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Study on the Variation of Vibration Characteristics in Rock Tunnels Depending on Ground Conditions and Tunnel Structures Using Ambient Vibration Measurements

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Abstract

This study investigates the vibration characteristics of rock tunnels using ambient vibration measurements, focusing on the effects of ground conditions and structural configurations. Although ambient vibration techniques have been widely applied to soil deposits, their application to rock tunnels remains limited due to small vibration amplitudes and the complex interaction between ground and structures.

Measurements were conducted in two tunnels in Japan under different geological and structural conditions. One tunnel was excavated but remained without lining and invert structures, while the other included sections with support, lining, and invert, allowing comparison of different construction stages. Fourier spectra and H/V spectral ratios were used to evaluate frequency characteristics.

The results indicate that vibration amplitudes inside the tunnel are significantly smaller than those outside, suggesting limited amplification within tunnels. In the excavated tunnel without structural components, dominant frequency peaks were not clearly identified, and spectral characteristics varied depending on location. In contrast, repeated measurements before and after invert installation indicate that structural conditions primarily affect vibration amplitude and spectral stability, as evidenced by the reduced spectral amplitudes and smoother H/V spectral ratios observed after invert installation.

These findings demonstrate that the predominant frequency is primarily governed by ground stiffness, whereas vibration amplitude and spectral stability are strongly influenced by structural conditions. The results highlight the importance of distinguishing between ground and structural effects when interpreting ambient vibration data in rock tunnels.

Keywords

Ambient vibration, Rock tunnel, Dynamic characteristics, Ground–structure interaction, H/V spectral ratio.

1 Introduction

Mountain tunnels are generally considered to have high seismic resistance due to the confinement effect of the surrounding ground. However, past earthquake events have reported damage in mountain tunnels, particularly in sections with unfavorable geological conditions or structural weaknesses. Therefore, understanding the dynamic characteristics of tunnel–ground systems is essential for rational seismic evaluation and maintenance of underground structures.

Ambient vibration measurement is a non-destructive and efficient technique that enables the evaluation of dynamic characteristics without interrupting tunnel operation. While this method has been widely applied to site characterization in soil deposits, its application to rock tunnels remains limited. This is mainly because vibration amplitudes in rock masses are relatively small and the dynamic response of tunnels involves complex interactions between surrounding ground and tunnel structures.

In addition, previous studies have mainly focused on either ground conditions or structural responses independently, and the combined influence of geological and structural factors on tunnel vibration characteristics has not been sufficiently clarified.

In this study, ambient vibration measurements were conducted in two mountain tunnels in Japan. One tunnel is in a completed state, while the other is under construction with varying structural conditions along the tunnel axis. These different geological and structural conditions provide a useful basis for evaluating their influence on vibration characteristics.

The objective of this study is to investigate the vibration characteristics of rock tunnels using ambient vibration measurements, focusing on the effects of ground conditions and tunnel structures. The dynamic characteristics were evaluated using Fourier spectra and H/V spectral ratios, and the governing factors of vibration behavior were discussed through comparative analysis.

2 Target tunnels and geological conditions

Two mountain tunnels in Japan were selected for this study, hereafter referred to as Tunnel A and Tunnel B.

Tunnel A is located in the southern part of Japan and has already been excavated through, although the lining has not yet been installed. The tunnel is constructed in sedimentary rocks of an accretionary complex of Paleogene age, consisting primarily of interbedded sandstone and mudstone. The surrounding ground is generally classified as soft rock with relatively low stiffness.

Tunnel B is currently under construction and is located in a mountainous area in the central part of Japan. The tunnel is excavated mainly in interbedded sandstone and mudstone formations and tuff breccia–mudstone alternations of Late Miocene age. The surrounding ground is classified as medium-hard to soft rock, showing moderate stiffness with locally heterogeneous features.

Fig.1 and Fig.2 present the geological longitudinal profiles of Tunnel A and Tunnel B, respectively, illustrating the variation of geological conditions along the tunnel axes. The locations of ambient vibration measurements conducted in this study are also shown in these figures.

In Tunnel B, multiple structural conditions are present along the tunnel axis due to the ongoing construction, including sections with only support, sections with lining, and sections where invert structures have been installed. In some sections, invert structures have not yet been installed, although they are planned to be installed along the entire tunnel length in the final design.

