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# Ground-born vibration at multileveled train tunnel crossing

Hoon-Ki Moon[1a], Kang-Hyun Kim[2b], Ho-Jong Kim[3c] and Jong-Ho Shin[*2]

[1]*Dasan consultants, Songi-ro 30-gil, Songpa-gu, Seoul 05800, Republic of Korea*
[2]*Department of Civil Engineering, Konkuk University, 120 Neungdong-ro, Gwangjin-gu, Seoul 05029, Republic of Korea*
[3]*Disaster Prevention Research Division, National Disaster Management Research Institute, Ulsan, Republic of Korea*

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**Abstract.** In recent railway projects where the railway connects between cities, newly planned tunnels are often located close to, or beneath an existing tunnel. Many claims and petitions have voiced public concern about the vibration and noise resulting from the situation. Vibrations and noises are engineering issues as well as environmental problems, and have become more important as people have become more concerned with their the quality of life. However, it is unlikely that the effects of vibration in situations where trains simultaneously pass a multileveled tunnel crossing have been appropriately considered in the phase of planning and design. This study investigates the superposition characteristic of ground-born vibrations from a multileveled tunnel crossing. The results from model tests and numerical analysis show that the ground-born vibration can be amplified by a maximum of about 30% compared to that resulting from the existing single tunnel. Numerical parametric study has also shown that the vibration amplification effect increases as the ground stiffness, the tunnel depth, and the distance between tunnels decrease.

**Keywords:** train-induced vibration; tunnel crossing; vibration superposition; model test; numerical analysis

## 1. Introduction

Complex underground-railway networks operate in many metropolitan cities. High speed railways connecting cities are often planned below the existing underground railways. In this case, situations where tunnels are multilevel-crossed can occur and the ground-born vibration generated by trains is problematic for residents adjacent to the tunnel crossing (Do *et al*. 2014, Djelloul *et al*. 2018, La *et al*. 2018). Sometimes, serious social conflicts between residents and project owners can be raised. However, it is worth noting that some tunnel crossings are important transfer stations, which means the train speed is slow and the vibration superposition effect is negligible.

Theoretically, when two same vibration waves propagate from vibration sources at different locations, the vibrations can be either amplified or cancelled out according to the principle of superposition and interference of waves in the area where they meet. This phenomenon is termed as ‘beating’ or ‘undulation’ and the one dimensional equation can be expressed:

$$\begin{aligned} y(x,t) &= y_m \sin(kx-\omega t) + y_m \sin(kx-\omega t+\phi) \\ &= 2y_m \cos(\frac{\phi}{2})\sin(kx-\omega t+\frac{\phi}{2}) \end{aligned} \quad (1)$$

where $x$ is the propagation axis, $t$ is time, $k$ is angular wave number, $y_m$ is amplitude, $\omega$: angular frequency and $\phi$ is phase angle. However, if the frequencies of the waves are slightly different, the superposition effect will be changed and the amplitude of the superposed wave can be written as:

$$y(x,t) = y_m \cos\left\{\frac{(k_1-k_2)x-(\omega_1-\omega_2)t}{2}\right\}\sin\left\{\frac{(k_1+k_2)x-(\omega_1+\omega_2)t}{2}\right\} \quad (2)$$

where the subscripts 1 and 2 indicate the waves propagating to the same direction from vibration sources at different locations: Eq. (2) means that he superposed wave has short period of cosine wave within long period of sine wave of which amplitude is almost doubled. If the amplitude of superposed wave exceeds safety criteria, then damages to structures may occur. Therefore the vibration amplification due to wave superposition can be concerned, and the multi-leveled tunnel crossing can have such problem when trains pass simultaneously.

The problems of vibrations in railway tunnels have been generally studied for a single tunnel using theoretical approaches, field measurements, laboratory tests (Aiello *et al*. 2008, Chatterjee *et al*. 2003, Huang *et al*. 2015, Koch 1979, Qian and Wen-Jun 2016, Yuksel and Kalkan 2007, Kwak *et al*. 2018), empirical methods (Kurzweil 1979, Pan and Xie 1990, Trochides 1991) and numerical methods (Balendra *et al*. 1991, Gupta *et al*. 2010, Hung and Yang 2010, Yang and Hung 2008, Wang *et al*. 2012, Yao *et al*. 2016, He and Koizumi 2001, Farghaly and Kontoni 2018). Xia *et al*. (2007) studied the vibration amplification of ground-born vibration due to the train in a tunnel in the various subsoil conditions using numerical method. They

*Corresponding author, Professor
E-mail: jhshin@konkuk.ac.kr
[a] Managing Editor
E-mail: moonhk@dasan93.co.kr
[b] Ph.D. Student
E-mail: kkl853fh@konkuk.ac.kr
[c] Senior Researcher, Ph.D.
E-mail: dutuby@korea.kr


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pointed out that the maximum acceleration found on the ground surface along the tunnel axis and the vibration amplification occurred in a certain area away from the tunnel axis on the surface.

The vibration problems at the tunnel crossing are three-dimensional, and have not been sufficiently studied due to various uncertainties such as composition of soil strata, the presence of underground structures, and the complexities in ground boundary conditions. The train vibration at a tunnel crossing has characteristics of irregular multi-sources, and is very difficult to simulate theoretically and numerically. Because a situation might occur in which trains pass simultaneously at the tunnel crossing, it is important to investigate the effect of vibration superposition. Neither practical regulation nor an evaluation method on the effect of vibration superposition when trains simultaneously pass the tunnel crossing has been reported yet. Moreover, research on the superposition effect of vibrations for crossing tunnels is hardly found. This study investigated the superposition characteristic of vibrations and the engineering significance of the vibration amplification at the tunnel crossing.

## 2. Numerical modeling

### *2.1 Numerical analysis method*

Because the wave propagation problem in rock mass can be modeled in small strain ranges, elastic behavior is generally assumed. In this study the mode superposition method of the time history analysis was adopted in solving the dynamic equations. This analysis requires free vibration analysis to decide mode shape and natural frequency. To perform the time history analysis, the modal superposition method which requires un-damped free vibration analysis to obtain mode shape and natural period is adopted.

$$[K]\Phi_n = \omega_n^2 [M]\Phi_n \tag{3}$$

where $[K]$: stiffness matrix, $[M]$: mass matrix, $\omega_n^2$: nth natural frequency (eigenvalue), $\Phi_n$: nth mode vector. The dynamic equilibrium equations can be rewritten and solved in terms of mode shape:

$$\Phi^T [M]\Phi\ddot{q}(t) + \Phi^T [C]\Phi\dot{q}(t) + \Phi^T [K]\Phi q(t) = \Phi^T p(t) \tag{4}$$

$$u(t) = \sum_{i=j}^{m} \Phi_i q_i(t) \tag{5}$$

where $\Phi_i$: $i$th mode shape and $q_i(t)$: solution for the $i$th shape.

The viscous boundary proposed by Lysmer and Waas (1972) were adopted to represent the geometric attenuation by which waves are propagated to the outside without returning to the model. The following damping coefficients are introduced at the model boundaries to consider the wave attenuation.

