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Voids delineation behind tunnel lining based on the vibration intensity of microtremors

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ABSTRACT

In-situ microtremor measurements and numerical simulations were carried out to study the microtremor characteristics of tunnel linings. Power spectrum density (PSD) of microtremor signals measured from three spans of a tunnel lining with or without defects (cracks and voids) was calculated and analyzed. The results revealed that the normalized ratio of comparative power spectrum density (*NRPSD*) obtained by calculating the ratios *RPSD*, which is the ratio of PSD between different orientations (axial, radial and circumferential), of damaged spans to that of the healthy span, can be used as an indicator for the void delineation. For a damaged lining where voids exist, the vibration intensity is enlarged greatly in the radial direction, resulting in a pronounced value of *NRPSD* by comparing the *NRPSD* of the radial orientation to that of other orientations. Influences of properties of rock–concrete interfaces, geometric properties (location, arc length, and depth) of voids, and mechanical properties of rocks and concrete on the values of *NRPSD* were estimated via numerical simulations. As a preliminary study, these results provide clear evidence that the vibration intensity characteristics of microtremors have a strong correlation with the existence of voids located between lining concrete and surrounding rock masses, which has high potential to be developed to an effective approach for health assessment of tunnel linings in the future.

1. Introduction

In many countries of the world, a great number of tunnels have been commissioned for several decades, and the persistent ageing of tunnels has caused many engineering problems. Voids located between concrete linings and rock masses, which are either produced during construction by outdated construction methods (e.g., fore-piling method) or generated along with the degradation of rock masses and lining concrete, are unfavorable to the stability of tunnels. The negative consequences can vary from minor lining surface corrosion to major deterioration that decreases load carrying capacity of tunnels (Meguid and Dang, 2009).

With the conventional methods of void inspection, typically the voids can be identified by tapping the lining surface with hammers and listening to the hollow drum sounds. As impact-generated vibrations reflect between the lining and the void surfaces, lining concrete where the voids exist resonates weakly and produces airborne sounds through seismic–acoustic wave conversion. Highly experienced operators are essential in this kind of inspection due to the lack of computer-aided methods for precise judgments. On the other hand, this method provides a possible approach for the void detection if the measured seismic waves could be digitized and quantified. Following this concept, vibration-based techniques have been proposed and utilized for damage assessment of composite structures, such as beams and cylinder shells (e.g., Doebling et al., 1996; Roytman and Titova, 2001; Tokimatsu, 1997). Microtremors, as a type of ambient vibration originating from natural or artificial oscillations without specific sources, recently, have attract more and more attention in the study of the seismic properties of concrete structures. The propagation of microtremors in concrete structures could be considered as a temporally and spatially stochastic process that is significantly affected by the internal structure of materials, which in turn can be used to detect deflects existing in materials and to assess the integrity of structures.

The first widely implemented microtremor method, proposed by Nakamura (1989), is the Horizontal to Vertical spectral ratio (H/V) method used to derive the dynamic characteristics of soil

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and rock ground. The applicability of Nakamura's method was verified and improved through in-situ investigations (Lermo and Chavez-Garcia, 1994; Konno and Ohmachi, 1998; Bonnefoy-Claudet et al., 2006). A number of studies have been conducted to investigate the applicability and reliability of the microtremor method on the health assessment of structures since 1990s (e.g., Chatelain et al., 2000; Tuladhar et al., 2004; Ikeda et al., 2010). However, little attention has been paid to the microtremor measurements for the damage identification of tunnel linings (Jiang et al., 2012; Gao et al., 2014).

Different numerical approaches have been applied to study the seismic properties of structures, among which, the Distinct Element Method (DEM) has attracted much attention especially in the problems when discontinuous media (e.g., fractured rock masses) are encountered (Zhang et al., 1997; Jiang et al., 2009). Zhao et al. (2006, 2008) studied seismic wave propagation across single or multiple rock fractures using DEM. The simulation results, including the reflection and transmission coefficients and the influence of joint stiffness on wave propagation, showed good agreements with the theoretical calculations.

In the present study, microtremor measurements were carried out on three spans of an aged tunnel. The first span contains both voids and cracks (S1), the second one contains only cracks (S2), and the third span does not have obvious voids and cracks (S3). The vibration intensity ratio of the measured ambient acceleration waves from these spans was analyzed. The features of these spans were incorporated into numerical models based on DEM to investigate the microtremor behaviors of tunnel linings. Influences of properties of rock–concrete interfaces, geometric parameters of the void, and mechanical properties of rocks and concrete on the vibration response of tunnel linings were studied.