These different geological and structural conditions provide a useful basis for evaluating the influence of ground conditions and structural stiffness on the vibration characteristics of rock tunnels. This allows the influence of each factor to be discussed in a systematic manner.

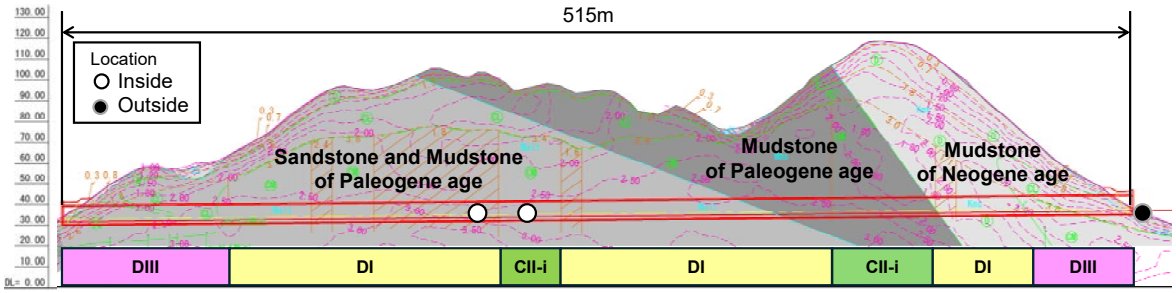


Fig. 1 Geological longitudinal profile of Tunnel A with measurement locations.

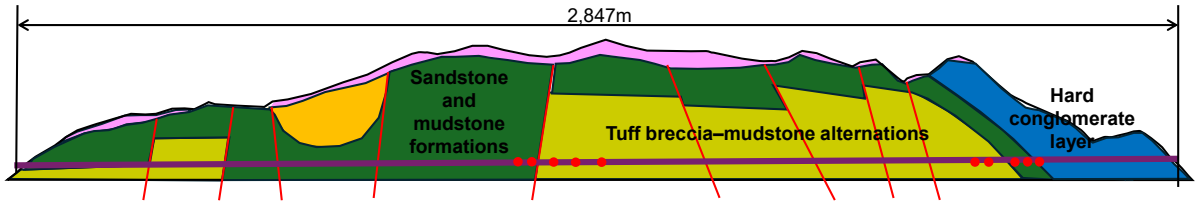


Fig. 2 Geological longitudinal profile of Tunnel B with measurement locations.

3 Measurement and analysis method

3.1 Measurement

Ambient vibration measurements were conducted in Tunnel A and Tunnel B to evaluate their dynamic characteristics. Velocity sensors were installed at representative locations within the tunnel cross-section as illustrated in Fig.3.

Measurements were carried out under ambient conditions without artificial excitation. The sampling frequency was set to 100 Hz for Tunnel A and 500 Hz for Tunnel B, and the duration of each measurement was approximately 10 minutes.

For Tunnel A, the natural frequency of the surrounding rock mass was assumed to be higher than 10 Hz, and the sampling frequency was determined accordingly. In contrast, no clear dominant frequency peak was identified in Tunnel B during preliminary observations. Therefore, a higher sampling frequency of 500Hz was adopted to capture a wider frequency range and to ensure reliable identification of frequency characteristics. This approach is consistent with the Nyquist criterion for frequency analysis.

In Tunnel B, measurements were conducted three times at different stages of construction. At selected measurement points (Support No.1345, No.1364, and No.1492), the first and second measurements were performed before the installation of the invert, whereas the third measurement was conducted after the invert had been installed.

The measurement locations were selected to represent different geological and structural conditions along the tunnel axis, as summarized in Table 1 and Table 2. Examples of the ambient vibration measurements are shown in Fig.3.

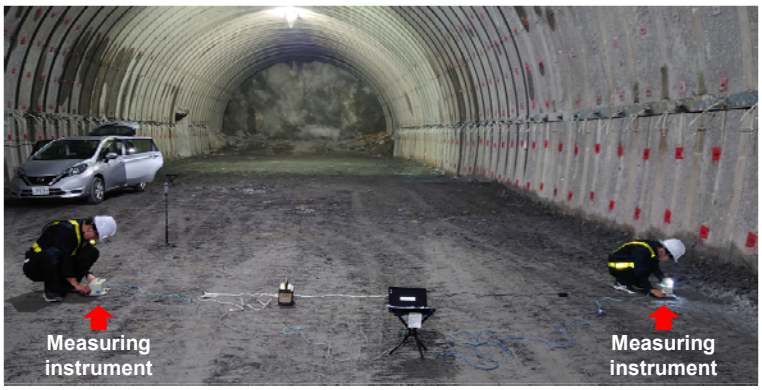


Fig. 3 Overview of ambient vibration measurements (A Tunnel).