In normal direction,

$$C_p = \rho A \sqrt{\frac{\lambda + 2G}{\rho}} = WA\sqrt{\frac{\lambda + 2G}{9.81W}} \tag{6}$$

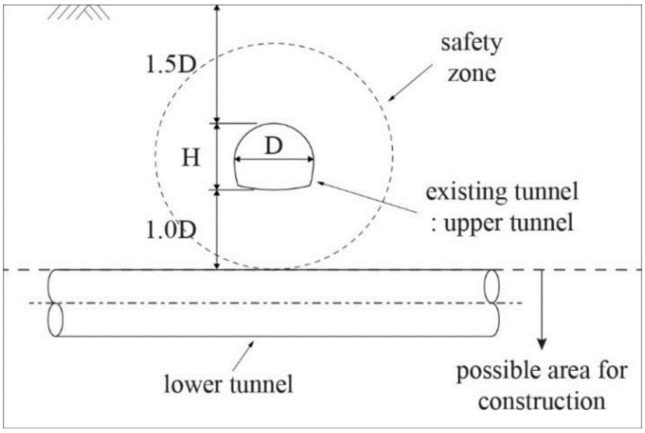



Fig. 1 Typical tunnel profile at the tunnel crossing

In shear direction,

$$C_s = \rho A \sqrt{\frac{G}{\rho}} = WA\sqrt{\frac{2G}{9.81W}} \tag{7}$$

where $\rho$: mass density, $W$: unit weight, $\lambda$: volume elastic modulus, $G$: shear elastic modulus, and $A$: cross section area.

### *2.2 Tunnel profile at the crossing and input train loads*

The location of the new tunnel to be constructed under the existing tunnel is greatly limited in order to secure the stability of the existing and operating tunnels. In many cases, the excavation of a newly constructed tunnel within 1D of an existing tunnel is not permitted, in order to prevent damage during excavation, as shown in Fig. 1.

Railway vibration is a repetitive loading generated by rolling friction between the wheels and the rail track, and its vibration frequency is dependent on the interval of rail segment and train velocity. Railway vibration propagates to the ground through the track concrete and ground base. The ground-born vibration from railway tunnels is generally measured in the range of 40-100Hz (Shin 2009).

It is important to evaluate the train load reliably to reasonably predict vibrations due to the train tunnel. However, it is not easy to obtain the time history of the train load, as various uncertainties exist in the vibrating system.

In this study, the train load was evaluated by applying the input identification technique that can reversely calculate the train load from the measured train vibrations (Shin 2009). The input identification analysis was performed through trial and error approach to determine the time history of the train load. In this approach, the following equation needs to be satisfied for the linear structural system.

$$U(\omega) = H(\omega) \cdot P(\omega) \tag{8}$$

where $U(\omega)$ and $P(\omega)$ are the Fourier spectrum of response and input load respectively, and $H(\omega)$ represents the frequency response function of the structural system according to unit load. After the frequency response

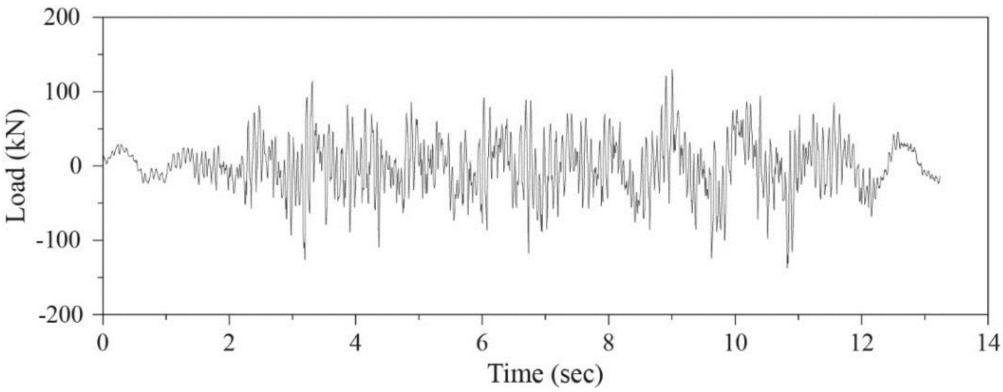
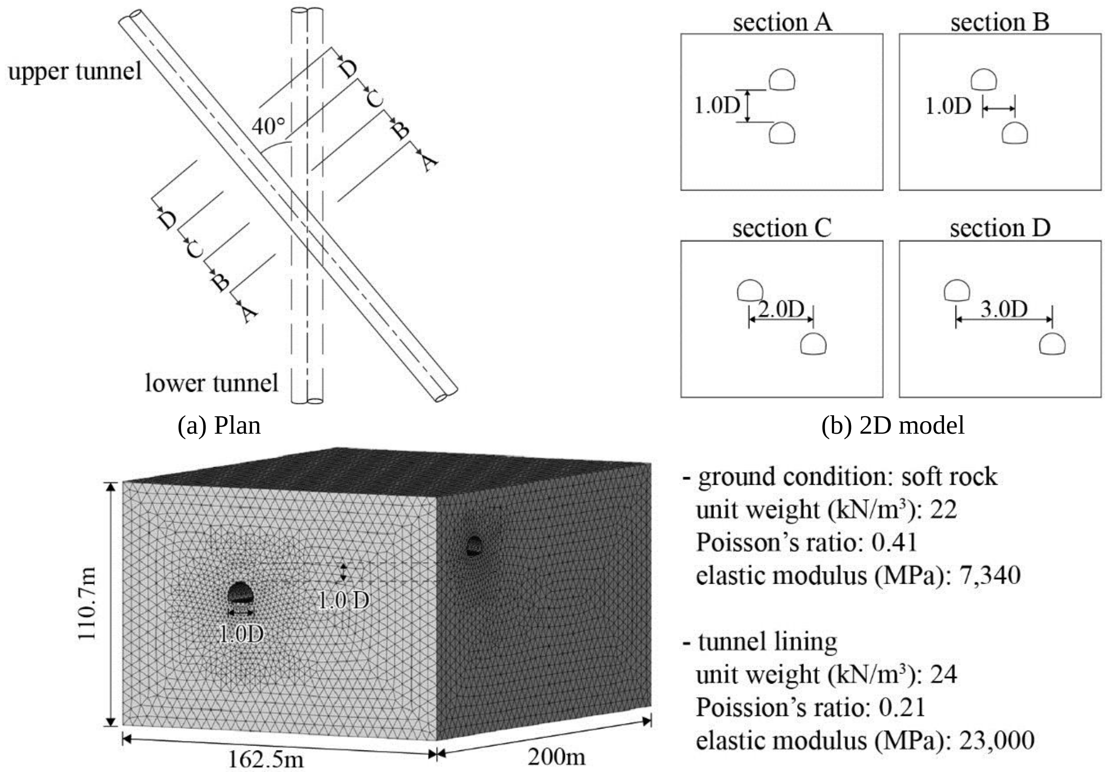


Fig. 2 Train loads on tracks



(a) Plan (b) 2D model

(c) 3D model

Fig. 3 Modeling of tunnel crossing

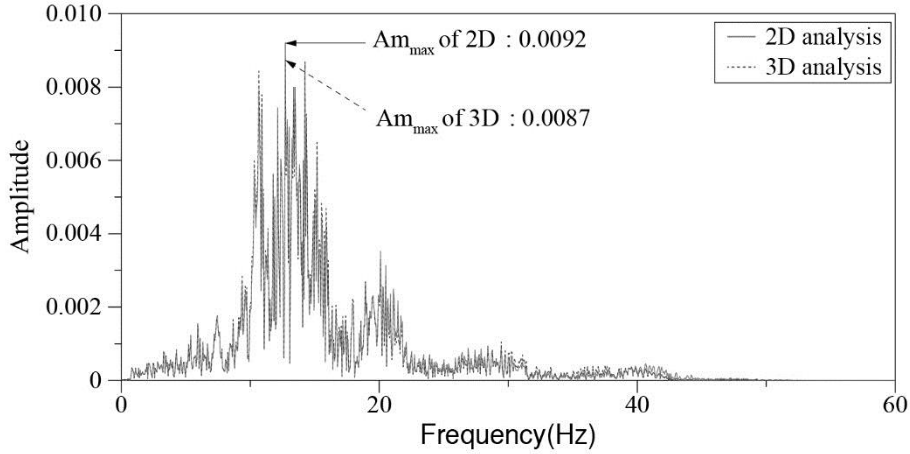
function of the structural system by unit load and Fourier spectrum of measured response have been obtained, the input train load $P(\omega)$ can be calculated. Fig. 2 shows the 2D input load determined by this method

At a tunnel crossing, a new tunnel is usually constructed under the existing railway tunnel. Assuming each tunnel houses a double track, the worst case is that where four trains pass simultaneously, two on the upper and two on the lower tunnels.

