ATTENUATION PROPERTIES OF GROUND VIBRATION PROPAGATED FROM SHINKANSEN TUNNELS

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Attenuation properties of train-induced ground vibration propagated from Shinkansen mountain tunnels were investigated based on field measurement. Vibration accelerations both in the tunnels and on the ground were measured at four locations during train passage with train speed up to 240km/h. The attenuation in the ground was investigated every 1/3 octave band based on the measurement data. The results show that attenuation in the ground is clear at high frequency range and tends to become large with frequency. The attenuation properties were investigated based on logarithmic regression equation and Bornitz formula. This paper shows the relational equation between frequency and coefficient of logarithmic regression equation, as well as that between frequency and material damping coefficient $\alpha$. The attenuation properties were also compared with that of shield tunnels of underground railway.

Keywords: Ground vibration, High-speed rail, tunnel, attenuation properties

1. Introduction

Ground-borne noise and vibration caused by passing trains in Shinkansen mountain tunnels are sometimes perceived in near-by buildings. Although the level of noise and vibration is normally small as compared with those caused by train passage on the ground or viaducts, they may pose a problem in residential buildings and facilities requiring silence and freedom from vibration. In this case, it is required to properly predict vibration attenuation in the ground.

Numerical calculation is an effective tool to predict the vibration attenuation in the ground. However, a simpler prediction method is desired at the schematic design stage, in which soil properties required for numerical calculation are not available yet and ground-borne noise and vibration needs to be roughly estimated at many locations. This research therefore investigates the attenuation properties based on the field measurement and proposes the simple prediction method of vibration attenuation in consideration of frequency characteristics.

2. Field measurement

2.1 Outline of field measurement

2.1.1 Measurement location

This research carries out field measurement at four locations in Japan [1-4]. The conditions of measurement locations are shown in Table 1. The tunnels are located in gravel layer at the location
A and B and in layer of pyroclastic flow or mudflow deposit at the location C and D. The depth of cover is 4.6 to 23.1. Slab tracks are applied.

<table>
<thead>
<tr>
<th>Measurement location</th>
<th>Cover depth</th>
<th>Train speed</th>
<th>Number of measurement positions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location A</td>
<td>4.6 m</td>
<td>200 - 240 km/h</td>
<td>5</td>
</tr>
<tr>
<td>Location B</td>
<td>23.1 m</td>
<td>200 - 240 km/h</td>
<td>6</td>
</tr>
<tr>
<td>Location C</td>
<td>5.5 m</td>
<td>190 - 210 km/h</td>
<td>5</td>
</tr>
<tr>
<td>Location D</td>
<td>9.2 m</td>
<td>190 - 210 km/h</td>
<td>7</td>
</tr>
</tbody>
</table>

Figure 1: Measurement position (Tunnel)

Figure 2: Measurement position (Ground surface)
2.1.2 Measurement and analysis method

Vibration acceleration is simultaneously measured both in the tunnels and on the ground surface with piezoelectric accelerometers, charge amplifiers and data recorders. Figs. 1 and 2 show measurement positions in the tunnels and on the ground surface, respectively. In the tunnels, steel cubes with piezoelectric accelerometers are fixed on tunnel lining and track bed. On the ground surface, steel plates are also fixed with plaster of Paris on soil or with epoxy adhesive on pavement. Vibration acceleration is measured in the tangential or vertical direction (Z-direction) and occasionally in the radial or horizontal direction (Y-direction).

The measured acceleration data during train passage are analysed with a 1/3 octave band analyser at time constant of 0.63 sec. Average levels are calculated after eliminating the data strongly influenced by wheel damage, background and other obstacles.

2.2 Measurement results

2.2.1 1/3 octave band spectrum

1/3 octave-band spectra are shown in Fig. 3, in which the reference value of vibration acceleration level is $10^{-5}$ m/s$^2$ according to the rule and regulation of vibration level meter in Japan.

