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Non-destructive evaluation of the grouted ratio of a pipe roof support system in tunneling

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ABSTRACT

The pipe roof system is widely used in the New Austrian Tunneling Method (NATM) as the main support system. Thus, the integrity of the pipe roof system influences the tunnel stability. The purpose of this study is to evaluate the grouted ratio of a pipe roof system using a non-destructive method in the laboratory and in the field. In the laboratory tests, four specimens embedded in soils and five non-embedded specimens are prepared with different grouted ratios of 0%, 25%, 50%, 75%, and 100%. The steel pipes are 6 m in length, 60.5 mm in external diameter, and 3.8 mm in thickness. Field tests are conducted with two fully grouted pipes with dimensions of 12 m in length, 60.5 mm in external diameter, and 3.8 mm in thickness. The reflection method of guided waves, which are generated by a hammer impact and are measured using an acoustic emission sensor, is used for the non-destructive testing. Experimental studies demonstrate that the group velocities and the main frequencies of the guided waves decrease as the grouted ratio increases for embedded and non-embedded specimen in soils. The variation of the main frequency, however, is more significant than the variation of the group velocity. In addition, the group velocities and main frequencies of the field specimens are lower than those of the embedded specimens. This study demonstrates that the variations of the group velocity and main frequency may be used effectively to estimate the grout ratio of a pipe roof system in tunneling.

1. Introduction

The New Austrian Tunneling Method (NATM) has been widely used in modern tunnel design and construction. The pipe roof support system plays an important role because it is the main support in the NATM. In the literature, the pipe roof support system is also referred to as the "steel pipe umbrella" (Peila, 1994), "forepole umbrella" (Hoek, 1999), "steel pipe canopy" (Gibbs et al., 2002), "long span steel pipe fore-piling" (Haruyama et al., 2005), and "umbrella arch method" (Aksoy and Onargan, 2010). The pipe roof system is especially useful in weak rock (fractural zone) excavation to prevent ground displacement and to improve the ground condition. During the installation of the pipe roof system, a grouting material is used to bond the steel pipe to the ground. However, the grouting material can flow out due to gravity; thus, it may not be sufficient to fill the drilled holes. This phenomenon results in the presence of non-grouted parts of the pipe roof support system. This problem may also occur in a rock bolt system. Kılıc et al. (2002) demonstrated that the maximum pull-out load increases as the grouted rock bolt length and area increase. Thus, the grouting quality affects the mechanical behavior of the rock bolt. Inspection of the grouting quality of a reinforced anchorage system, such as rock bolts, soil nails, and pipe roofs, is important to increase the stability of tunnels and slopes.

As an evaluation technique for the support system in the NATM, rock bolt pull-out tests have traditionally been performed. However, the pull-out test is a destructive method, which influences the role of the rock bolt because the tensile force is directly transmitted to the rock bolt. In addition, in the case of the pipe roof system, the pull-out test method is practically difficult to perform because a steel pipe is a hollow cylinder with a length of at least 6 m. Therefore, improved methods that save time and are economical, accurate, and non-destructive are required.

Over the past ten years, several studies have been performed on the inspection of rock bolt grouting integrity with non-destructive testing methods. The ultrasonic guided wave is

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known for its long-range propagation ability with low energy reduction in slender materials, such as pipes, rods, and plates. Thus, numerous studies using ultrasonic guided waves have been performed to suggest an evaluation method to determine the integrity of the anchorage reinforcements. During the early development, several conceptual studies were attempted. Pavlakovic et al. (1998, 1999) proposed an analytical model and experimental concept to inspect the length of post-tensioning tendons and performed experimental studies to predict the reflection coefficient from various defects in embedded steel bars. Na et al. (2002) conducted a laboratory experiment to detect the amount of separation at the interface between the concrete and steel bar using the amplitude versus frequency curve from the captured guided waves. Beard et al. (2003) proposed a pulse-echo technique to evaluate the length, break, and defect of the grouted rock bolts by measuring the attenuation and reflection coefficient. A few numerical approaches have been used to analyze the behavior of guided waves in grouted rock bolts. Pavlakovic et al. (2001) studied the possibility of a non-leaky mode to overcome the energy leakage problem in grouted or embedded rock bolts. Zhang et al. (2006) simulated the effect of the input wave frequency in grouted rock bolts to determine the optimum input signals and to determine various factors of the wave characteristics in grouted rock bolts. Cui and Zou (2006) simulated the attenuation of the guided waves propagating in grouted rock bolts and compared the simulation results with experimental results.