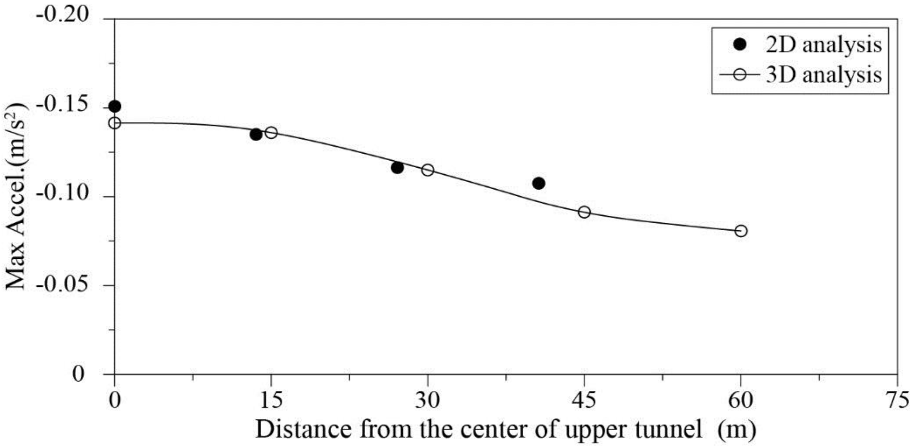
### *2.3 2D and 3D modeling*

The problem of ground vibration at the crossing section of tunnels is obviously a problem requiring three-dimensional analysis. However, three-dimensional. modeling requires excessive effort and computer resources. If 2D analysis could replace 3D analysis, it is possible to save the time and cost. In order to investigate an appropriate engineering modeling method, both 2D and 3D analyses were carried out. The ground conditions considered in this study are chosen from typical ground profiles of Seoul area, and the tunnel is set to the standard cross section of Seoul Metro (D = 10.6 m) (Shin *et al.* 2013). The situation shown in Fig. 3(a) was considered as an analysis model where a new tunnel crosses 1.0D below the bottom of the upper tunnel at the intersection angle of about 40°.

Fig. 4(a) presents the 2D and 3D analysis results at the ground surface of the tunnel center (section A). Both results show very similar patterns in frequency and amplitude. The maximum vertical acceleration from 3D analysis is slightly lower than that of 2D analysis by about 5%.




(a) Results at the ground surface of the tunnel center (section A, $Am_{max}$: maximum amplitude)




(b) Maximum ground-born acceleration

Fig. 4 Comparison of 2D and 3D results

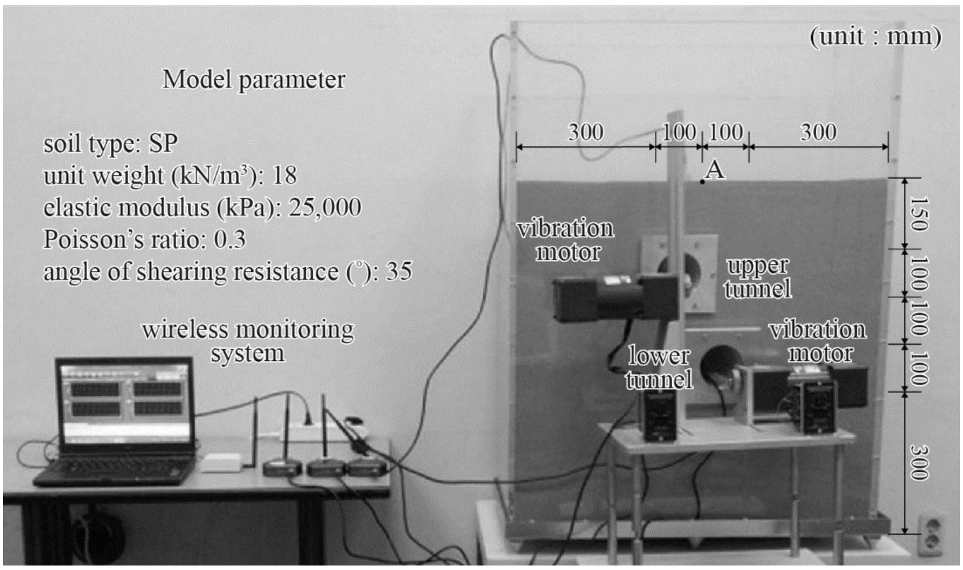
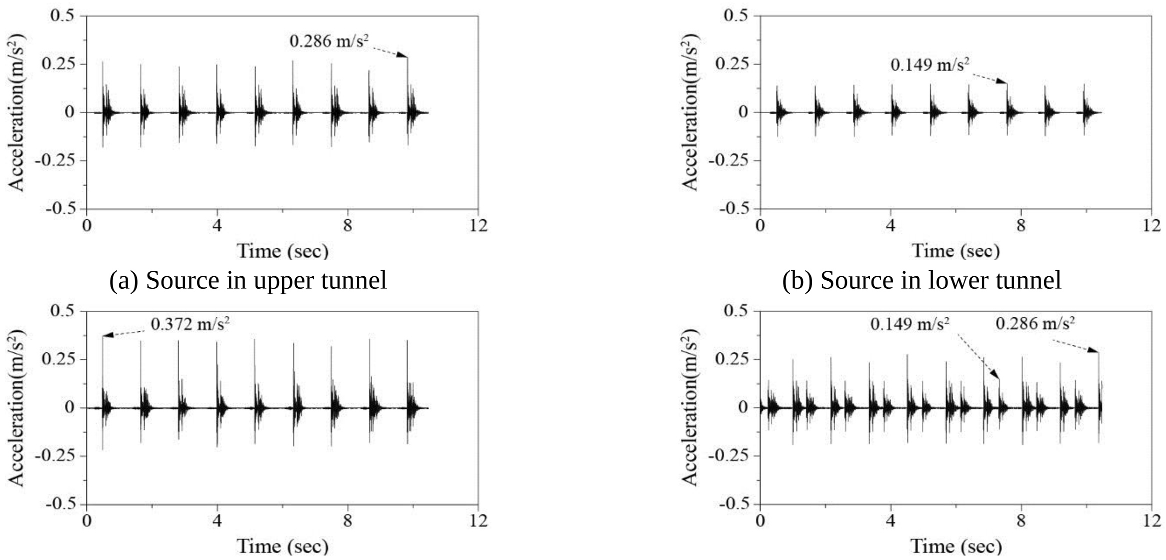



