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The nature frequency identification of tunnel lining based on the microtremor method

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Abstract

Many tunnels all over the world have been in service for several decades, which require effective inspection methods to assess their health conditions. Microtremor, as a type of ambient vibration originating from natural or artificial oscillations without specific sources, has attracted more and more attentions in the recent study of the microtremor dynamic properties of concrete structures. In this study, the microtremors of the tunnel lining were simulated numerically based on the Distinct Element Method (DEM). The Power Spectra Density (PSD) of signals obtained from numerical simulations were calculated and the nature frequencies were identified using the peak-picking method. The influences of the rock-concrete joint, the rock type and the concrete type on the nature frequencies were also evaluated. The results of a comprehensive numerical analysis show that the nature frequencies lower than 100 Hz can be identified. As the bonding condition becomes worse, the nature frequencies decrease. The nature frequencies change proportionally with the normal stiffness of the rock-concrete joint. As the concrete grade decreases, the third mode of frequency also decreases gradually while the variation of the first two modes of frequencies can hardly be identified. Additionally, the field microtremor measurements of tunnel lining were also carried out to verify the numerical results.

Keywords: Tunnel lining; Frequency; Vibration intensity; Microtremor measurement; Numerical simulation

Introduction

Mountain tunnel structures are an important part of the road networks. To date, a great number of tunnels have been in service for more than 40 years and the persistent ageing of them causes many problems to the concrete linings, such as corrosion, buckling, fracturing, generation of internal voids and seepage induced by flaws (Malmgren, Nordlund, & Rolund, 2005). The deteriorations and damages of linings decrease the integrity of tunnels and subsequently affect the workability, serviceability and safety of tunnels (Aktan, Catbas, Grimmelsman, & Tsikos, 2000; Bhalla, Yang, Zhao, & Soh, 2005). Therefore, the maintenance of tunnel linings is essential to provide the required level of safety and serviceability to road users.

At present, the integrity of the mountain tunnel is commonly evaluated by using the ground penetrating radar (GPR) method, the ultrasonic method, the magnetic method, etc (Daniels, 2004; Jiles, 1990; Poranski, Greenawald, & Ham, 1996). However, only local information of the structure condition can be measured by highly-experienced operators, and the considerable time and cost are required to estimate the overall structural integrity in

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the most previous techniques (Park & Choi, 2008). Relatively, a more effective approach for evaluating the whole structural condition is to utilize the measured dynamic responses of a structural system to assess the physical properties of the structure (Choi, Park, Park, & Stubbs, 2006). There are two methods available for measuring the vibration response of a structure, including the forced vibration test and the ambient vibration test.

Unlike other structures, the mountain tunnels are subjected to rock-structure interaction of its surrounding rock masses. Hence, its dynamic behavior is controlled by the stiffness of the tunnel lining, the surrounding rock masses and the concrete-rock joints (Gao, Jiang, & Li, 2016; Wiehle, 1964). The forced vibration test is not applicable for the damage detection of large-scale structures, where the huge reaction mass shakers are necessary (Gao et al., 2016; Peeters, Maeck, & Roeck, 2001). With the development and application of the high sensitivity accelerometer, the low-cost ambient test has become the main test method for the structural damage identification. The ambient vibration measurement is a kind of output data-only dynamic testing and a modal analysis procedure is carried out based on the output data. Thus far, the ambient test has been applied to various types of structures including bridges (Magalhas, Cunha, & Cartano, 2009), buildings (Michel, Guéguen, & Bard, 2008), historical structures (Júlio, Rebelo, & Gouveia, 2008), and mechanical structures (Pierro, Mucchi, Soria, & Vecchio, 2008). Microtremor, as a type of ambient vibration originating from the natural or artificial oscillations without specific sources, has attracted lots of attentions in the recent study of the microtremor dynamic properties of concrete structures (Chatelain et al., 2000; Ikeda, Yoshitaka, & Yasutsugu, 2010; Tuladhar, Yamazaki, Warnitchai, & Saita, 2004). However, few attentions have been focused on the microtremor test on the damage identification of tunnel linings.

The occurrence of damage and deterioration in a structure causes changes in the nature frequencies of the structure. The most widely used parameter in dynamic tests is the predominant frequency due to that the nature frequency can be acquired conveniently. Especially in some large-scale civil structures, other model characteristics (e.g., the model shapes) would be economically unfeasible to measure. In this paper, the microtremors of the tunnel lining were simulated using the Distinct Element Method (DEM). The nature frequency of the concrete lining was identified from the acceleration data of ambient vibration. The influences of the rock-concrete joint, the rock type and the concrete type on the nature frequencies were also investigated. For the purpose of verification, a field test was also carried out.