Table 1. Summary of Tunnel A conditions and measurement locations.

Locations	Geological condition	Structural condition
Outside	Talus deposit	No
No.250	Sandstone–mudstone alternation	Support
No.300	Sandstone–mudstone alternation	Support

Table 2. Summary of Tunnel B conditions and measurement locations.

Locations	Geological condition	Structural condition
Lining Block 31	Hard conglomerate layer	Lining + Invert
Lining Block 33	Sandstone and mudstone formations	Lining + Invert
Lining Block 36	Sandstone and mudstone formations	Lining + Invert
Lining Block 41	Tuff breccia–mudstonealternations	Lining + Invert
Lining Block 45	Tuff breccia–mudstonealternations	Lining + Invert
Support No.1345	Tuff breccia–mudstonealternations	Support (+ Invert)
Support No.1492	Tuff breccia–mudstonealternations	Support (+ Invert)
Support No.1636	Sandstone and mudstone formations	Support
Support No.1655	Sandstone and mudstone formations	Support

3.2 Analysis

The recorded velocity time histories were processed to evaluate the frequency characteristics of the tunnel–ground system. First, the data were detrended and filtered to remove noise components.

Fourier spectra were calculated to identify dominant frequency components at each measurement location. The predominant frequency was determined based on the peak of the spectral amplitude. In addition, the horizontal-to-vertical (H/V) spectral ratio was computed to evaluate amplification characteristics and to further identify predominant frequencies.

These analyses were used to compare the vibration characteristics among different measurement locations and to examine the influence of geological and structural conditions on the dynamic behavior of the tunnels.

Although ambient vibration measurements were conducted in three directions, namely the transverse (X), longitudinal (Y), and vertical (Z) directions of the tunnels, only the transverse direction (X) is presented in this paper for clarity and consistency, as it is considered to be the most representative direction for evaluating tunnel deformation behavior.

4 Results and Discussion

4.1 Tunnel A

Fig. 4 shows the results of ambient vibration measurements in Tunnel A, including the velocity time histories and H/V spectral ratios.

The velocity time histories indicate that the vibration amplitudes inside the tunnel are significantly smaller than those outside. The maximum vibration velocity outside the tunnel is approximately 0.001–0.002 mm/s, whereas that inside the tunnel is around 0.0001 mm/s, corresponding to roughly one-tenth of the external amplitude. The waveforms are generally random, and no clear dominant periodic motion is observed.

The H/V spectral ratios show that, outside the tunnel, a peak appears at around 15–20 Hz, which is considered to be influenced by artificial sources such as drainage pump operation. In contrast, inside the tunnel, peaks are observed at approximately 1–3 Hz at both the sidewall and the tunnel center.

In the higher frequency range above 10 Hz, the spectral characteristics vary depending on the location. In some sections, random peaks are observed, whereas in others, the spectral ratio tends to be close to unity, particularly in the tunnel center.

These results suggest that the vibration characteristics inside the tunnel are influenced by both the surrounding ground conditions and the structural configuration.

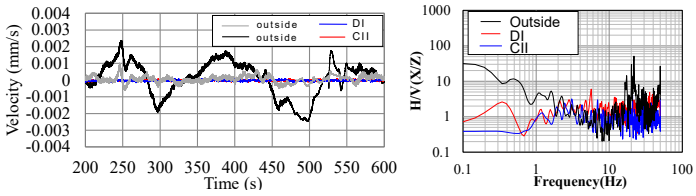


Fig. 4 Overview of ambient vibration measurements (A Tunnel).

4.2 Results of Tunnel B

Fig 5 to Fig 8 shows the results of ambient vibration measurements in Tunnel B, including Fourier spectra and H/V spectral ratios at different construction stages.