Recently, improved techniques to practically evaluate the integrity of rock bolts have been studied. Han et al. (2009) developed the transmission method, in which the guided waves are generated on the rock bolt tip using a piezo disk element and are measured with an acoustic emission (AE) sensor on the head of the rock bolt. The first arrival time of the guided waves was calculated to evaluate the grouted length. The velocities of the guided waves increased as the grouted length decreased. Lee et al. (2012) used the wavelet transform to calculate the group velocities of the guided waves for the grouted rock bolts. The detection of the first arrival time in the time domain is difficult due to noise at the high frequencies. However, because the wavelet transform provides frequency and time information, the travel time is easily calculated. Yu et al. (2013) suggested the reflection method in which the wave generation and the measurement are performed on the exposed rock bolt head to evaluate the non-grouted ratio of the rock bolts. The reflection method provided good performance for previously installed rock bolts.

In the case of the pipe roof system, the steel pipe differs in length, shape, and grouting material compared with the rock bolt. Thus, additional research applicable to the pipe roof system was required. The purpose of this study is to examine the experimental applications and analysis methods for evaluating the grouted ratio of the pipe roof system. Experimental studies were conducted in the laboratory and in the field. The laboratory experiments were performed with nine grouted steel pipes. Five of these were non-embedded steel pipes that were grouted only along the pipes. The others were embedded steel pipes that were grouted and installed in a chamber filled with weathered soils. The field experiments were conducted with two fully grouted steel pipes. The guided waves were generated using the hammer impact and were captured by the AE sensor (Yu et al., 2013). The recorded signals were analyzed using the Fourier transform and wavelet transform to calculate the main frequencies and the group velocities. This study includes fast Fourier transform and wavelet theory, the calculation of group velocities, the selection of a main frequency, experimental studies of laboratory and field experiments, a summary and conclusions.

2. Theoretical background

2.1. Fourier transform

The Fourier transform is a useful mathematical method to analyze signals subjected to frequency spectrum or bandwidth. The Fourier transform calculates time domain information from frequency domain information and vice versa. Eq. (1) is called the Fourier transform of $f(t)$, and Eq. (2) is called the inverse Fourier transform of $F(\omega)$.

$$F(\omega) = \int_{-\infty}^{+\infty} f(t)\exp(-i\omega t)dt \tag{1}$$

$$f(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} F(\omega)\exp(i\omega t)d\omega \tag{2}$$

where $f(t)$ is a given signal in the time domain; $F(\omega)$ is the Fourier transform of $f(t)$ in the frequency domain; i is an imaginary number $\sqrt{-1}$; and ω is the angular frequency. The waveform $f(t)$ and transform $F(\omega)$ comprise a Fourier transform pair. The Fourier transform is the inner product of $f(t)$ and a periodic function at various frequencies. Thus, the Fourier transform presents the frequency distribution through spectral analysis for different frequencies. In addition, the Fourier transform can be used to analyze and detect periodic signals because most periodic signals are represented as the sum of the sinusoid signals with different frequencies, magnitudes, and phases. While the Fourier transform is effective for finding the frequency information, it converts the entire length of the signal into frequency information. Therefore, the Fourier transform is not suitable for a nonstationary signal in which frequencies vary with time (Kim and Melhem, 2003). Furthermore, the location of the frequency information in the time domain is not provided by the Fourier transform.

2.2. Wavelet transform

The wavelet transform provides information about a signal that a Fourier transform or short time Fourier transform has difficulty extracting because the wavelet analysis is a localized transform in the time and frequency domains. The application of the wavelet transform in geophysics originated in the early 1980s for the analyses of seismic signals. Aggelis et al. (2008) performed an impact-echo test and wavelet transform analysis to estimate fully or partially grouted positions in a tunnel lining. Ni et al. (2008) used the wavelet transform to detect a pile defect using signals obtained from numerical simulations and sonic-echo tests. Furthermore, the frequency information of the wavelet transform shows whether the pile is surrounded by soil. Ni et al. (2010) used the wavelet transform on ground penetrating radar (GPR) data to obtain better quality GPR images than the traditional GPR profiles for buried pipes.

The wavelet transform of a function $f(t)$ is defined as the integral transform with a family of functions $\psi_{u,s}(t)$ and is given as follows (Grossmann and Morlet, 1984; Daubechies, 1988):

$$WT(u,s) = \int_{-\infty}^{+\infty} f(t)\overline{\psi_{u,s}(t)}dt = \frac{1}{\sqrt{|s|}}\int_{-\infty}^{+\infty} f(t)\overline{\psi\left(\frac{t-u}{s}\right)}dt \tag{3}$$

$$\psi_{u,s}(t) = \frac{1}{\sqrt{s}}\psi\left(\frac{t-u}{s}\right) \tag{4}$$

where $f(t)$ is a given signal in the time domain; $\psi(t)$ is the mother wavelet (or basis function), as shown in Fig. 1(a); $\overline{\psi(t)}$ is the complex conjugate of $\psi(t)$; u is the translating parameter; and s is the scaling parameter. The translating parameter u is related to a location of the mother wavelet function, which is shifted in the time domain, as shown in Fig. 1(b). Thus, the wavelet transform provides