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TRAFFIC INDUCED GROUND VIBRATIONS FROM VIADUCT: PREDICTION AND MITIGATION PROCEDURES

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Abstract
Ground vibrations induced by road traffic viaduct have been dealt with in view of the viaduct-soil interaction under the passage of vehicles. First, the field experimental measurements are interpreted by the wave propagation theory. Based on the observed data at the viaduct foundation, a hybrid prediction is made successfully for the nearby ground response, with a aid of the information separately obtained from the substructure FEM model. Secondly, the vibration mitigation is attempted by taking the alternative WIBs (Wave Impeding Barriers) of honeycomb cells or concentric ring walls around the vibration emitting foundation. From the computation analysis these WIBs proved to be of significantly effective for the vibration mitigation.

INTRODUCTION

The traffic induced vibrations are increasingly affecting built-in areas alongside tracks, causing disturbances to residents and malfunctioning to vibration-sensitive facilities. These vibrations include mostly the low frequencies from 3 to 8 Hz. The vibration legislation in Japan limits the vibration acceleration level (VAL) below the range of 60 (or 65) dB during daytime while 50(or 55) dB during nighttime, depending on the type of area zoning. Protection of the built-in areas from exposures to detrimental environment vibrations or vibration pollution is strongly desired.

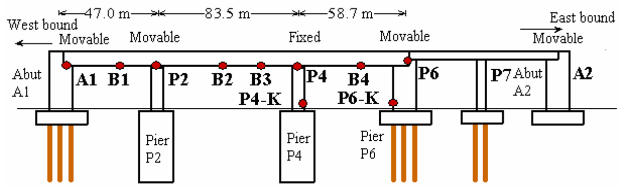
Different types of counter measures have been attempted against traffic-induced vibrations. They are open trenches or in-fill trenches with bentonite, concrete walls or a row(s) of concrete piles or steel sheet-piles. These barriers aim at creating screens to protect structures and facilities in their shadow zone. Recently, Takemiya developed innovative wave impeding barriers (WIBs), called honeycom WIBs（Takemiya, 2004; Takemiya and Shimabuku, 2006）. They are considered on the wave field off or around structural foundations. During the wave propagation across the WIB zone, the frequency contents are modulated because of the energy scattering, and the high-damping fill-in materials dissipate it inside individual cells so that the wave amplitudes are significantly reduced across WIBs. The frequencies for mitigation can be determined beforehand by the knowledge of the free field waves from the soil profile at site.

This paper, based on the field measurement data at a road traffic viaduct site, first clarifies the mechanism of vibration propagation in ground from the traffic on it. Then, the mitigation effect is discussed by use of the honeycomb-WIB around viaduct foundations by the 3-dimensional computer simulation by the finite element method(FEM).

FIELD MEASUREMENT

The *Figure 1* is a targeted viaduct for investigation. The structural design takes the three-span continuous girder whose connection to the pier P4 is rigid and other connections to the rest of piers are free to move along the viaduct axis. The viaduct has a curvature of 1/800 so that beside of the vertical loading by traffic, the lateral loading results substantially due to their centrifuge force action by the motion.

The vibration measurements were conducted by using a single truck (20 *tf* weight) run on the viaduct as well as under the normal traffic flow both at the viaduct and the nearby ground. The accelerations are recorded at representative points of the viaduct, as indicated in *Figure 1* and at the nearby ground surface as indicated in *Figure 2*. The time histories associated with a single truck run are shown in *Figure 3* and their Fourier amplitudes are obtained (omitted for depiction here). The arrows on the time scale correspond the times at which the vehicle is positioned at the indicated locations.