Fig. 5 Test model

Fig. 4(b) compares the maximum vertical accelerations along the lateral distance from the center of the upper tunnel. 3D analysis using the model shown in the Fig. 3(a) and 2D analysis of 4 sections shown in Fig. 3(b) were performed. The results agree well in general and indicate that three-dimensional behavior can be reasonably




(a) Source in upper tunnel

(b) Source in lower tunnel

(c) Source in both upper and lower tunnel

(d) Effect of phase difference

Fig. 6 Ground-born acceleration (location A)

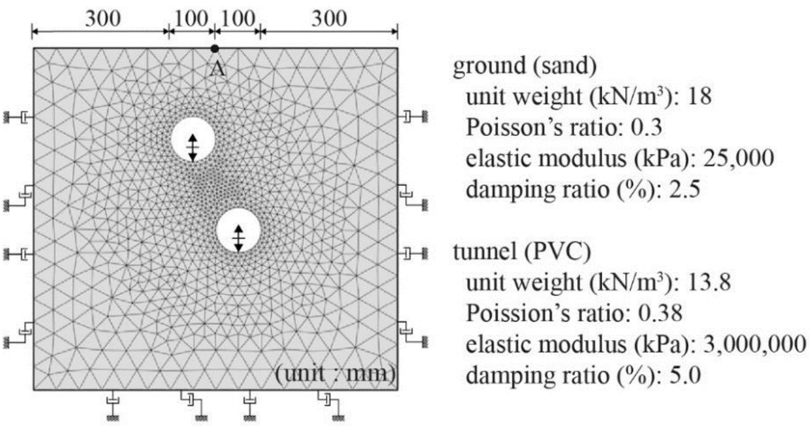



Fig. 7 Modeling of model test

simulated in two-dimensions by applying the input load per unit width.

### *2.4 Validation of numerical modeling using model tests*

To investigate the superposition characteristic of vibration between trains in two tunnels and to evaluate numerical modelling performance, simple model test simulating the parallel tunnels crossing is devised. Fig. 5 shows the test set up. A soil container with the dimensions of width 800mm, depth 400mm, and height 1,100mm was prepared by using transparent acryl plates. The ground was made from sand, and PVC pipes with 100mm diameter were used for tunnels. The depth of the upper tunnel was 150mm, which is one and a half times the diameter of the tunnel. A vibration absorber (non-woven fabric) was installed at the boundaries between the ground and the container to simulate the vibration attenuation through the ground.

The arrangement of soil particles can be changed as the test proceeds since sand tends to be compacted during vibration. In order to eliminate this effect, the initial state of the ground was compacted as close as possible to the minimum void ratio so that volume change does not occur during the test.

The vibrations caused by the railway system were observed in a wide range from low frequencies of 0.5-1.0Hz generated by train cars to high frequencies of 30-60Hz generated by rail tracks. The vibration source of the model test simulates the vibration of the train car. A test with a simultaneous vibration both in the upper and lower tunnels was carried out. Ground-born vibration was measured by using a wireless receiver at the center of the two tunnels on the ground surface.

Fig. 6 shows the measured ground-born accelerations at point A for each test case. The maximum acceleration showed 0.286m/s$^2$ when vibrations were loaded only at the upper tunnel, 0.149m/s$^2$ when vibrations were loaded only at the lower tunnel, and 0.372m/s$^2$ when vibrations were loaded at both the upper and lower tunnels. The effect of superposition of simultaneous vibrations of neighboring tunnels was increased by a maximum of 30% compared to the case of the upper tunnel only. Fig. 6(d) shows the

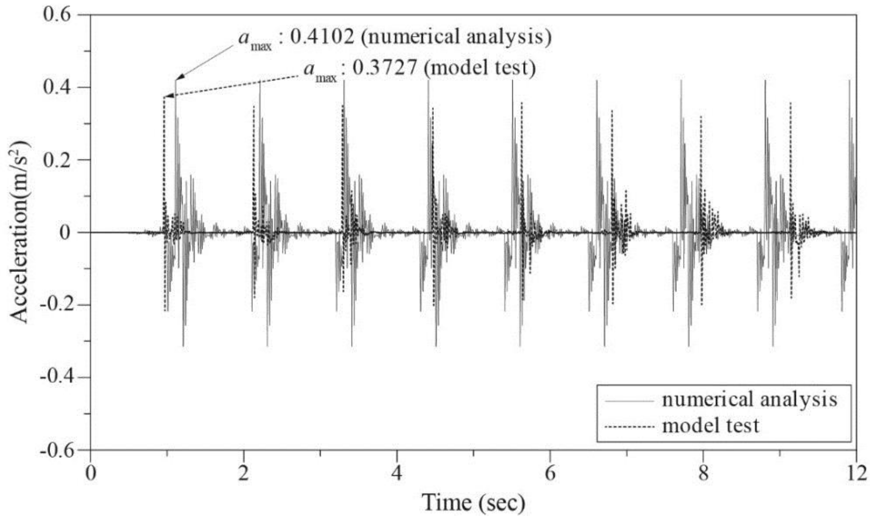



Fig. 8 Numerical simulation of model test ($a_{max}$ : maximum acceleration)

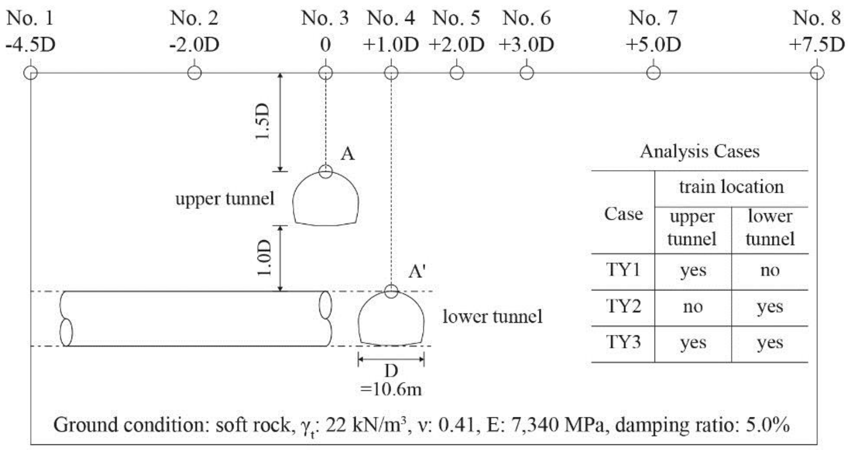



Fig. 9 Model for typical analysis and analysis cases

ground-born acceleration when the phase difference (0.65sec) between upper and lower tunnels is given. In this case, the effect of superposition is hardly shown.

Although the model test does not fully represent the multi-source vibration of real trains, the results confirm that when two trains with the same vibration period and phase pass simultaneously at the tunnel crossing, significant amplification of vibration can occur.

The two-dimensional modeling method proposed in the previous section is first applied to simulate the model test. Fig. 7 shows the numerical model of the model test. The ground was modeled with a plane strain solid element, and the tunnel was modeled with an elastic beam element.