2. In-situ microtremor measurements on a tunnel lining

The measurements were carried out on the Satomi tunnel located in Sasebo City, Nagasaki Prefecture, Japan. The Satomi tunnel was built in 1992 with a length of 529 m. A detailed inspection was implemented in 2009 and the existence of defects such as cracks and voids on the tunnel lining were identified. Some of these defects were identified for the first time in the lining concrete after it has been commissioned for around twenty years, due to the deterioration of lining concrete. According to the tunnel inspection results, three typical spans with different health conditions were selected for microtremor measurements, which are labeled as S1, S2 and S3 as shown in Fig. 1.

Since the amplitude of microtremors usually ranges from several mgals to tens of mgals (1 gal = 0.01 m/s^2), high-precision accelerometers are required in microtremor measurements. In the measurements, compact type accelerometers with a resolution of 1 mgal were utilized. The measurement system consists of a power unit, a data acquisition unit, and two accelerometers, as shown in Fig. 2. Alternate traffic regulation was implemented to allow one side of tunnel lining to be measured without blocking the traffic. Tunnel inspection results showed that voids often occur on the crown and arch of lining, therefore, two points located on the crown and arch, respectively (C1 and C2, see Fig. 2) were selected for measurements during the limited measuring time. The procedure for installing accelerometers is shown in Fig. 3. First, a small hole was drilled on the lining by a hammer drill at the location where the microtremors were to be measured, and then a bracket was mounted in this hole using an expansion anchor. The position of the bracket was adjusted to ensure that the accelerometer it held could achieve absolute vertical and horizontal positions. Finally, the accelerometer was mounted on the bracket by screws. The components of microtremors in the vertical, horizontal and axial directions were measured, which were then converted into the components in the axial, radial and circumferential orientations of tunnel through vector conversion. The measurements lasted 300 s for each sample with a recording interval of 0.001 s. A typical example of the measured acceleration waves is shown in Fig. 4, in which, most waves have the amplitude of accelerations within ±500 mgal.

3. Power spectrum density analysis of microtremors measured on the tunnel lining

The predominant frequency of an objective can be estimated from the calculated power spectrum density (PSD) of the measured time-domain acceleration waves by

$$P(f) = \frac{1}{T}|X(f)|^2 \tag{1}$$

where f is the frequency, T is the time and $X(f)$ is the frequency spectrum. The PSD of measured microtremors was calculated to acquire the peak frequency, using the Welch's averaged periodogram method implanted in MATLAB (MATLAB, 2003).

As an example, the frequency-domain spectra of measured waves on S3 at different directions are shown in Fig. 5. The frequency spectra at the low-frequency range (0–100 Hz) show different characteristics with that at the high-frequency

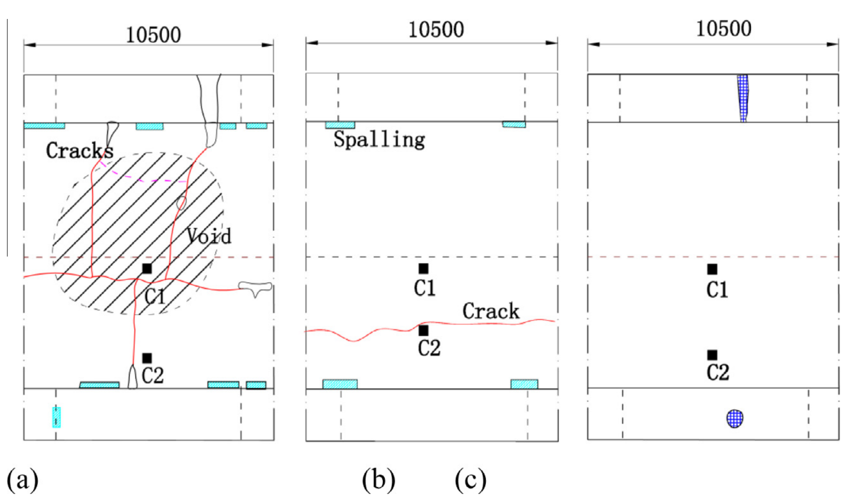

Fig. 1. Inspection results of spans S1, S2 and S3. (a) S1: severely damaged span (a void, three circumferential cracks, and one axial crack exist on the lining; (b) S2: moderate damaged span (one axial crack exists on the lining surface); (c) S3: healthy span. Unit: mm.