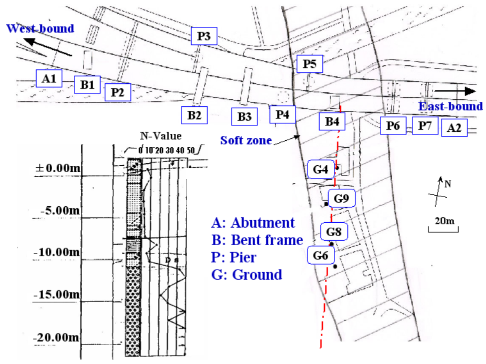
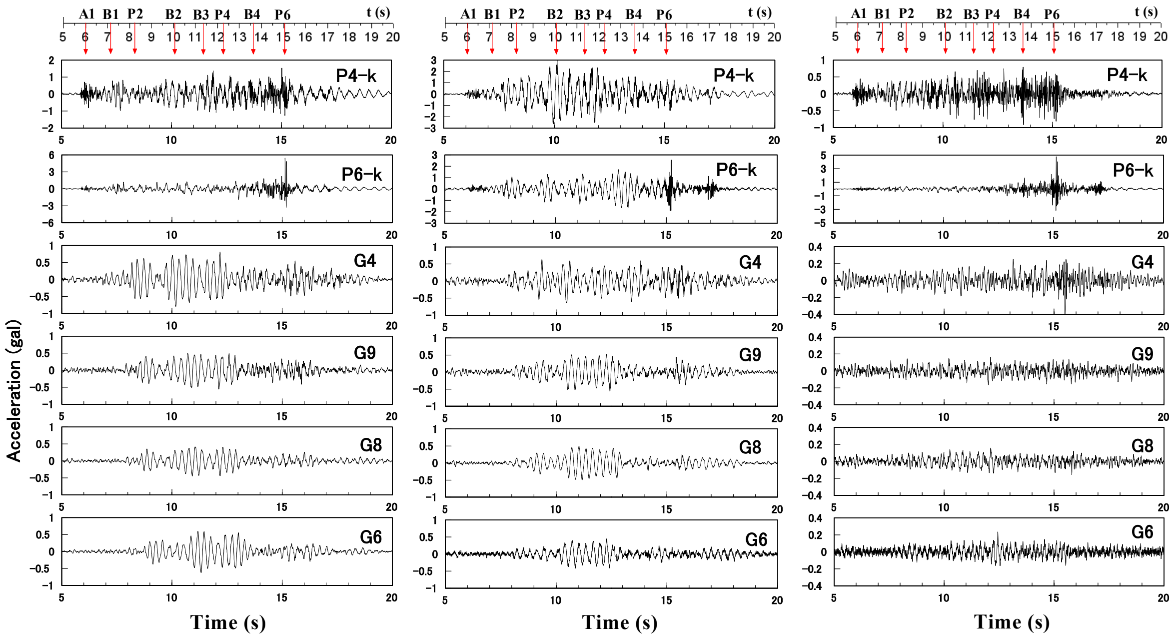


Figure 1 -A viaduct structure for analysis *Figure2-A traffic viaduct and measurement points*

It is noted that the motions are very reflective of the multiple running cars on the girder.

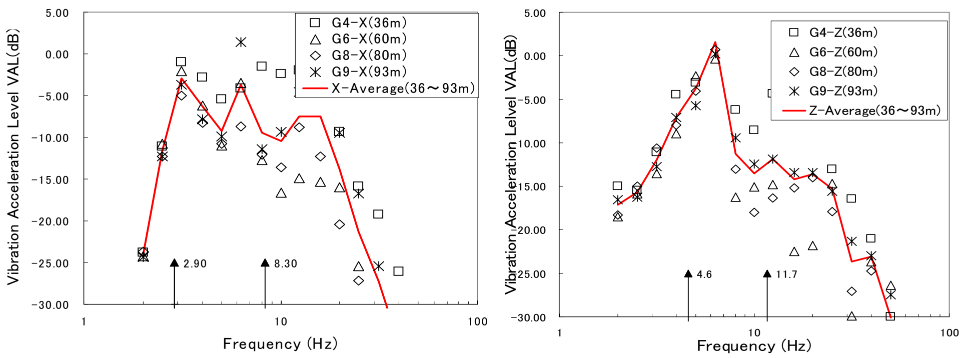
Regarding the viaduct response under a vehicle(s) passage, Takemiya, Chen and Ida, (2006) gave detailed interpretation. It reflects the higher localized eigenmodes due to the position of the vehicle and of the lower global eigenmodes due to the motion of the total vehicles. The more interest for investigation is given here on the nearby ground. In *Figure 3* depicted are the ground acceleration responses for a single East-bound vehicle passage. The amplitudes are attenuated and the frequency contents are significantly shifted as the distance is increased from the viaduct. The major peak fre-