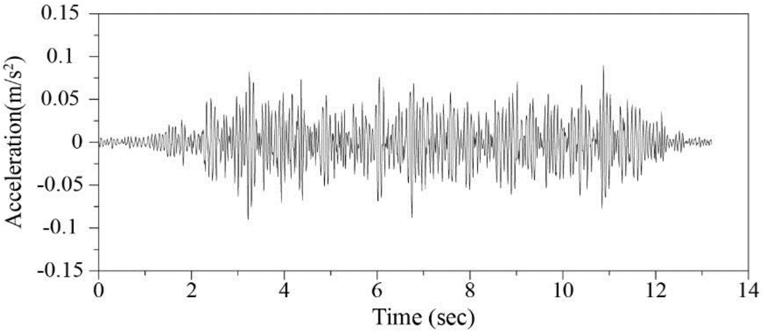
Since the three-dimensional conditions of the model test were modeled in two dimensions, the determination of input vibration is of significance. The input vibration of the 2D numerical analysis was evaluated by carrying out several tentative analyses applying the source only on the upper tunnel. The vibration load which gives the same results as those of the model test was determined for the input load. Further analysis was then performed by applying the load to both the upper and lower tunnels simultaneously.

Fig. 8 shows a comparison of the results from numerical analysis and the model test for the simultaneous vibration in both tunnels. The result of the numerical analysis was greater than that of the model test measurement by about 10% at point A. The difference seems to have resulted from the idealized boundary conditions applied to numerical analysis. Despite the modeling limit, it can be generally concluded that the vibration superposition behavior at the tunnel crossing can be reasonably represented through the 2D numerical modeling method.

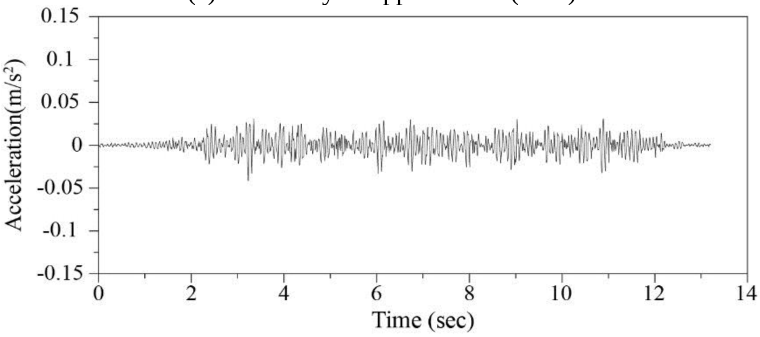
## 3. Representative analysis

### *3.1 Analysis model*

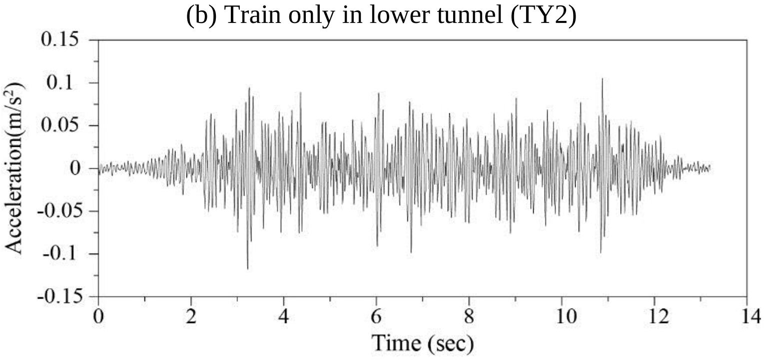
A tunnel crossing in the Seoul metropolitan area was considered for the typical analysis (Shin *et al.* 2011). The vertical and horizontal distances between tunnels are 1.0D, and the ground condition was assumed to be soft rock. Fig. 9 shows the cross-section at the tunnel crossing. Each tunnel has double tracks, and it is assumed that four trains pass through the inbound and outbound tunnels simultaneously. Three case of analysis were carried out



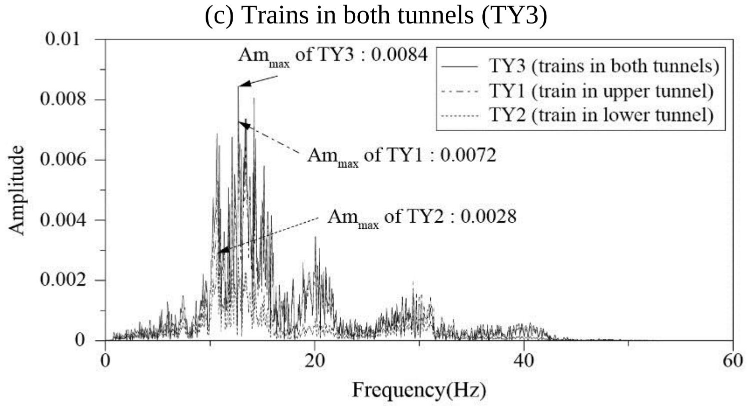

(a) Train only in upper tunnel (TY1)




(b) Train only in lower tunnel (TY2)




(c) Trains in both tunnels (TY3)




(d) Frequency domain

Fig. 10 Ground-born vibration at the surface (at No.3)

including trains only in each of the upper and lower tunnels and trains in both tunnels.

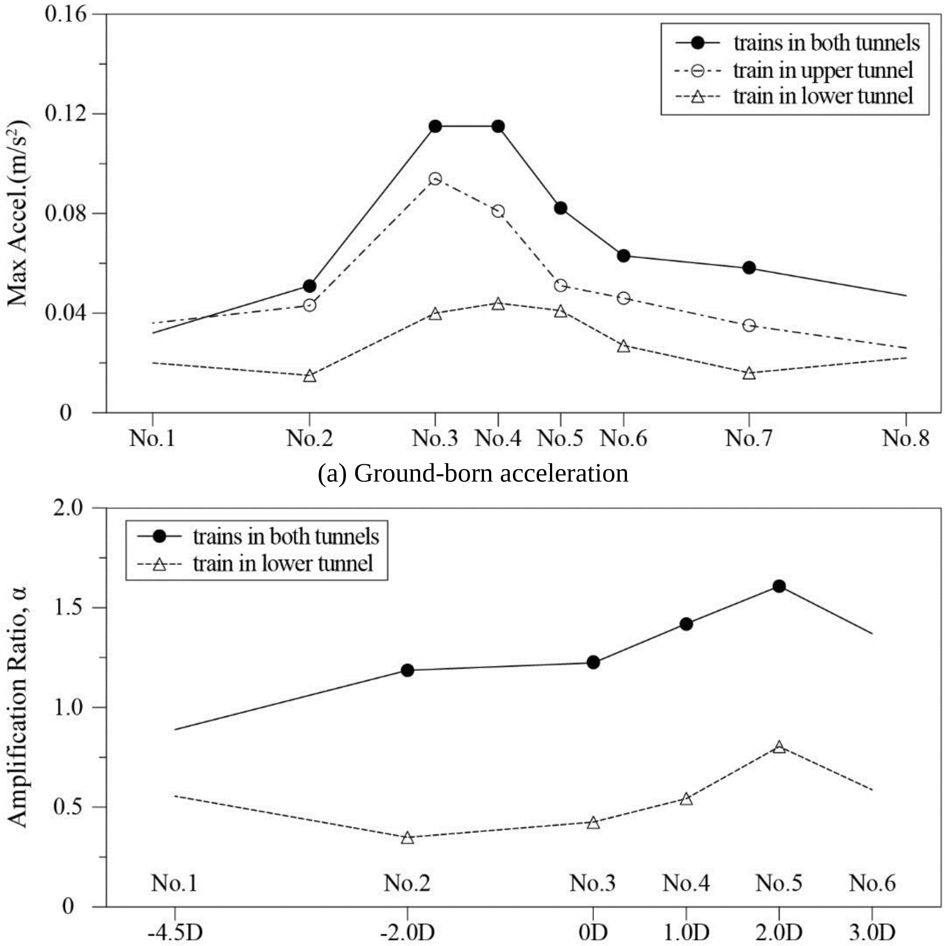
### 3.2 Results

Fig. 10 shows the results of the analysis at the location of ground surface No. 3. Only the vertical ground-born acceleration is presented.

