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Research on ambient vibration-based quantitative assessment of tunnel lining defect using laser Doppler vibration measurement

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Abstract

The necessity for automated and information-based inspection methods for the daily maintenance of tunnels is becoming increasingly apparent, given the ongoing increase in the number of tunnels. The paper sets out a method for non-contact detection that uses a laser Doppler vibrometer based on ambient vibration. The approach involves the introduction of a dimensionless quantitative index termed Fundamental Frequency Deterioration Degree (FFDD), which is based on the fundamental frequency itself. To validate this method, laboratory ambient vibration detection tests were conducted on cubic concrete samples which consider strength, cavity, and cracks under compression. The PDV-100 laser Doppler vibrometer was utilized for the purpose of ambient vibration collection. The findings demonstrate a strong correlation between concrete defects and the fundamental frequency. The correlation between FFDD and concrete defects serves to validate its accuracy. The method was applied in situ to detect and assess grouting defects in a newly constructed metro tunnel, thus further validating its use in real-world scenarios.

Keywords

Tunnel lining defect, Quantitative assessment, Ambient vibration, Laser Doppler vibrometer.

1 Introduction

The construction of tunnels has witnessed significant growth globally, particularly in China, over the past few decades. However, such expansion has raised concerns regarding the deterioration and defects that can arise due to natural and man-made factors, as well as the effects of aging on concrete lining structures. Issues such as cracks, cavities, deformations, and leakage have become pressing matters for the daily operation, management, and maintenance of tunnel linings. Inefficient defect detection may eventually lead to structure fracture and even serious safety accidents, leading to immeasurable property losses and casualties (Xu and Qian 2024). Hence, accurate detection and assessment of these damages are crucial initial steps toward effective maintenance and extending the service life of these engineering structures.

Traditional detection methods for tunnel damage, which rely on manual inspection, are time-consuming, subjective, and prone to human error. Additionally, the working environment poses safety risks for personnel (Menendez et al. 2018). Although some non-artificial methods have beenpartially employed in tunnel engineering, the efficiency of drilling cores, acoustic detection, and 3D laser scanning is relatively low. Moreover, geological radar requires contact with the lining surface, making it challenging to meet the requirements of rapid and efficient testing of tunnel linings. Thus, a non-contact and high-efficiency non-destructive detection method is necessary.

Ambient vibration as a continuous, low-amplitude vibrations always present in the surrounding environment is an available tool to characterize the dynamic behavior of the structure itself. Thus, valuable information for structural integrity could be retrieved due to the relationship between the structure stiffness and the dynamic characterization such as fundamental frequency (Du et al. 2024). Currently, ambient vibration measurement technology using patch accelerometers offers advantages such as low cost, good environmental performance, and excellent deviation stability, making it suitable for detecting tunnel lining diseases (Jiang and Zhang 2021). However, it faces challenges in terms of low detection efficiency and contact-based detection. On the other hand, laser Doppler vibrometers (LDVs) technology enables rapid and efficient remote vibration measurement and finds extensive applications in areas such as dangerous rock safety detection and landslide safety and stability evaluation (Du et al. 2017; Du et al. 2022). However, its effectiveness in detecting lining structure defects is not yet clear, and further research is needed to explore its fundamental principles and potential applications.

Thus, this paper quantitatively evaluates tunnel lining defects through the ambient vibration building upon knowledge from damage mechanics and vibration mechanics. On one hand, laboratory experiments are conducted to investigate the material strength level, the presence of an internal cavity, and the occurrence of lining cracks in different concrete specimens by applying the laser Doppler vibrometer. A dimensionless quantitative index called Fundamental Frequency Deterioration Degree (FFDD) based on the fundamental frequency is introduced. Subsequently, the proposed index is employed in situ for detecting and assessing grouting defects in a newly constructed metro tunnel, thereby validating its efficacy.

2 LDVs-based ambient vibration test and assessment methodology

2.1 LDVs-based ambient vibration test methodology

LDVs-based ambient vibration test methodology is a non-invasive technique used to assess the dynamic characteristics of soil and rock layers or structures. It employs the principles of laser Doppler vibrometer to measure ground motion resulting from microtremors or ambient vibrations. By measuring the velocity of ground or structure motion in response to microtremors, the test provides valuable data. During the test, a laser beam is directed toward the surface of the ground or structure, and a sensor detects the reflected light. As the ground or structure vibrates, the frequency of the reflected light undergoes a Doppler shift proportional to the velocity at that point. The acquired velocity data is communicated between the sensor and analysis software in a laptop through the USB data acquisition. The acquired velocity data is then processed to obtain microtremor spectra. These spectra reveal amplitude and phase variations of ground or structure motion at different frequencies. From these spectra, important parameters such as dominant frequency, amplification factor, and resonant frequency can be determined.