(a) Along viaduct axis (b) Perpendicular to viaduct axis (c) Vertical

Figure3-Acceleration time histories by a test run of a 20ft truck（A1→P2→P4→P6→P7→A2）

quencies are observed around 3 Hz and 5Hz in every horizontal component. The along distance component shows more predominance at 3Hz than the longitudinal direction while closer to 5Hz in the transversal direction. The vertical vibration, on the other hand, has wider spread of frequencies below 10Hz at the ground surface as well as at the viaduct foundation. In order to clarify the frequency changing transmission of waves in ground, which is called a dispersive nature, the 1/3-octove band frequency amplitudes is depicted in *Figure 4* for the vibration components along the viaduct axis and for the vertical components at every measurement points in *Figure 2*. Interesting to note is the finding that the former that corresponds mainly to the out-of-plane motion comprising the SH waves shows a significant sharp increase of frequency contents at 3Hz and keep substantial contents above it, while the latter that corresponds mainly to the in-plane motion of the P and SV indicated a sharp peak at 5 Hz and above it a drastic decrease.

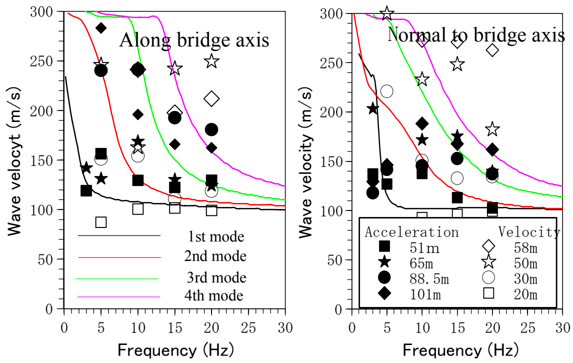


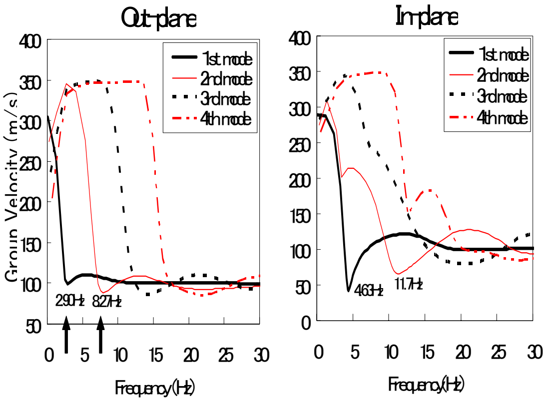
(a) Horizontal (parallel to viaduct axis) (b) Vertical

Figure 4 - 1/3-Octove band spectral density

SITE-SPECIFIC CHARACTERISTICS

The SASW (Spectral Analysis of Surface Waves) (Gucunski and Woods, 1992) has been applied to the measurement data in order to understand more the traffic induced wave propagation in ground. The results are depicted in *Figure 5* (given by solid symbols) in which the data from the velocity measurement (open symbols, Takemiya and Shimabuku, 2006) are also added. The theoretical prediction is also indicated by lines from the thin layer method（Kausel and Roesset, 1981）, for the first four wave modes. The dispersive nature of the wave propagation is clearly noted. In view of the predominant peak frequencies in the range of 3 to 6Hz, the modal contributions are significant from the first and second modes. At 3Hz predominance, the phase velocity is read off as around 170m/s for the in-plane first mode motion and 150m/s for the corresponding out-of-plane motion. The concerned wavelengths are then estimated respectively as 60m/s and 50m/s roughly.





(a)Along viaduct axis (b) Perpendicular to viaduct axis (a)In-plane motion (b) Out-of-plane motions

Figure 6 - Phase velocity vs. frequency Figure 7- Group velocity vs. frequency

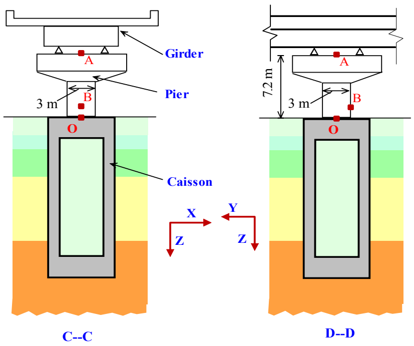
For the layered ground, the wave propagation is better interpreted in terms of the group velocity of *Figure 6*. This quantity indicates the representative speed of the gross wave energy transmission. In reference to Takemiya and Shimabusku (2006), the modal shapes at the Airy phase frequencies confirm that the amplitudes of major ground motions are mostly in the surface soil of 15m depth.

