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Research on signal processing of segment-grout defect in tunnel based on impact-echo method

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HIGHLIGHTS

- The segment-grout structure with defects was simulated experimentally.
- STFT and WT were carried out to analyze the signals.
- Energies of wavelet packet were calculated.

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ABSTRACT

In shield tunneling construction, grout of precast concrete segments is widely applied to various geological conditions. However, the connection performance between the grout and segments after the grout cannot be determined by destructive means, such as coring. The impact-echo method is used extensively in nondestructive testing of civil engineering structures. Nevertheless, there are inadequate researches on determining defects in segment-grout structure. In this paper, the segment-grout structure was simulated experimentally and artificial defects were introduced in the grout. The Short-time Fourier Transform (STFT) and Wavelet Transform (WT) of signals obtained by the impact-echo method were carried out to analyze the time-frequency domain features of the impact-echo signals with and without defects in the grout. On this basis, defects in the grout layer were determined. Finally, energies of wavelet packet were calculated and characteristic relative energy indexes of wavelet packet at different positions were detained. It's found that the values at positions without defects are relatively low. It's demonstrated that the signal analysis of impact-echo method has to combine time-frequency domain information and energy distribution for detection of defects in the grout layer. Wavelet transform and energy analysis methods are effective means to detect defects in the grout layer.

1. Introduction

In shield tunneling construction, it is necessary to install precast segments and place grout into the gap between the segment and surrounding rocks after the shield tunneling machine advances, aiming to resist the pressure and prevent stress relief of the soil mass. This will prevent collapse of the soil layer caused by tunnel excavation. Defects in the grout layer may decrease the integrity and influence the stress transfer and permeability of the tunnel lining. In engineering practice, the quality of grouting is guaranteed by controlling the grout pressure and grout volume, but it is not impossible to determine whether there are defects in solidified grout. Existing researches mainly focus on proportioning of grout mixtures as well as the stresses on the segments and surrounding rocks in the tunnel. Only a few researches on defect detection in the grout after solidification have been reported.

As an effective non-destructive method, the impact-echo method [1,2] is widely used in defect detection in concrete structures. And sometimes it's more effective than ground penetrating radar (GPR) which can be affected by internal steel bars. It uses an excitation source (steel ball or electromagnetic impactor) to impact the concrete surface and then determines the structural thickness and defect location according to the propagation of P-wave in the structure. Also, the lamb wave theory is studied in the propagation [3]. Lin et al [4] applied the impact-echo method to test internal layer defects in the concrete slabs. Many researchers have studied the relationship between the reflection laws of the impact-echo method and the structure, including the modes of vibration, defect size and depth [5,6]. Impact-echo method is effective in detecting grout defects in post-tensioning structure [7]. Many research results demonstrated that phase [8,9], frequency

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analysis of stress wave after propagation in the structure can be used to detect the thickness, presence of voids and evaluate the structural quality of interfaces in multi-layer structures [10–12]. researches show time-frequency analysis [13–16]is powerful tools in signal processing and can be combined with extreme learning machines [17].

Song and Cho [18,19] applied the impact-echo method into evaluation on contact quality of shotcrete and surrounding rock in tunnels and found that the impact-echo method can recognize different shotcrete quality defects. Aggelis et al [20] applied the impact-echo for evaluating grout of tunnel segments for the first time and analyzed the echo characteristics from multiple perspectives. Kang et al [21] carried out an experiment on the leakage caused by the damage of water pipes and found that the impact-echo method has good distinguishing ability under certain conditions. The impact-echo method can be used not only for defect detection in one-layer concrete structures, but also defect evaluation in multi-layer structures. However, the signals due to reflected waves are more complicated. It cannot detect defects accurately through the frequency-domain analysis alone, but has to combine the time-frequency analysis. In this paper, an impact-echo experiment on a segment-grout specimen with an artificial defect in the grout was carried out. Signal differences under the existence and absence of the defect were compared through time-domain analysis, frequency-domain analysis, wavelet transform and wavelet packet energy calculation.

2. Experimental study

2.1. Impact-echo experimental study

In this study, a model of a precast segment and grout was created. A simulated flaw was created in the grout behind the segment wall in the shield structure and signal processing of the impact-echo waveforms was studied.