To identify the vibration superposition effect quantifiably, amplification ratio α was used, which is defined as follows.

$$\alpha = \frac{a_{\max c}}{a_{\max s}} \tag{9}$$

where $a_{max\,s}$ is the maximum ground-born acceleration due to the upper tunnel train only and $a_{max\,c}$ is the




(a) Ground-born acceleration

(b) Amplification ratio

Fig. 11 Maximum ground-born acceleration

maximum ground-born acceleration due to the lower tunnel train only and both upper and lower tunnel trains.

By comparing Fig. 10(a), 10(b) and 10(c), it is apparent that the vibration superposition effect is significant. The maximum acceleration for the case of the upper train source (TY1) is $0.090\mathrm{m/s^2}$, while that of the case of both tunnel sources (TY3) is $0.118\,\mathrm{m/s^2}$. Therefore, the vibration superposition amplified the ground-born vibration by 1.31 times. Fig. 10(d) compares the results transferred into the frequency domain. The maximum acceleration appeared at the frequency range of 10-20Hz.

Fig. 11(a) shows the maximum ground-born acceleration for each case. The largest value is obtained at the center of the upper tunnel. The amplification ratios at No. 3 and No. 4 are 1.22 and 1.42, respectively. It is interesting to note that the maximum amplification occurs at a certain distance from the tunnel center.

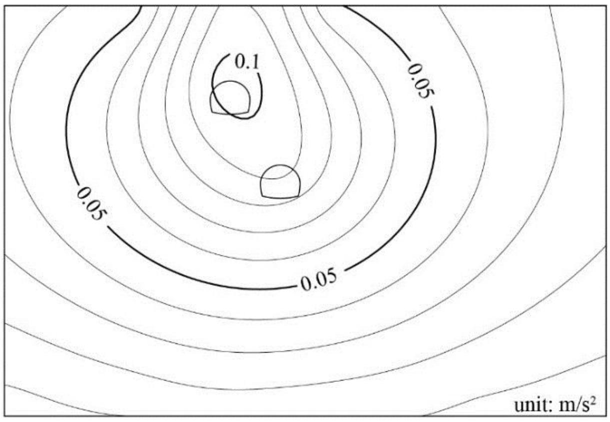
The maximum vertical accelerations at arbitrary locations on the cross section were calculated for each analysis case, and the results are presented as contour lines as shown in Fig. 12. The uniform acceleration line shows the maximum possible acceleration that can occur for the entire length of time the train takes to pass. However, this does not mean that the maximum accelerations occur simultaneously.

When the train passes through only the upper tunnel, the contour lines of the maximum acceleration are formed in the shape of concentric circles around the upper tunnel and they take the form of a long shape in the directions of the ground surface and the lower tunnel, which are free surfaces. The maximum ground acceleration occurs at the crown of the lower tunnel when trains pass through the tunnels simultaneously and the contour line with a shape of a gourd bottle appears around the lower tunnel. The ground-born vibrations were greatly influenced by the tunnel with the shallower depth.

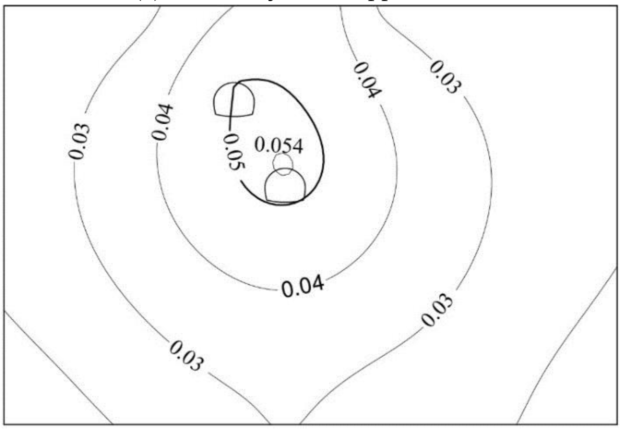
## 4. Effects of influencing factors

### 4.1 Influencing factors and analysis cases

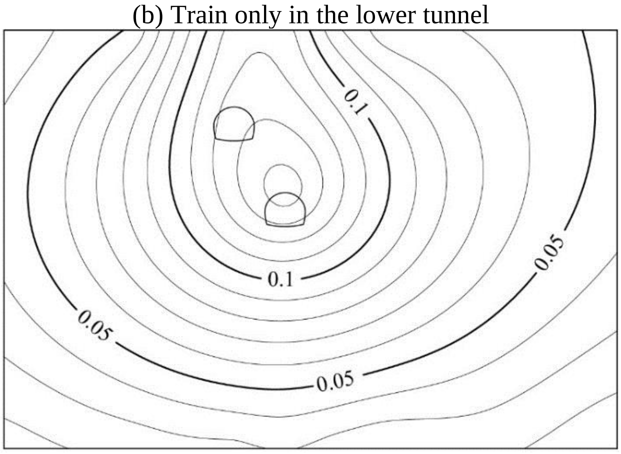
The vibration superposition in the actual tunnel crossing will be influenced by various factors such as ground stiffness, tunnel depth, and distance between tunnels. In this study, the effect of these factors on ground-born vibration was investigated by performing a numerical parametric study. The influencing factors and analysis cases are shown in Table 1.




(a) Train only in the upper tunnel




(b) Train only in the lower tunnel




(c) Trains in both tunnels

Fig. 12 Contour of maximum acceleration for source location

### 4.2 Effect of ground stiffness

The effect of ground stiffness on vibration superposition is investigated. The analysis was carried out for different ground conditions such as weathered rock, soft rock, and hard rock. Fig. 13 shows the maximum ground-born acceleration for different ground stiffnesses in the tunnel crossing for simultaneous train passing. It shows that the maximum ground-born acceleration decreases with an increase in ground stiffness. This is because the constraint effect of particles increases as the ground stiffness increases.

Table 1 Analysis cases and material properties

| Influencing factors | Symbol | Ground condition | Upper tunnel depth (S) | Distance between tunnels Vertical ($D_v$) | Distance between tunnels Horizontal ($D_h$) |
|---|---|---|---|---|---|
| Ground stiffness | MP1 | Weathered rock2) | 1.5D | 1.0D | 1.0D |
| | MP2 | Soft rock3) | | | |
| | MP3 | Hard rock4) | | | |
| Tunnel depth (upper tunnel) | OV1 | Soft rock | 1.0D | 1.0D | 1.0D |
| | OV2 | | 1.5D | | |
| | OV3 | | 2.0D | | |
| Distance between tunnels | LO1 | Soft rock | 1.5D | 1.0D | 0D |
| | LO2 | | | 1.5D | |
| | LO3 | | | 2.0D | |
| | LO4 | | | 1.0D | 1.0D |
| | LO5 | | | 1.5D | |
| | LO6 | | | 2.0D | |
| | LO7 | | | 1.0D | 2.0D |
| | LO8 | | | 1.5D | |
| | LO9 | | | 2.0D | |

1) D: Tunnel diameter
2) $\gamma : 21\ \mathrm{kN/m^3}$, $\nu : 0.43$, $E : 3{,}000$ MPa
3) $\gamma : 22\ \mathrm{kN/m^3}$, $\nu : 0.41$, $E : 7{,}340$ MPa
4) $\gamma : 26\ \mathrm{kN/m^3}$, $\nu : 0.36$, $E : 25{,}300$ MPa

Fig. 14 shows the contour lines of maximum accelerations at the crossing section for different ground conditions. The maximum acceleration appeared mostly at the crown of the lower tunnel, and it showed bulbe-shaped contour lines of concentric circles around the lower tunnel.