HYBRID PROCEDURE FOR VIBRATION PREDICTION

The hybrid simulation is taken that makes use of the measured data at the viaduct pier (*Figure 7*). The substructure procedure evaluates the internal force action at the foundation top when loaded by vehicles on the girder. Once the impedance functions are obtained from the model in *Figure 8*, as $\boldsymbol{K}_0(\omega)$ to comply with the foundation degrees of freedom as a rigid body, they are applied in turn to the foundation-ground system to recover the ground response. These steps are described by the followings.

$$\boldsymbol{P_0}(\omega)e^{i\omega t} = \boldsymbol{K}_0(\omega)\boldsymbol{U_0}(\omega)e^{i\omega t} \quad (1) \qquad \boldsymbol{P}(\omega)e^{i\omega t} = \boldsymbol{K}(\omega)\boldsymbol{U}(\omega)e^{i\omega t} \quad (2)$$

where the critical aspect lies in predicting the displacement at the foundation top. The FEM is applied for this purpose by employing the model in *Figure 8*



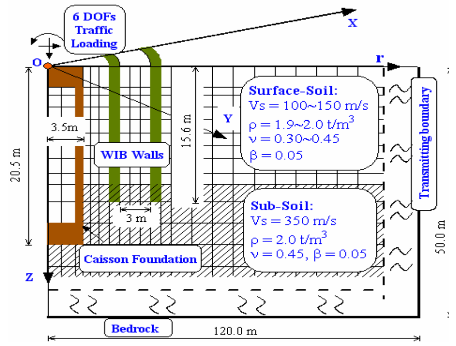
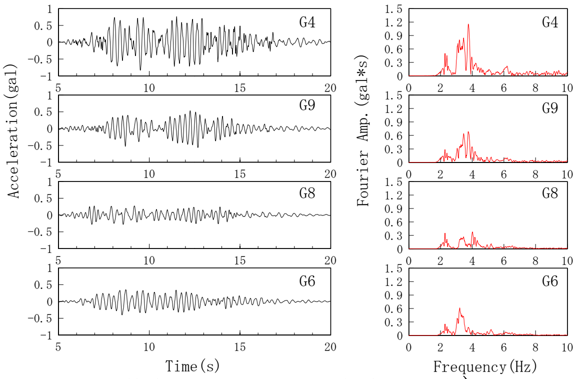
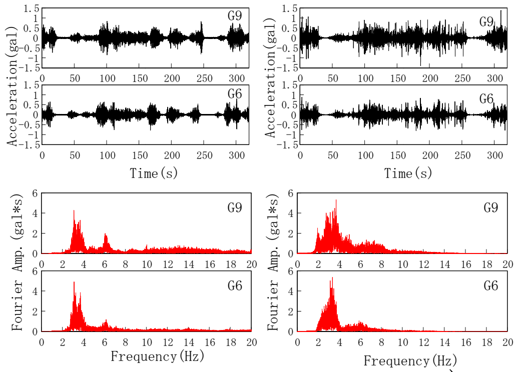
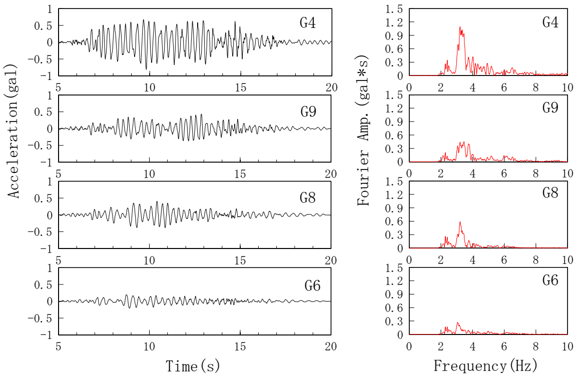


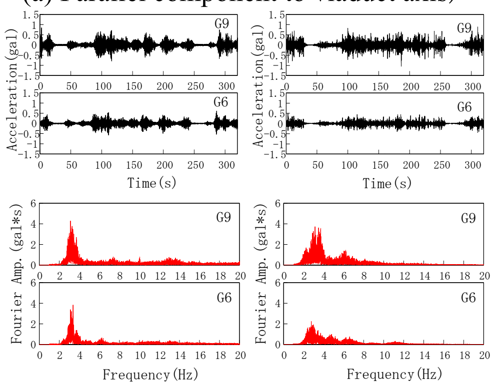
Figure 7- Viaduct pier　　*Figure 8 - FEM for foundation with WIB and ground*