Given the knowledge of vibration mechanics and structure mechanics, it is possible to detect damage in an object by observing a decrease in its stiffness, which is indirectly reflected in the natural vibration frequency. Therefore, utilizing ambient vibration for object damage detection proves to be a feasible approach. Its test and assessment flow are as depicted in Fig. 1.

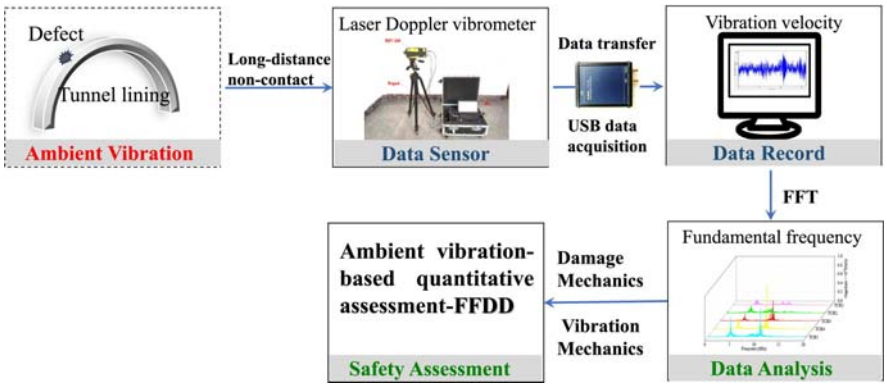


Fig. 1 Flow of the LDVs-based ambient vibration test and assessment methodology.

2.2 Fundamental frequency deterioration degree (FFDD)

Based on the principles of damage mechanics, it is understood that the presence of defects in a material will result in the dissipation of energy within it. This dissipation corresponds to an irreversible change in the material's internal structure. In the case of a one-dimensional linear problem, the extent of deterioration (referred to as DD) can be quantified by examining the change in elastic modulus before and after the occurrence of damage, as outlined below.

$$DD = 1 - \frac{\tilde{E}}{E} \tag{1}$$

where, E is the modulus of elasticity in the healthy state of the material with the unit of *MPa*; $\tilde{E}$ is the material modulus of elasticity in the damaged state with the unit of MPa. Elastic wave propagation velocity of the elastic isotropic body C_p can be obtained through the elastic parameters as shown in Equation (2).

$$C_p = \sqrt{\frac{E}{\rho}\frac{1-v}{(1+v)(1-2v)}} \tag{2}$$

where ρ is density with unit of kg/m^3 and v is the Poisson's ratio. Poisson's ratio remains constant regardless of the defect morphological characteristics of the material (Prassianakis and Prassianakis 2004). Therefore, the propagation velocity $\tilde{C}_p$ of elastic waves in the damaged body can be expressed as follows:

$$\tilde{C}_p = \sqrt{\frac{\tilde{E}}{\tilde{\rho}}\frac{1-v}{(1+v)(1-2v)}} \tag{3}$$

where $\tilde{\rho}$ is the density of the damaged elastic body. Generally, when the structure has only local small damage, the density and wavelength of the structure before and after damage change little (Jiang et al. 2023). According to the quantitative relationship between wavelength λ and wave velocity C_p, Equation (1) can be rewritten considering the natural vibration frequency as follows.

$$DD = 1 - \frac{\tilde{E}}{E} = 1 - \frac{\tilde{\rho}\tilde{\lambda}^2\tilde{\omega}^2}{\rho\lambda^2\omega^2} \tag{4}$$

where, λ and $\tilde{\lambda}$ are the wavelengths in the health and damage state with unit of m, and ω and $\tilde{\omega}$ are the natural frequencies in the health and damage state with unit of Hz. Then Equation (4) can be simplified as:

$$DD \approx 1 - \frac{\tilde{\omega}^2}{\omega^2} = FFDD \tag{5}$$

Equation (5) demonstrates that the quantitative assessment of damage in concrete structures can be achieved by comparing the fundamental frequency values before and after the occurrence of damage. This index is referred to as the fundamental frequency-based deterioration degree (FFDD).