### 4.3 Effect of tunnel depth

In many cases, urban railway tunnels are built at depths of 1.0D ~ 2.0D. To investigate the effect of tunnel depth on vibration superposition, analyses were performed on the cases of 1.0D, 1.5D, and 2.0D depth (S) of the upper tunnel in soft rock. The lower tunnel is assumed to be located 1.0D from the upper tunnel horizontally and vertically.

The maximum ground-born accelerations for different depths of the upper tunnel are shown in Fig. 15. It is shown that the ground-born acceleration decreases linearly as the tunnel depth increases.

Fig. 16 shows the contour lines of maximum accelerations for different tunnel depths. The contour lines take a vertically-long shape as the depth increases. The location of maximum acceleration moves downward, as the tunnel depth increases.

### 4.3 Effect of distance between tunnels

The effect of distance between tunnels on vibration superposition was investigated. The existing tunnel with the depth of 1.5D in soft rock ground was considered. The locations of the lower tunnel vary vertically and

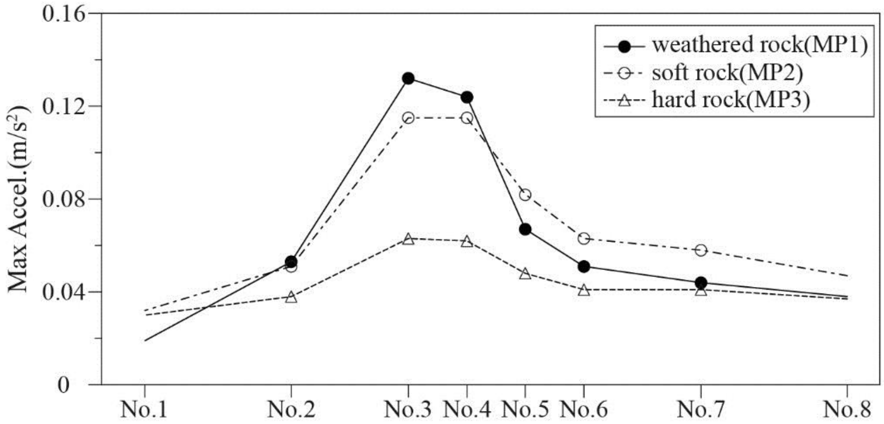
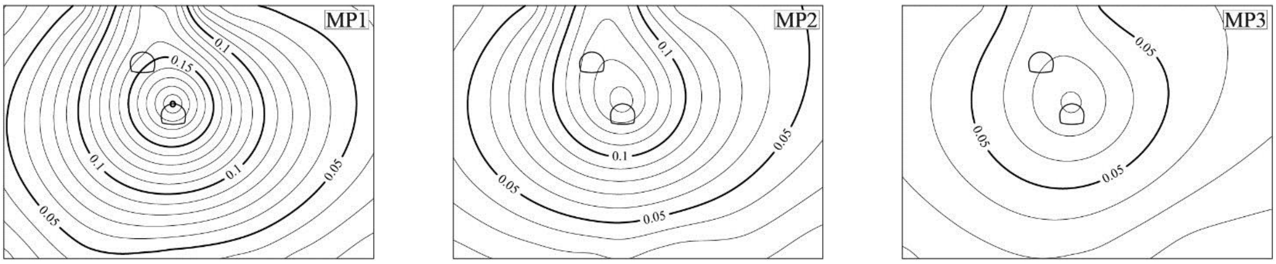



Fig. 13 Effect of ground stiffness




(a) Weathered rock (b) Soft rock (c) Hard rock

Fig. 14 Contours of maximum acceleration for different ground conditions ($D_h$ = 1.0D, $D_v$= 1.0D)

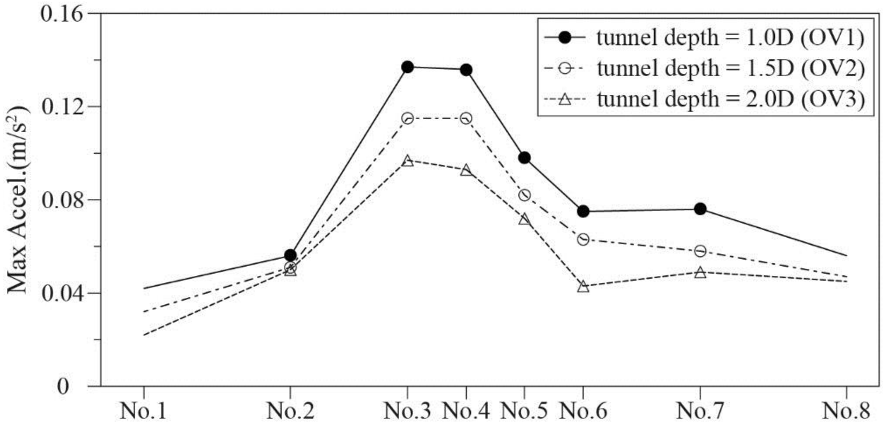
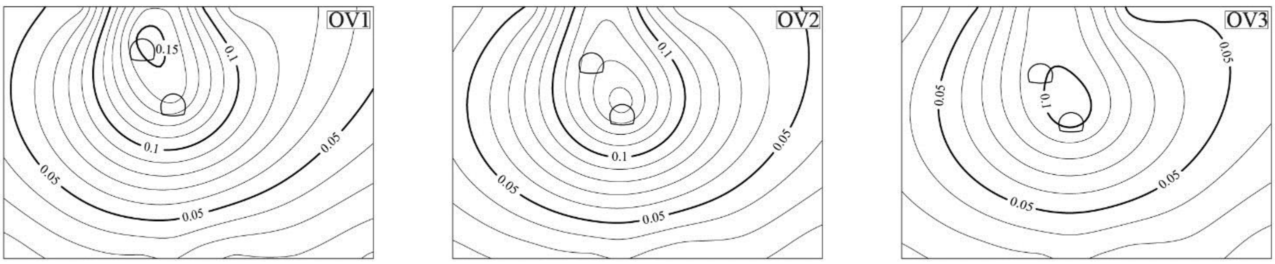



Fig. 15 Effect of tunnel depth ($D_h$ = 1.0D, $D_v$= 1.0D)