The principle of microtremor method and simulation method based on distinct element

Comparing with theoretical and experimental studies, the numerical simulation provides a convenient and low-cost approach to study the dynamic problems of engineering, especially when theoretical solutions are difficult to be obtained. In this study, the tunnel was simplified as a plane strain model and the dynamic properties in the cross section were investigated. The numerical simulations were performed by using the DEM code of UDEC to investigate the microtremor vibration behavior of the tunnel lining.

In the old tunnels that were built using the poling-board method, shotcrete was not used and incomplete contact usually exist between the rock mass and the lining concrete. In numerical simulations, the unbonded contact can be simplified as weak joints with low normal and shear stiffness, which are treated as interfaces between distinct bodies (i.e., the discontinuity is treated as a boundary condition in the DEM) (UDEC, 2000). The Mohr-Coulomb model and Coulomb slip model were adopted to represent the mechanical behavior of rock masses and joints, respectively. Those types of elements can effectively simulate the dynamic deformational behavior of rock mass, lining concrete and joints. The shape and size of the numerical model are shown in Fig. 1. It is a semicircular arch with a radius of 4.5 m. The height of springing line is 2.5 m. The thickness of the concrete lining is 0.7 m. The physic-mechanical properties of the surrounding rock mass, lining concrete and concrete-rock joints are listed in Table 1, which are determined according to the typical properties of concrete and the laboratory tests on a kind of granite located in the Kyushu area, Japan. Since the microtremor will not cause the failure of the rock mass and lining concrete, the tensile strength, cohesion and friction angle

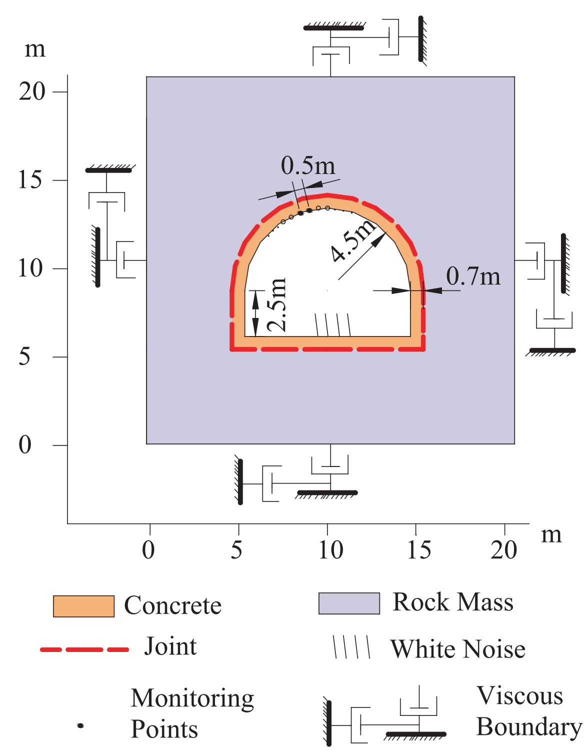

Fig. 1. Model of numerical simulation.

Table 1
Material properties used in numerical simulation.

Parameters		Units	Values
Intact rock	Density	kg/m^3	2500
	Elastic modulus	GPa	20
	Poisson ratio	–	0.25
	Tensile strength	MPa	7.2
	Cohesion	MPa	10.3
	Friction angle	°	30
Concrete	Density	kg/m^3	2500
	Elastic modulus	GPa	30
	Poisson ratio	–	0.25
	Tensile strength	MPa	1.4
	Cohesion	MPa	2.7
	Friction angle	°	35
Joint	Normal stiffness	MPa/m	400
	Shear stiffness	MPa/m	40
	Cohesion	MPa	0.05
	Friction angle	°	15

have no influences on the microtremor behavior of the model.

In the numerical simulation, a stationary Gaussian white noise with a frequency range from 0 to 110 Hz was input on the floor of the tunnel to represent the exciting source (e.g., passing vehicles). The element size was set to be 0.2 m in order to simulate the propagation of stress waves accurately. The Rayleigh damping with a ratio of 0.7% was utilized during dynamic calculations to represent the material's attenuation effect. The boundaries of the model were set as viscous boundaries to minimize wave reflections at boundaries. The acceleration histories of the lining surface in both the horizontal direction and the vertical direction were recorded at regular distance intervals of 0.5 m in order to obtain the nature frequencies (see Fig. 1). 32,768 discrete time signal data at each monitoring point were recorded during numerical simulations with a sampling interval of 0.001 s.