The concrete segment grade is C50. The precast segment was obtained from the Nanjing Ligao Segment Co., Ltd. The size of each segment is 1200 mm × 1200 mm × 350 mm (Fig. 1). The radial clearance behind the segmental lining in tunnel shield construction is generally 100 mm. The grout layer in the specimen is 100 mm thick and the concrete segment is 350 mm thick. The plane dimensions of the grout layer and the concrete segment are 1200 mm × 1200 mm (Fig. 2).

Grout in practical engineering was simulated by casting a grout layer against the segment. The reflection coefficient at the segment-grout interface was determined to be −0.7, which would produce strong reflection of P-wave at the grout interface and still ensure the collection of signal of the wave that is transmitted into the grout and reflected by the defect. Ordinary Portland cement PO42.5 and fly ash were the main cementing materials of the grout. Bentonite was used to prevent grout separation and cement sedimentation as well as increase the stability of the grout. Mixture proportions of the grout are listed in Table 1. Material properties of the segment provided by the company and grout layer obtained from laboratory test are shown in Table 2.

A foam defect was embedded in the grout to simulate a void. The foam defect embedded in the left side of specimen and no defects were present on the right side (Fig. 2). As stated, the concrete segment thickness (h) is 350 mm. The foam plate width (d) has to meet $d > h/3$ and is set at 150 mm in order to realize successful detection of defects in the grout, and extend the full length of the segment. The foam plate thickness was set 20 mm and buried at 30 mm away from the segment-grout interface. The templates that support the concave surface of the segment were placed and the grout layer specimen was prepared. The specimen was supported on a shelf to prevent damage and falling off of the grout layer during transportation. The impact-echo test was performed from bottom as shown in Fig. 2.

The IES impact-echo equipment (Olson Company, USA) is shown in Fig. 3. It is composed of the computer, connecting line and the rolling sensor integrating the exciter and signal reception sensor. A length of 1024 data points was record in each test position and the auto gain is used to magnify signals. The sampling frequency was 100 kHz. In other words, one data point was collected every 10 us.

2.2. Theoretical calculation

According to the theory, the calculation formula of plate thickness [22] is:

$$T = \frac{\beta C_P}{\alpha f_T} \tag{1}$$

where f_T is thickness frequency of the plate; β is the shape coefficient which depends on the Poisson's ratio (μ), ranging between 0.945 and 0.957 [23]; and α depends on whether the phase of the P-wave that is reflected by the interface has been changed and its value is related to the acoustic impedance of different reflection interfaces ($\alpha = 2$ for plate structure with voids). In this experiment, the thickness frequency at different positions was calculated according to the given thicknesses of the segment and grout layer as well as preset defect position. Peak frequencies from signal analysis were compared with theoretical values from Eqs. (2) or (3).

$$f_T = \frac{\beta C_P}{\alpha T} \tag{2}$$

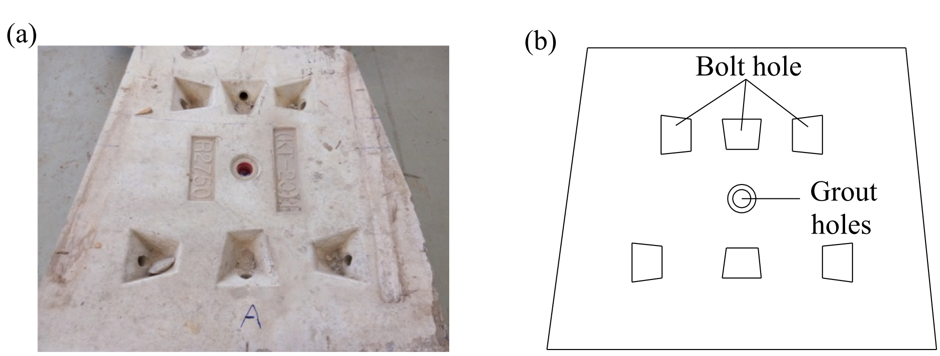

Fig. 1. Segment specimen: (a) Segment; (b) Plane view of the segment.