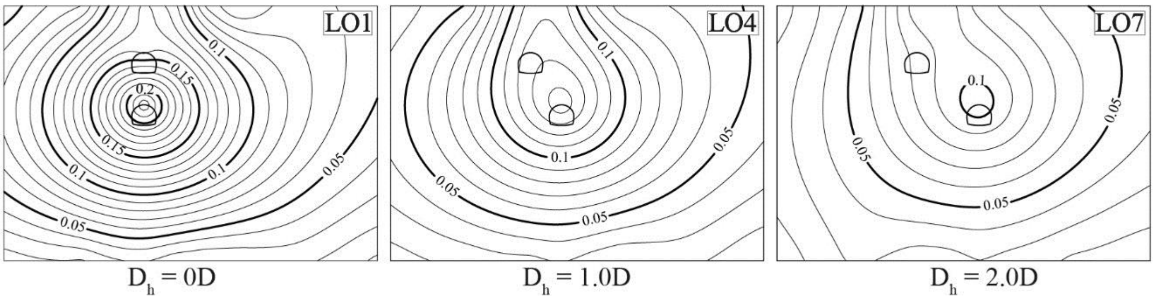



(a) S = 1.0D (b) S = 1.5D (c) S = 2.0D

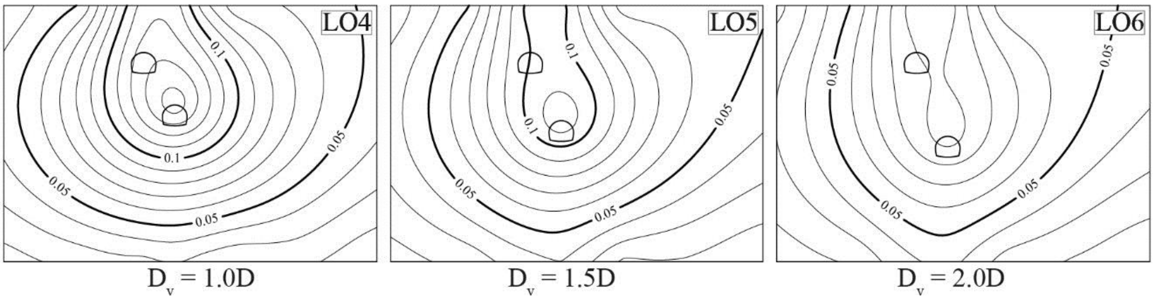
Fig. 16 Contours of maximum acceleration for different tunnel depths

horizontally from the existing tunnel. A total of 9 cases were considered by changing the horizontal distance ($D_h$) to 0D, 1.0D and 2.0D, and the vertical distance ($D_v$) to 1.0D, 1.5D and 2.0D from the existing tunnel.

Fig. 17 shows the contour lines of the maximum accelerations at the crossing section. Fig. 17(a) shows that the maximum acceleration apparently decreases as the distance between tunnels increases. The vibration




(a) Effect of lateral distance between tunnels ($D_v = 1.0D$)




(b) Effect of vertical distance between tunnels ($D_h = 1.0D$)

Fig. 17 Contours of maximum acceleration for varying distances between tunnels

amplifying effect is more sensitive to the horizontal distance than to the vertical distance. The effect of the superposition of accelerations significantly decreases as the horizontal distance increases. Especially, it shows that the location of the maximum acceleration moved from the lower tunnel to the ground surface. Fig. 17(b) shows the contour lines for the vertical distances. The center of thecontour lines was maintained closely to the lower tunnel, although the effect of superposition apparently decreases as the vertical distance increases.

## 5. Discussion

Several options can be taken to investigate dynamic behavior. In this paper, maximum acceleration is mainly considered, which has significance when damage to buildings and machine equipment is concerned. However, if considering the vibration effect on the human body, the RMS (root mean square) would be more appropriate. In our experience, when an argument develops between the experts who support the project owner and those whosupport the citizens of the influencing area, the maximum acceleration is typically one of the priority variables for discussion on the engineering of the dynamic effect.

The situation of crossing tunnels in urban areas is a frequent occurrence today. Therefore, it would be very meaningful to provide engineering guidelines to establish the influencing zone where the effect of vibration superposition is important, since the amplification characteristics of ground-born vibration are dependent on the ground condition, tunnel depth, and distance between tunnels. Therefore, some regional guideline, particularly for Seoul in this case, could be established from the result of this study.

By combining the results presented in the previous sections, the contour line of maximum acceleration can be obtained as shown in Fig. 18. For the case with $0.1 m/s^2$ (which in about 80 dB (V) in decibel scale) or faster acceleration, of which the value could be reference in terms of environmental regulation, is set as the zone of concern, the zone is shown as the shaded area in Fig. 18. The shaded area has a depth of 5.0D from the ground surface and a width of 2.5D from the center of the upper tunnel. This guideline can be used to evaluate the superposition effect ofvibrations at the tunnel crossing, in the phase of the preliminary study of a new railway route under the existing tunnel.

## 6. Conclusions

This study investigated the engineering significance of the effects of vibration superposition at a tunnel crossing by using the numerical analysis. The numerical modelling of vibrations at the tunnel crossing was validated through the model test.

The superposition effect of vibrations at the tunnel crossing was apparent. When trains simultaneously passed the tunnel crossing, the ground-born acceleration increased by a maximum of about 30% compared to the case where the train passes only through the existing upper tunnel.

The characteristics of vibration superposition at the tunnel crossing were investigated in terms of ground stiffness, tunnel depth, and distance between tunnels. The numerical parametric study also showed that the vibration amplification effect also increased as the ground stiffness, the tunnel depth, and the distance between tunnels decreased.

Numerical results showed that the areas that require verification of the vibration amplification are in the range of

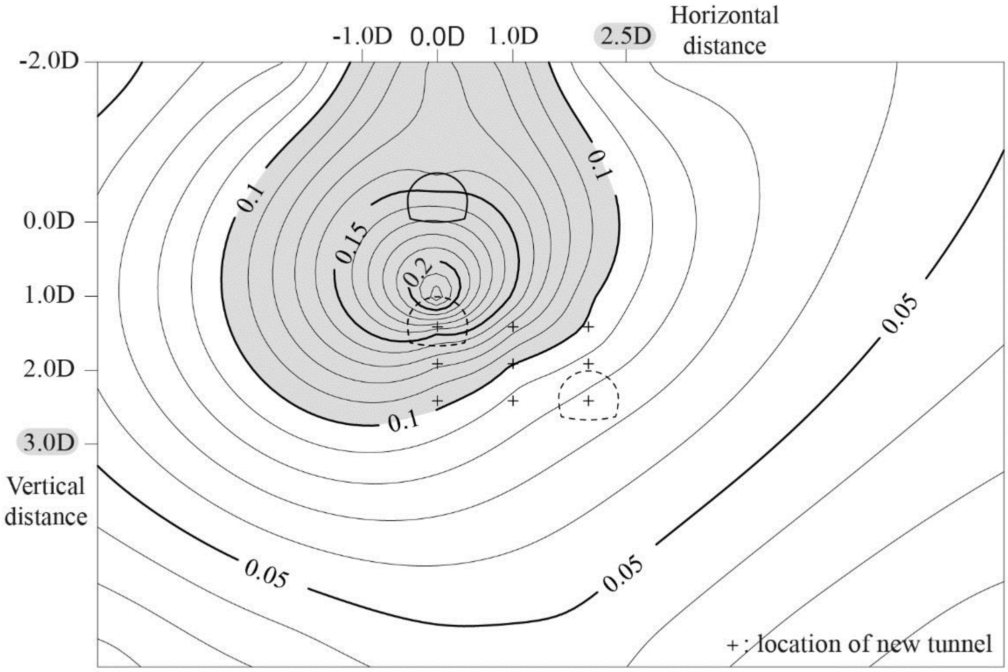



Fig. 18 Train-induced vibration influencing envelope (unit: m/s$^2$)

a vertical distance of 5.0D from the ground surface, and a horizontal distance of 2.5D from the center of the upper tunnel in the soft rock condition.

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