The Fourier spectra obtained at the measurement locations indicate that, in the sections with only support, the spectral amplitudes tend to be relatively large and distributed over a wide frequency range. Clear dominant peaks are not consistently observed, and the spectral shapes vary depending on the measurement location. In contrast, in the sections where lining and invert have been installed, the spectral amplitudes generally decrease, and the distribution becomes more stable. Although distinct peaks are still not always observed, the overall variability of the spectra is reduced compared to the support condition.

At specific measurement points (Support No.1345 and No.1492), a comparison of measurements conducted before and after invert installation shows that the vibration amplitude decreases after the installation of the invert. This trend is consistently observed across multiple locations.

The H/V spectral ratios also show differences between construction stages. In the support condition, the spectral ratios tend to fluctuate significantly, whereas in the lining and invert condition, the spectra become relatively smoother and more stable.

These results indicate that the decrease in spectral amplitude observed at Support No.1345 and No.1492 after invert installation reflects improved structural stiffness, whereas its influence on predominant frequency appears limited compared to that of ground conditions.

4.3 Governing factors of vibration characteristics

Based on the results obtained from Tunnel A and Tunnel B, it is evident that both ground conditions and structural configurations influence the vibration characteristics of rock tunnels.

The predominant frequency is mainly controlled by the stiffness of the surrounding ground, whereas the vibration amplitude and spectral stability are strongly affected by the structural condition of the tunnel.This distinction is clearly supported by the observed reduction in vibration amplitude following the installation of invert structures in Tunnel B.

Therefore, when interpreting ambient vibration measurements in rock tunnels, it is essential to distinguish between the effects of ground and structural conditions, particularly because the small amplitudes typically observed in rock tunnels may obscure clear spectral characteristics.

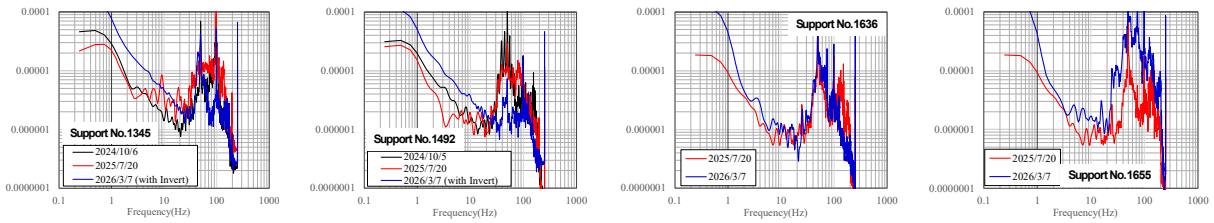


Fig. 5 Fourier spectra of Support(B Tunnel).

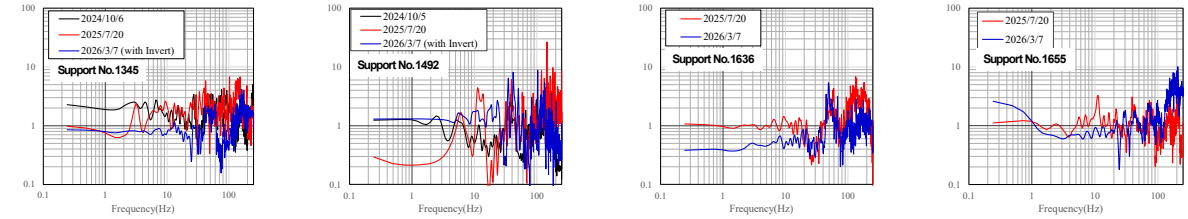


Fig. 6 Fourier spectra of Support(B Tunnel).