Results and analysis

The 'spectral peak-picking method' has been widely used in spectrum analysis for nature frequency identification. The Power Spectrum Density (PSD) P(f), is given 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 Power Spectrum Density (PSD) was calculated from the acceleration data to acquire the nature frequency, by using the Welch's averaged periodogram method implanted in MATLAB (MATLAB Reference Guide, 2003). A hamming window with a length of 2048 and 50% data overlapping was adopted to smooth the curve and to reduce the leakage error. The spectral resolution is 0.488 Hz. The PSD amplitudes were normalized by using the sum of the squares of the PSD corresponding to each frequency, as given by

$$NPSD(f) = P(f) \Bigg/ \sqrt{\sum_{k=1}^{n} P(f)^2} \tag{2}$$

where $NPSD(f)$ is the normalized PSD corresponding to the frequency f; k is the number of frequency points; n is the maximum number of frequency points; $P(f)$ is the PSD. Since the tunnel model is two-dimensional, the determination of the nature frequencies requires the establishment of a measuring grid over the structure to record the whole vibration behavior. Therefore, the average of all normalized PSD at the individual monitoring point is calculated and a so-called ANPSD spectrum is obtained:

$$ANPSD(f_k) = \frac{1}{n}\sum_{i=1}^{n} NPSD_i(f_k) \tag{3}$$

where $NPSD_i(f_k)$ is the normalized PSD for the frequency f_k at the monitoring point i.

Using the averaged algorithm, those energy peaks are eliminated in the individual spectra that were caused by short-term disturbances (e.g. the passing truck), and meanwhile, the loss of nature frequencies on nodes where mode shape is zero can also be avoided. The representative average spectrum of tunnel is shown in Fig. 2, indicating that the nature frequencies are dominant. Three nature frequency peaks can be identified as 65, 70 and 93 Hz, in spite that the first nature frequency (65 Hz) is close to the second one and is not as obvious as others.

Influence of the rock-concrete joint

The supporting system has a great influence on the natural frequency of structures, and the decrease of the contact stiffness between the rock mass and the lining will reduce the natural frequency of the system (Chowdhury, 1990). The influences of the joint normal stiffness on the power spectrum are shown in Fig. 3. A series of concrete-rock joints with different stiffness were simulated. With the decrease of the normal stiffness of joints, the nature frequency decreases, and the frequency difference between the

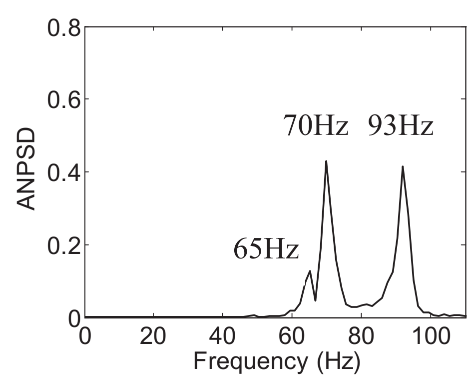

Fig. 2. The average of normalized power spectrum.

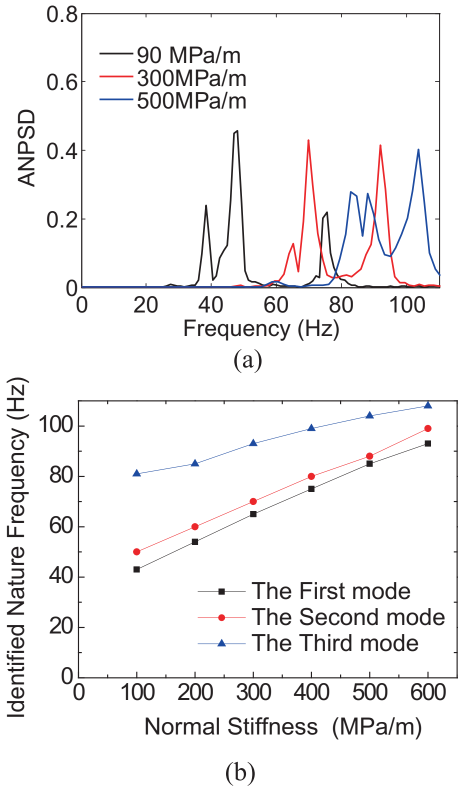

Fig. 3. Influence of the concrete-rock joint on the power spectrum: (a) the power spectrum of tunnel lining corresponding to different normal stiffness of concrete-rock joint; (b) the relation between the nature frequency and the normal stiffness of concrete-rock joint.

second and the third modes increases. The relation curves between the nature frequencies for each mode and the normal stiffness exhibit approximately linear characteristics, indicating that the nature frequency changes proportionally with the normal stiffness of the rock-concrete joint (see Fig. 3b).