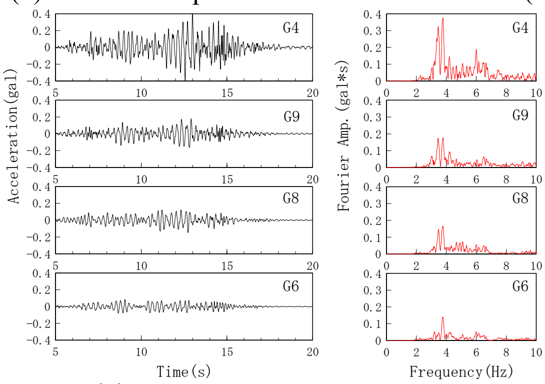


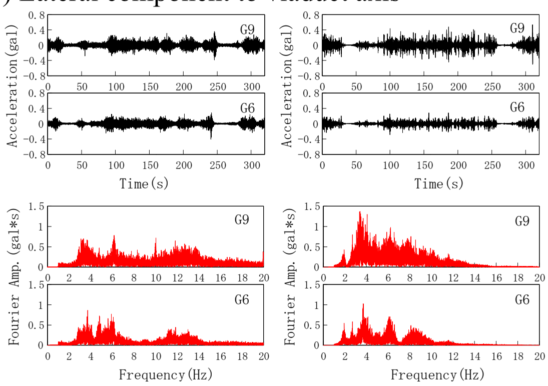
(a)　Parallel component to viaduct axis)　　(a) Parallel component to viaduct axis)





(b)　Lateral component to viaduct axis　　(b) Lateral component to viaduct axis





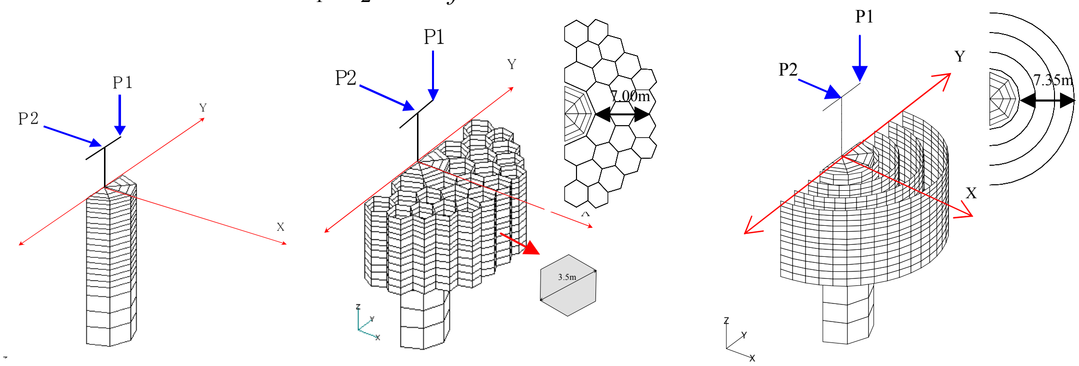
(c) Vertical component　　(c) Vertical component

Figure 9 - Simulations for a single truck run　　*Figure 10 - Simulation for normal traffic flow*

Prediction accuracy is checked for the hybrid method. *Figure 9* shows the simulation results for a single truck run on the viaduct. These time histories are compared with those obtained from the measurement in *Figure 4*. The consequences for the normal traffic flow are shown in *Figure 10* in comparison also with the measurements. The contributions from the piers P4 and P6 are simply superimposed. The loading situation is very random of vehicles on the viaduct but the frequency contents are almost the same among measurements when the Fourier transforms are obtained. The simulation results fit well the measurements both in the time histories and the Fourier amplitudes.