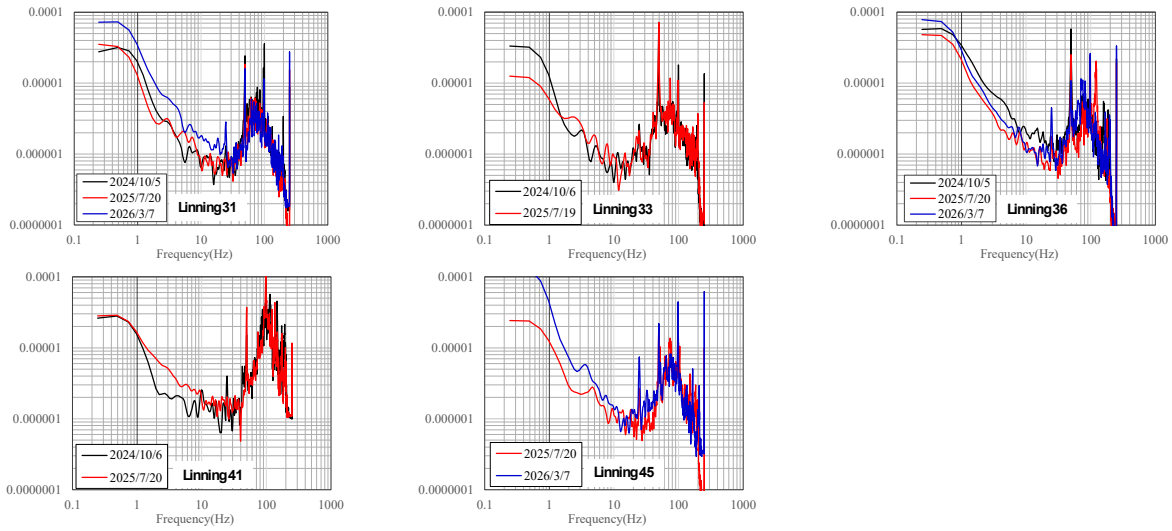


Fig. 7 Fourier spectra of Linig and Invert (B Tunnel).

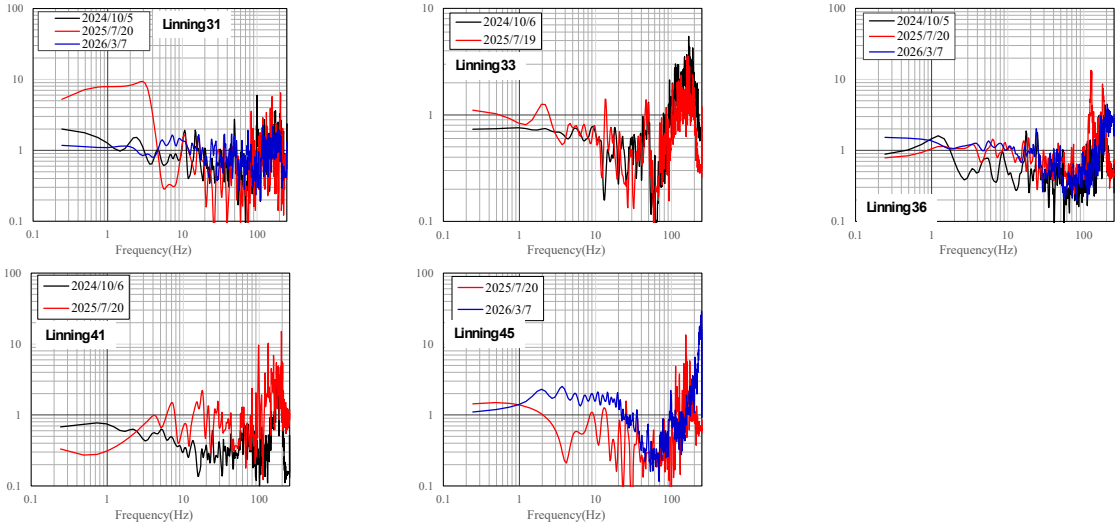


Fig. 8H/V spectral ratios of Linig and Invert (B Tunnel).

5 Conclusions

This study investigated the vibration characteristics of rock tunnels using ambient vibration measurements, focusing on the effects of ground conditions and structural configurations.

The results demonstrated that the vibration amplitudes inside the tunnel are significantly smaller than those outside, indicating that amplification effects within the tunnel are generally limited. Furthermore, the predominant frequency is primarily governed by the stiffness of the surrounding ground, whereas the vibration amplitude and spectral stability are strongly influenced by the structural condition of the tunnel. In particular, repeated measurements at the same locations revealed that the installation of invert structures leads to a reduction in vibration amplitude and a stabilization of spectral characteristics.

These findings highlight the importance of distinguishing between the effects of ground and structural conditions when interpreting ambient vibration data in rock tunnels. The proposed approach is expected to contribute to the rational evaluation of tunnel behavior and its application to seismic assessment and maintenance.

As future work, continuous measurements under different geological and structural conditions are required to improve the reliability of ambient vibration-based evaluations and clarify their influence on tunnel vibration characteristics.