The vibration acceleration spectra in the tunnels have wide-range frequency components including high frequency ones more than 100Hz. On the other hand, the spectra on the ground surface have absolute peaks from 63 to 80Hz. In these figures, it is observed that the high frequency components more than 100Hz, which are observed in the tunnels, attenuate in the ground.

![Figure 3: Vibration acceleration level in 1/3 octave band (ref $10^{-5}$m/s$^2$)](image)

(a) Location A

(b) Location B

Figure 3: Vibration acceleration level in 1/3 octave band (ref $10^{-5}$m/s$^2$)
2.2.2 Attenuation in the ground

The attenuation in the ground is investigated for every 1/3 octave band based on the measurement data. Relative acceleration level $\Delta L_{VA}$ (dB) is defined as;

$$\Delta L_{VA}(f) = L_{VA}(f) - L_{VA0}(f)$$

where $L_{VA}(f)$ (dB) is vibration acceleration level in the vertical direction of ground surface at $f$ (Hz), $L_{VA0}(f)$ (dB) is the level at reference point in tunnels at $f$ (Hz) and $f$ (Hz) is 1/3 octave band centre frequency. Reference points are set up on the upper part of sidewall on the radial (Y) direction. Fig. 4 shows the relationship between frequency and relative acceleration level. The attenuation in the ground becomes larger with increasing frequency.

![Graphs showing attenuation in the ground](image)

Fig. 4: Relative acceleration level in 1/3 octave band

Fig. 5 shows the relationship between the propagation distance and relative acceleration level at the bands of 31.5, 63 and 125Hz. Propagation distance is defined as shown in Fig. 6 in this research. At 31.5Hz, some plots show positive values, which indicates amplification, and distance attenuation is not clear. On the other hand, the distance attenuation is observed at 63 and 125Hz. The figures show that distance attenuation becomes clearer as frequency increases.
3. Prediction method of attenuation in the ground

3.1 Logarithmic regression formula

The attenuation properties in the ground are analysed based on the following logarithmic regression equation;

\[ L_{VA}(f) - L_{VA0}(f) = -A \log_{10}\left( \frac{R}{R_0} \right) \]  

where \( L_{VA}(f) \) (dB) is vibration acceleration level in the vertical direction of ground surface at \( f \) (Hz), \( L_{VA0}(f) \) (dB) is the level at reference point in tunnels at \( f \) (Hz), \( f \) (Hz) is 1/3 octave band centre frequency, \( A \) is a coefficient regarding vibration attenuation in the ground, \( R \) (m) is the propagation distance and \( R_0 \) (m) is the distance from the source to the reference point. The value of \( R_0 \) is assumed to be 1.0m in this research.

The coefficient \( A \) is calculated with respect to each 1/3 octave band and each measurement site by means of the least square method based on the relationship between the propagation distance and relative acceleration level. Fig. 7 shows the relationship between frequency and average coefficient \( A \) and suggests that the coefficient \( A \) becomes larger with increasing frequency.
The following equation is obtained with a regression analysis for the vibration attenuation from Shinkansen mountain tunnels.

$$A = 0.18 f$$

Fig. 8 makes a comparison of coefficient $A$ between the Shinkansen mountain tunnels and shield tunnels of underground railway [5]. The results of mountain tunnels denote the same tendency of those of shield tunnels in the sense that the coefficient $A$ becomes larger with increasing frequency.

### 3.2 Empirical equation

#### 3.2.1 Fundamental equation

To investigate the attenuation properties in the ground, the following equation is applied as a fundamental equation [6];

$$U_R = U_0 e^{-\alpha (R - R_0) \left( R / R_0 \right)^n}$$

where $U_R$ is vibration amplitude at the point of distance $R$, $U_0$ vibration amplitude at the reference point, $n$ the geometrical damping coefficient, $\alpha$ the material damping coefficient, $R$ propagation distance from the reference point and $R_0$ distance from the source to the reference point. The equation takes into account both geometrical and material damping.