3-D FEM MODEL ANALYSIS FOR VIBRATION MITIGATION

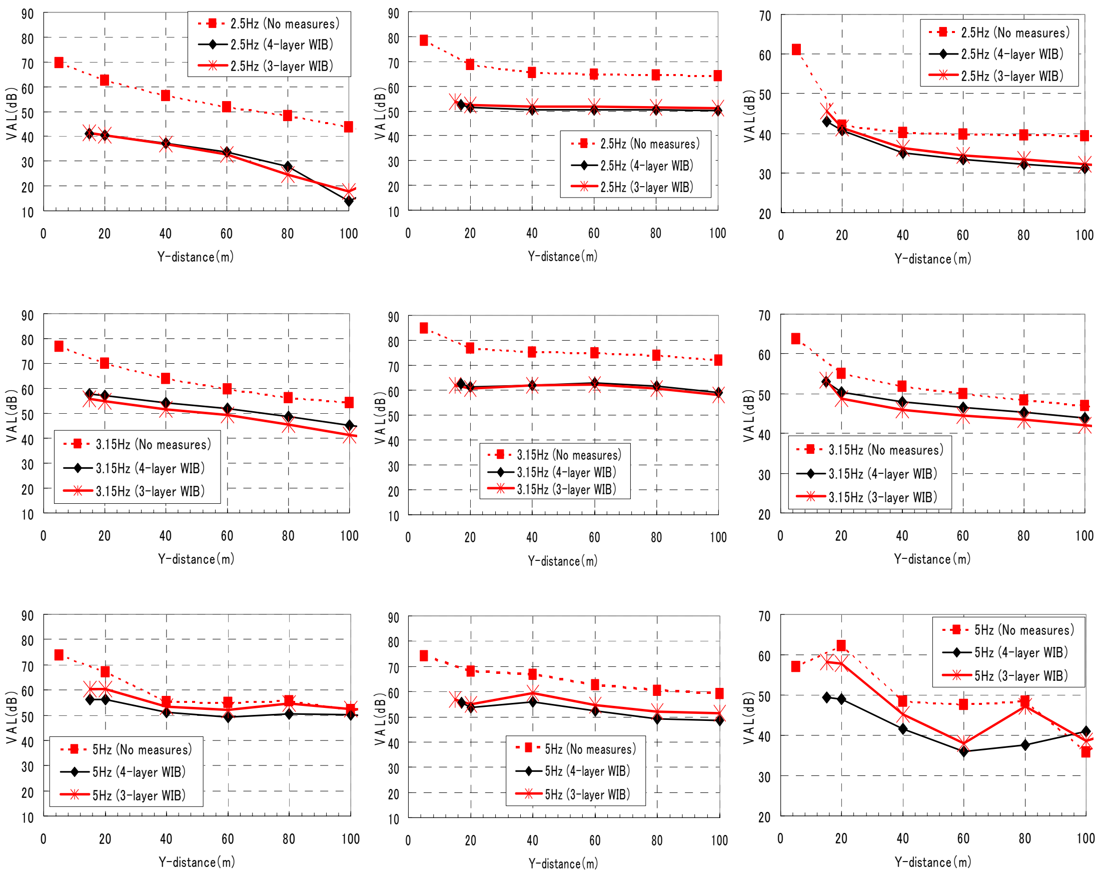
In order to reduce the vibration in the vicinity of the viaduct the WIB measure is considered. Herein, a cluster of hexagon cells or honeycomb-cells are arranged around the viaduct foundation as illustrated in *Figure 11*(*b*), the computer simulation has been conducted based on the models of the 3-dimensional configuration that takes into account of the cell geometry. Further, for a simplification, in view of the good matching comparison with the field measurement data (Takemiya, Chen and Ida, 2006), we may assume a multiple ring-type WIB model in *Figure11*(*c*). Focusing on the pier-foundation-soil interaction, the viaduct motion under traffic is replaced by the force action at the pier top horizontally P_1 as well as P_2 vertically. To be consistent with the field measurement P_1=P_2=20 *tf* are taken into account.



(a) Caisson foundation P4 (b) Honeycomb-WIB around P4 (c)Ring-WIB around P4

Figure 11 - Computation models for viaduct foundation and WIB

The computation is carried out by using the 3-dimensional finite element method. The girder and pier parts are modelled by beam elements, and the pier and soils by solid elements, and the honeycomb cells and the ring walls by shell elements. The honeycomb-WIB is designed against the low frequencies at 5 Hz or below. This low frequency is the main-targeted range as observed from the neighborhood ground of the viaduct. The dimension of the WIB is determined so that the depth is 13.6m with the reference to the soil deformation profile along depth and the soil layering structure at the site. The representative size of the cell is fixed as 3.5m. The extent of the WIB is considered by concentric layers of cells to fulfill the 1/3 of the most important wavelength at least, as predicted from the site characteristic. The consequence is illustrated