Influence of lining concrete type

Several types of concrete have been widely used to built tunnel linings, which affect the stiffness of lining obviously. The properties of common types of concrete are listed in Table 2. The variation of stiffness usually causes changes in the nature frequency of the tunnel lining. Fig. 4 shows the influence of the concrete type on the nature frequency. As the concrete grade decreases, the third mode frequency also decreases gradually; nevertheless, the variation of first two mode frequencies can hardly be identified. It shows that the high-frequency modes are more sensitive to the change of lining stiffness.

Table 2
Properties of different types of concrete used in numerical simulations.

Concrete type	Density (Kg/m^3)	Elastic modulus (GPa)	Poisson ratio
C20	2500	22	0.27
C40	2500	30	0.2
C50	2500	38	0.2

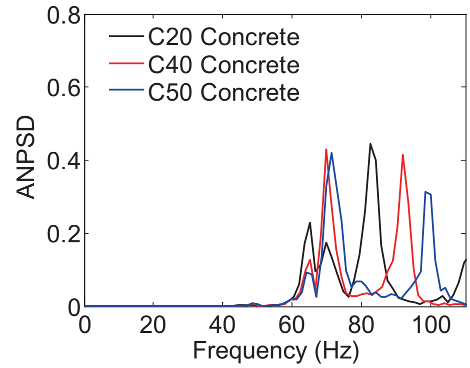

Fig. 4. The power spectrum of the tunnel lining with different types of concrete.

Table 3
Properties of rocks used in numerical simulations.

Material	Density (Kg/m^3)	Elastic modulus (GPa)	Poisson ratio
Hard rock	2600	47	0.2
Medium rock	2550	30	0.22
Soft rock	2500	20	0.25
Weathered rock	2260	7	0.3

Influence of rock mass type

Besides the rock-concrete joint and the concrete lining, the surrounding rock mass remains as another key issue to affect the overall properties of the tunnel system. Therefore, it is necessary to analyze the influence of the rock types on the nature frequency of tunnel lining. The properties of typical types of rocks are listed in Table 3 and the power spectra of the tunnel lining within different rock types are shown in Fig. 5. Except in the case of the weathered rock, there is no obvious influence of rock types on the nature frequencies and the variation of the spectrum amplitude is less than 10%. In the case of the weathered rock, the spectrum presents different characteristics: many frequency peaks appear, which bring difficulties to the nature frequency identification. The results indicate that variations of nature frequencies of the tunnel lining that induced by failures (e.g., joints) can be estimated obviously when the surrounding rocks are unweathered, while special attentions need be paid in the peak picking if the rock mass is highly weathered.

Field test

In order to verify the numerical results of the microtremor characteristics of tunnel linings, field tests were carried out on the Satomi tunnel located in the Sasebo City,

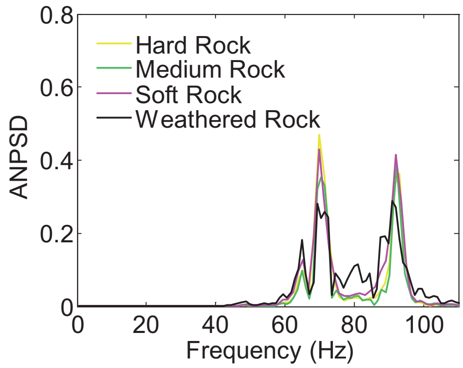

Fig. 5. The power spectra of the tunnel lining within different types of rock masses.

Nagasaki Prefecture, Japan. The Satomi tunnel was built in 1992 with a length of 529 m. The measurement system consists of the power, the PC & data acquisition device and two accelerometers, as shown in Fig. 6. The accelerometers were installed at two positions (C1 & C2, see Fig. 7) on a healthy span of the tunnel lining. The specification parameters of the accelerometer are shown in Table 4. Three components of the microtremors in the vertical and horizontal directions of tunnel were measured, respectively. The measurements lasted for 300 s with an interval of 0.001 s.