The geometrical damping coefficient $n$ is assumed to be 0.5 in this research, considering that tunnels are infinitely long structures existing in the ground and vibration propagated from tunnels is body wave from buried line source. The equation (4) is changed to the following one by representing it in vibration acceleration levels in the 1/3 octave bands (dB);

$$L_{A3}(f) - L_{A30}(f) = -10 \log_{10}(R / R_0) - 8.68 \alpha f (R - R_0)$$

![Figure 7: Relationship between frequency and coefficient A](image1.png)

![Figure 8: Comparison of coefficient A between Shinkansen mountain tunnels and underground shield ones](image2.png)
where $L_{VA}(f)$ (dB) is vibration acceleration level in the vertical direction of ground surface at $f$ (Hz), $L_{VA0}(f)$ (dB) is the level at reference point in tunnels at $f$ (Hz), $f$ (Hz) is 1/3 octave band centre frequency, $R$ (m) is the propagation distance, $R_0$ (m) is the distance from the source to the reference point and $\alpha(f)$ is material damping coefficient at $f$ (Hz).

### 3.2.2 Investigation of material damping coefficient $\alpha$

The material damping coefficient $\alpha$ is calculated with respect to each 1/3 octave band and each measurement site. As there are multiple measurement points on the ground surface, the values of $\alpha$ are calculated by means of a regression analysis. Fig. 9 shows the relationship between frequency and material damping coefficient $\alpha$ with respect to each measurement location. This figure indicates that the values of $\alpha$ tend to increase with increasing frequency. Most of material damping coefficient $\alpha$ is negative in the frequency band of 16 to 40Hz with comparatively short wave length.

The average values of $\alpha$ at four locations are calculated with respect to each 1/3 octave bands. Fig. 10 makes a comparison of material damping coefficient $\alpha$ between the Shinkansen mountain tunnels and shield tunnels of underground railway [5]. The results of mountain tunnels roughly corresponds to those of shield tunnels.

#### Figure 9: Relationship between frequency and material damping coefficient $\alpha$

![Figure 9: Relationship between frequency and material damping coefficient $\alpha$](image)

#### Figure 10: Comparison of material damping coefficient $\alpha$ between Shinkansen mountain tunnels and underground shield ones

![Figure 10: Comparison of material damping coefficient $\alpha$ between Shinkansen mountain tunnels and underground shield ones](image)

### 3.2.3 Relational equation between material damping coefficient $\alpha$ and frequency

As it is observed that the material damping coefficient $\alpha$ is correlated with frequency as described in Fig. 10, the $\alpha$ is expressed as a function of frequency as;

$$\alpha = af - b$$  \hspace{1cm} (6)

where $\alpha$ is material damping coefficient, $f$ (Hz) frequency and $a$ and $b$ positive constant.
Fig 10 shows the average values of $\alpha$ at four locations. The coefficients of $a$ and $b$ are decided to be 0.001 and 0.06 respectively by a regression analysis, and the following equation regarding the material damping coefficient $\alpha$ and frequency $f$(Hz) is obtained.

$$\alpha = 0.001f - 0.06$$

(7)

The attenuation in the ground can be predicted by using the equations (5) and (7).

4. Conclusion

The attenuation properties of ground vibration propagated from Shinkansen mountain tunnels are investigated based on the field measurement data at four locations. The following conclusions are derived.

1) Vibration acceleration spectra in the tunnels have wide-range frequency components including high frequency ones above 100Hz, while those on the ground surface have peaks at 63 to 80Hz.
2) Attenuation in the ground becomes larger with increasing frequency. Distance attenuation also becomes clearer as frequency is higher.
3) Coefficient $A$ in logarithmic regression equation is calculated with respect to each 1/3 octave band based on the measurement data and becomes larger with increasing frequency. Relational equation between frequency and coefficient $A$ is obtained.
4) The material damping coefficient $\alpha$ with respect to each 1/3 octave band is calculated and became larger with increasing frequency. The relational equation between frequency and material damping coefficient $\alpha$ is proposed for Shinkansen mountain tunnels. This equation enables calculation of the vibration attenuation in 1/3 octave bands with the empirical equation considering geometrical and material damping.

REFERENCES