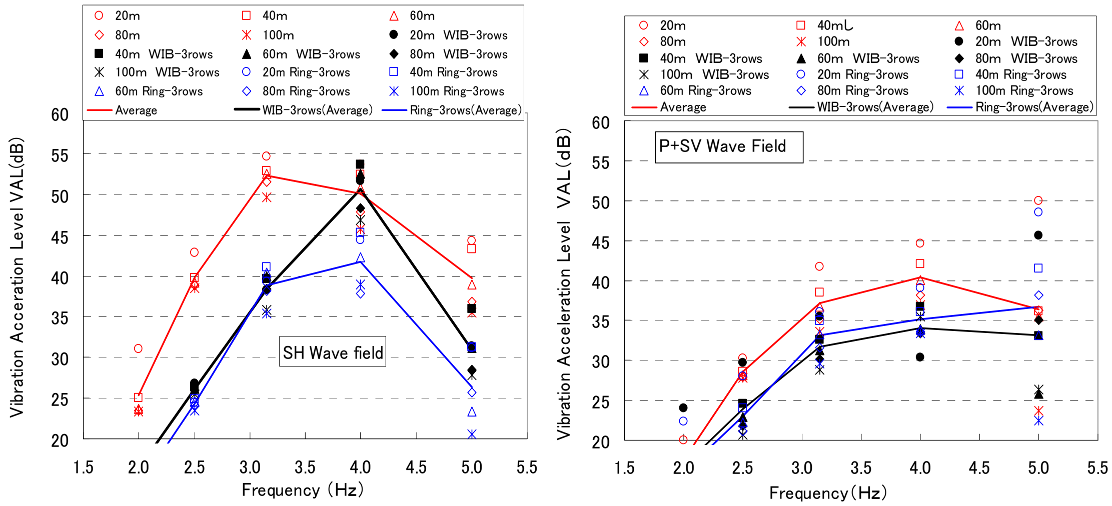


(a) Lateral component (b) Parallel component (c) Vertical component

Figure 12 - Ground responses due to vertical loading: $VAL = 20 \log \dfrac{A}{A_0}; A_0 = 10^{-5}[m/s]$

in *Figure 11(b)*. The computation results in *Figure 12* suggests that three layers of cells fare acceptable, leading more than 10 dB reduction for the horizontal VAL response and several dB for the vertical response. From the contour figures for the ground response (Takemiya and Shimabuku, 2006), the zone for wave propagation is clearly noted different according to the loading direction. For the eccentric vertical loading, due to the rocking of the foundation, the wave emits and propagates along the viaduct axis, supposedly by the SH wave. The most significant intensity appears around the 3Hz driving frequency. At the same time, the in-plane wave exists propagating toward normal direction to the viaduct, supposedly by the P and SV waves. The 3-layer concentric honeycomb WIB works significantly for the response reduction for the targeted low frequencies, most effectively below 5Hz. Regarding the wave field due to the horizontal loading along bridge axis, the wave emits and propagates toward the normal direction to the loading direction, most significantly at the 3.15Hz. This is supposed to be the SH wave field. The honeycomb WIB subdues this wave field significantly.

In order to substantiate the reduction effect by shifting up of the cut-off frequency of the concerned wave field, the VAL amplitudes at the 1/3-octove frequencies are shown for different distances from the loaded foundation P4 in *Figure 13*. The evidence is much more gained for the SH wave field than for the P and SV wave field.



(a) For an eccentric vertical load (b) For a horizontal load

Figure 13 - Ground velocity response amplitudes due to harmonic loading on top of viaduct pier

CONCLUSIONS

This paper aims at developing an effective measure against the traffic induced low frequency vibrations in ground. First, based on the field measurements of a road viaduct site, the wave field is examined for the dispersive characteristics. Then, honeycomb type wave impeding barrier (WIB) is chosen around the vibration emitting foundation of the viaduct and alternatively a concentric ring WIBs are also considered. The size of the WIB is properly determined with the knowledge of the concerned wave field at site. In order to check its vibration reduction effect, a three dimensional soil-structure and wave field analyses have been conducted by the finite element method. From the computation results for the present case study, the proposed WIB proved to work for mitigation of the ground response more than 10 dB and most effectively for the SH wave at 3Hz that is supposedly the most targeted environmental vibration along the viaduct.

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