3 Laboratory ambient vibration test for concrete samples

3.1 Specimen preparation and laboratory test procedure

Tunnel lining structures are often subject to material aging, cavities, cracks and other defects and diseases due to various factors. Three indicators including concrete strength deterioration, cavity and crack (through and non-through) were chosen as experimental design factors. Table 1 lists the specific design scheme for the current study.

Table 1. Non-destructive test design scheme for concrete specimen.

Liningdefect	Design factor	Value (Case No.)
Aging	Strength value/MPa	25(D1), 30(D2), 35(D3), 40(D4), 45(D5), 50(D6)
Cavity	Hollow balldiameter/mm	0(CA1), 20(CA2), 30(CA3), 40(CA4), 50(CA5),60(CA6), 70(CA7), 80(CA8), 90(CA9)
Crack	Through crack:length × depth/mm × mm	0 × 0(TCR1), 35 × 150(TCR2), 70 × 150(TCR3), 105 × 150(TCR4), 140 × 150(TCR5)
	Non-throughcrack:length × depth/mm × mm	0 × 0(NTCR1), 35 × 75(NTCR2), 70 × 75(NTCR3), 105 × 75(NTCR4), 140 × 75(NTCR5)

Concrete specimens measuring 150 mm × 150 mm × 150 mm were chosen for the study. Two specimens were prepared for each defect type to achieve the required accuracy for the fundamental frequency. All specimens were kept at a constant temperature of 25°C for approximately 28 days to ensure proper curing.

Regarding the effect of concrete strength, a reference specimen with a uniaxial compression strength (UCS) of 50 MPa was used (refer to asUCS50). Five additional cases were designed with UCS values of 45 MPa, 40 MPa, 35 MPa, 30 MPa, and 25 MPa. For assessing the effect of cavities, hollow plastic balls were inserted at the center of the concrete specimens during the molding process. The diameters of the plastic balls were selected as 20 mm, 30 mm, 40 mm, 50 mm, 60 mm, 70 mm, 80mm, and 90 mm. Since the presence of hollow balls has minimal impact on the strength of the specimens, they were not removed during subsequent testing. To examine the effect of cracks, mortar concrete was embedded with thin iron sheets to create cracks. The iron sheet, half the height of the specimen for through cracks (150 mm), and full height for non-through cracks (75 mm), was placed diagonally across the specimen. After molding, the iron sheets were removed to better simulate the authenticity of specimens with crack defects. The design and physical appearance of the specimens are illustrated in Fig. 2.

An ambient vibration test was conducted on the specimen under uniaxial compression using a laboratory Laser Doppler vibrometer system, as shown in Fig. 3. The applied loads for this test ranged from 0 MPa to 3 MPa, with increments of 0.5 MPa. Each specimen underwent three tests, and the average value was taken for analysis to minimize data dispersion. The velocity-time history data captured by the Laser Doppler vibrometer system was transformed into velocity-frequency data using Fast Fourier Transform (FFT). Subsequently, the first natural frequency (also known as the fundamental frequency) in the frequency domain was used to calculate the fundamental frequency-based deterioration degree (FFDD).

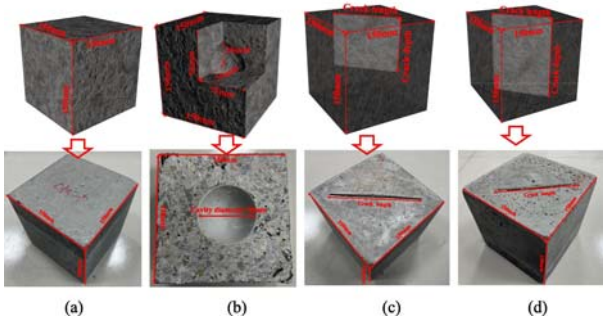


Fig. 2 Design and physical concrete specimen. (a) Specimen with UCS of 30 MPa; (b) Specimen with cavity; (c) Specimen with non-through crack; (d) Specimen with through crack.

