducer location, a measurement location correction factor, K_l, is introduced and the following equation is used to correlate the amplitude ratio measured on the grout surface at Point C (Fig. 1) and the amplitude ratio at the central of the rebar at Point B (Fig. 1)

$$R_B = K_l R_c \tag{3}$$

where, R_B is the amplitude ratio at Point B and R_c is the amplitude ratio measured on the grout surface at Point C. In that test setup, the most proper location for the output transducer was 27 to 32 mm from the central of the rebar on the grouting surface.

It is the intention of this part of the research to identify rock bolt defects, such as insufficient rebar length and lack of grouting. The objective is to study the effects on the attenuation and group wave velocity when a rock bolt has an insufficient rebar length or when there is lack of grout at the ground end. For clarification in this paper, the exposed end of a bolt, where the input transducer is installed, is called input end and the other end installed in the ground is called ground end.

Based on the numerical simulation of rock bolt tests using guided waves of Cui and Zou (2006), where the accuracy was verified by comparing the results of simulation and laboratory tests, seven grouted rock bolt models were created in this research to compare the attenuation and group wave velocity behavior in fully grouted rock bolts and rock bolts with an insufficient rebar length or grout void. Two laboratory samples are used to verify the results obtained from the numerical study.

2. Model and input parameters

Each rock bolt model consists of a steel bar embedded in a cylindrical concrete block with geometries specified in Table 1. The sample IDs of FG stands for fully grouted rock bolts, MG stands for rock bolts with a missing grout at the ground end, and IR stands for rock bolts with an insufficient rebar length at the ground end. The guided wave behaviors were compared for the three groups of grouted rock bolts (Figs. 1 to 3): fully grouted rock bolts (Samples FG500, FG750 and FG1000), rock bolts with an insufficient rebar length (Samples IR500 and IR750) and rock bolts with missing grout at the ground end (Samples MG750 and MG1000). The input parameters of these models are listed in Table 2 and the maximum element size used in these models is listed in Table 3.

Numerical simulations are conducted using LS-DYNA, a commercial software package (Livermore Software Technology Corporation, 2001). To save computing time, axisymmetric condition of these samples is considered and only one quarter of a sample was created. One of the finite element models (IR750) is shown in Fig. 4. Other details of the finite element model can found from the LS-DYNA manual.

It was found in previous tests (Cui, 2005) that when a receiver was installed on the grout surface, clear and analyzable signals were received only for input signals within a narrow range of wave frequency, which depends on the sample physical properties and diameters. It was demonstrated that clear waveforms could be obtained using input signals with frequency between 28 kHz and 31 kHz. The input wave frequency in this study is limited to this range.

The ultrasonic wave at a specified frequency is transmitted to the rebar at the input end (Point A in Fig. 1) and the waveforms obtained along the central of the rock bolt (rebar) are studied. For simplicity, the first wave packet recorded in this setup is called the input group and the same wave packet recorded the 2nd time after being reflected back from the ground end is called the echo group

The typical input group and the echo waveforms obtained at Point B (Figs. 1 and 2) of Samples FG500 and IR500 are shown in Fig. 5a) and b), respectively. The input frequency is 31 kHz.

It can be observed from Fig. 5 that the maximum amplitude of the echo groups of Samples FG500, fully grouted, and IR500, with insufficient rebar length, arrived at almost the same time, indicating that the echo groups traveled the same length of time. Although sample IR500 has longer grout, its rebar length is the same as FG500. It is most likely that the echo of Sample IR500 is reflected from the end of the rebar. It is also noticeable that the echo amplitude of Sample IR500 is smaller than that of Sample FG500, indicating an energy loss at the first reflection point (the end of the rebar) for Sample IR500. The same pattern is observed when the waveforms for Samples FG750 and IR750 are compared.

Table 1
Model geometry.

Sample ID	Free length		Bolt diameter (mm)	Grouted rebar length (mm)	Total grout length (mm)	Total rebar length (mm)	Diameter of concrete cylinder (mm)
	At input end (mm)	At ground end (mm)					
Sample FG500	50	0	20	500	500	550	160
Sample FG750	50	0	20	750	750	800	160
Sample FG1000	50	0	20	1000	1000	1050	160
Sample IR500	50	0	20	500	1000	550	160
Sample IR750	50	0	20	750	1250	800	160
Sample MG750	50	1500	20	750	750	2300	160
Sample MG1000	50	1500	20	1000	1000	2550	160
Sample LIR500	50	0	20	500	1000	550	160
Sample LMG500	50	1500	20	500	500	2050	160