A typical example of the measured acceleration waves is shown in Fig. 8. The ANPSD spectrum of the measured signals was calculated, as shown Fig. 9. Three nature frequency peaks (71 Hz, 78 Hz and 88 Hz) can be identified. Thus, the similar tests results with numerical simulations were acquired, that verified the numerical simulation effectively. However, in the future, more field tests are needed, focusing on various impact factors (e.g., rock-concrete joints, concrete types).

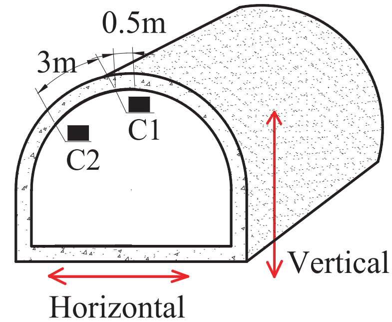

Fig. 7. Accelerometer configurations in field tests.

Table 4
Specification parameters of the accelerometer.

Type	LS-10C
Max. acceleration	±30 m/s^2
Frequency range	DC ~ 110Hz
Resolution	1mgal
Size	37(H) × 37(W) × 40(D)
Weight	220 g(include Cord)

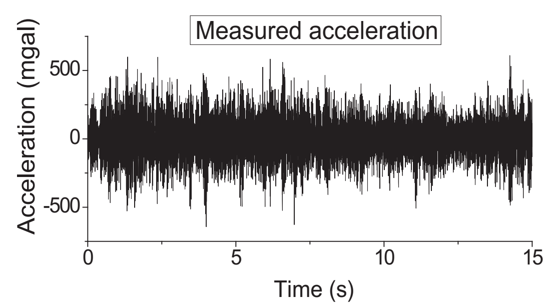

Fig. 8. An example of the acceleration waves.

Conclusions

In this study, the microtremor characteristics of the tunnel lining were simulated numerically. Based on the average of normalized power spectrum density (ANPSD) of microtremors, the nature frequencies of the concrete lining in the mountain tunnel were identified using the peak picking method. The influences of rock-concrete joint, rock type and concrete type on the nature frequencies were also evaluated.

As the bonding condition becomes worse, the nature frequency of lining decreases and the frequency difference between the second and third modes increases. The nature frequency changes proportionally with the normal stiffness of the rock-concrete joint.

As the concrete grade decreases, the third mode frequency also decreases gradually; however, the variation

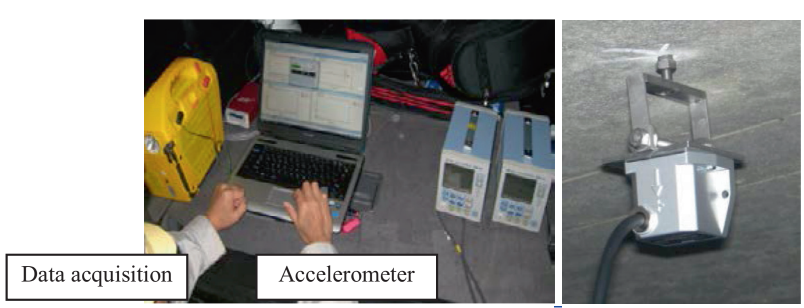

Fig. 6. Measurement system in field tests.

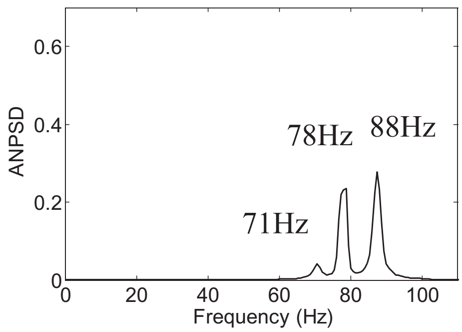

Fig. 9. The average of normalized power spectrum in Satomi tunnel.

of first two modes of frequencies can hardly be identified. The high-frequency modes are more sensitive to the changes of lining stiffness.

In the case of unweathered rocks, the rock properties have no obvious influence on the nature frequencies and the variation of the spectrum amplitude is less than 10%. In the case of weathered rock, the spectrum presents a different characteristic: many frequency peaks appear, which confuse the nature frequency identification.

The microtremor analysis method presented in this study only needs to measure the acceleration waves on the surface of the tunnel lining, with the significant advantages that it is convenient for application; it brings negligible damage to the lining concrete and its cost is low. The nature frequency can be identified easily from the measured microtremors. Meanwhile, more field tests regarding various influencing factors will also be necessary to extend this method for future engineering practices.

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