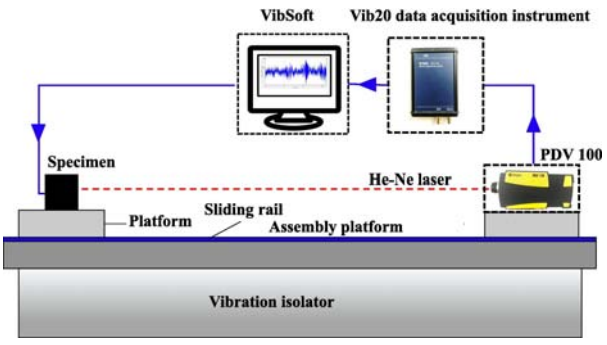


Fig. 3 LDVs-based ambient vibration test for concrete samples in laboratory.

3.2 FFDD-based deterioration assessment

The proposed assessment index for concrete damage, FFDD, is calculated using Equation (5) based on ambient vibration. Fig. 4 displays the FFDD of the concrete specimen about concrete damage under

different compression stresses. Dimensionless quantities are considered: UCS/UCS50 for strength effect, Cavity volume/Specimen volume for cavity effect, Crack length/Specimen diagonal length for crack effect. For the reference specimen, the FFDD is zero according to Equation (5). The FFDD of each specimen shows an exponential relation to the strength with a correlation coefficient of up to 0.75 and quadratic polynomial relations to the defect dimension, with a correlation coefficient of up to 0.93. In cases of strength degradation, the FFDD reaches its maximum value of 14.57% when the UCS/UCS50 of the concrete decreases from 1.0 to 0.5. In cases of internal cavities, the maximum FFDD of 25.11% is observed with a cavity maximum diameter of 90 mm (CV/SV = 0.1885). In cases of cracks, the FFDD reaches its maximum value of 6.63% for non-through cracks and 13.53% for through cracks, with a maximum crack length of 140 mm (CL/SDL = 0.65997). The positive correlations indicate that the proposed ambient vibration-based FFDD can quantitatively assess defects.

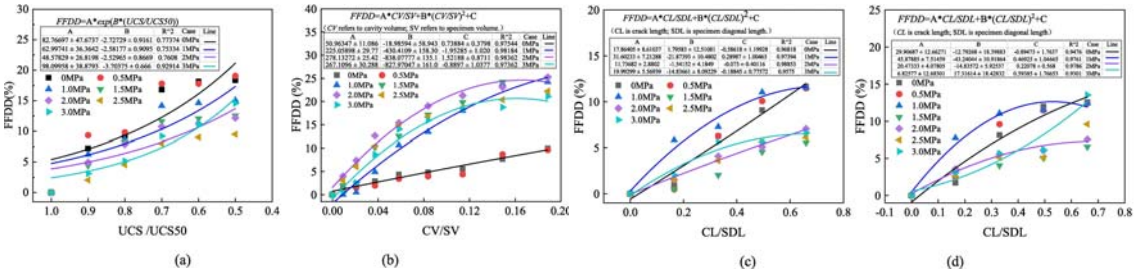


Fig. 4 FFDD of the concrete specimen regarding concrete defect under different compression stresses. (a) Strength effect; (b) Cavity effect; (c) Non-through crack effect; (d) Through crack effect.

4 In-situ application of ambient vibration detection

A newly constructed metro tunnel was detected to check its grouting quality behind shield segments. The same PDV 100 laser Doppler vibrometer is applied for field detection. Detection results were compared to those obtained with Ground Penetrating Radar (GPR) technology. Figure 5 illustrates GPR images indicating the presence of grouting defects in the tunnel segments. Figure 6 presents the fundamental frequency and the corresponding FFDD (calculated using Equation (5)) detected by the PDV-100 laser Doppler vibrometer. When the grouting quality is fine, the fundamental frequency remains constant with a very small floating range. However, when a grouting defect is present, the fundamental frequency decreases.

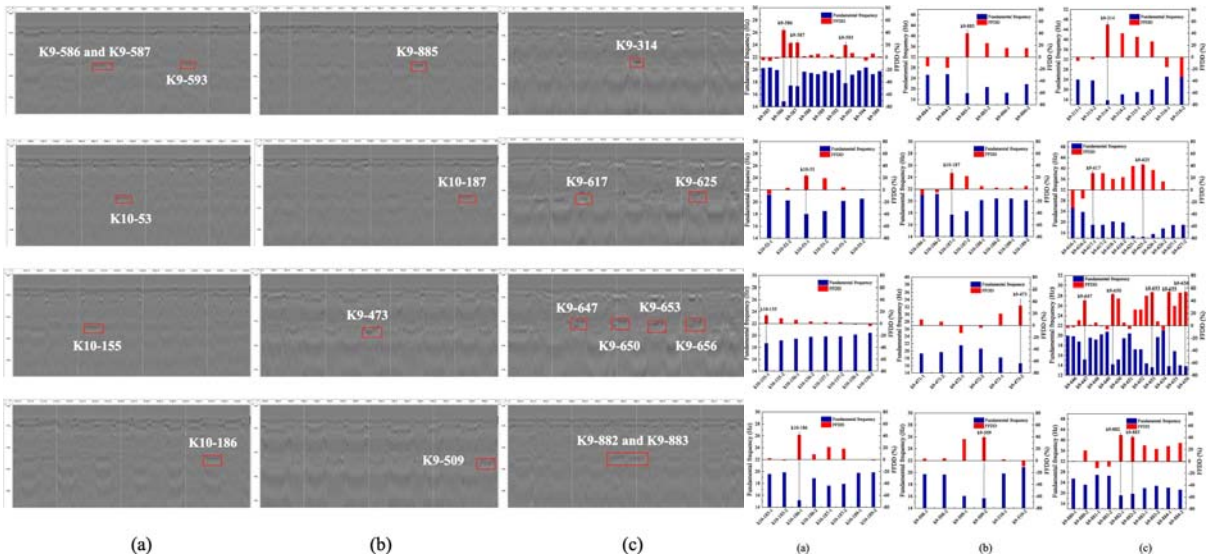


Fig. 5 GPR images with a grouting defect in the newly built metro tunnel. (a) Sidewall; (b) Spandrel; (c) Crown.

Fig. 6 Fundamental frequency and correspondingly calculated FFDD detected by PDV-100 laser doppler vibrometer. (a) Sidewall; (b) Spandrel; (c) Crown.

The correlation between the size of grouting defects and the proposed ambient vibration-based quantitative assessment index FFDD was investigated using GPR images, as depicted in Fig. 7. The analysis reveals a linear relationship between the length of the defect and FFDD, with a correlation coefficient of 0.9584. This linear correlation indicates that the LDVs-based ambient vibration assessment is an effective method for quantitatively evaluating tunnel lining defects, both in laboratory settings and on-site.

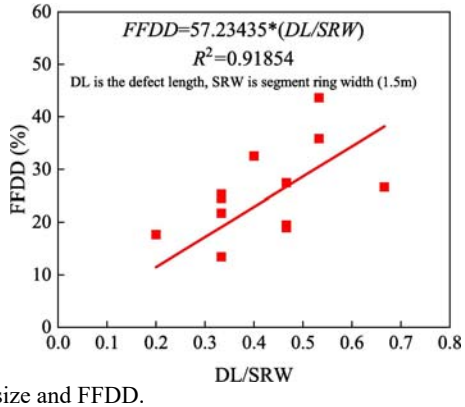


Fig. 7 Correlation between the defect size and FFDD.

5 Conclusions

Investigation of tunnel lining defects using ambient vibration-based quantitative assessment is conducted in this study. A dimensionless quantitative index called Fundamental Frequency Deterioration Degree FFDD is developed for assessing lining defects, based on the knowledge of damage mechanics and vibration mechanics.

Laboratory ambient vibration tests using laser Doppler vibrometer are performed on cubic concrete specimen. The results obtained from laboratory tests indicate strong relationships between the fundamental frequency of the concrete specimen and pre-designed defects. Additionally, the proposed FFDD of each specimen shows a positive correlation with both strength degradation and defect dimensions. These positive correlations demonstrate that the proposed ambient vibration-based FFDD can quantitatively assess concrete deterioration.

The laser Doppler vibrometer is then applied in-situ to detect the grouting quality in a newly-built metro line, in contrast to the SIR-3000 GPR instrument. The proposed FFDD based on the in-situ ambient vibration is calculated quantitatively assess grouting quality. A linear correlation between the grouting defect size and FFDD is observed to confirm the effectiveness of ambient vibration-based quantitative assessment using laser Doppler vibrometer in an in-situ setting.

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