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A PREDICTION METHOD OF ROAD TRAFFIC NOISE BY THE BOUNDARY ELEMENT METHOD ALONG ELEVATED TRACKS

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INTRODUCTION

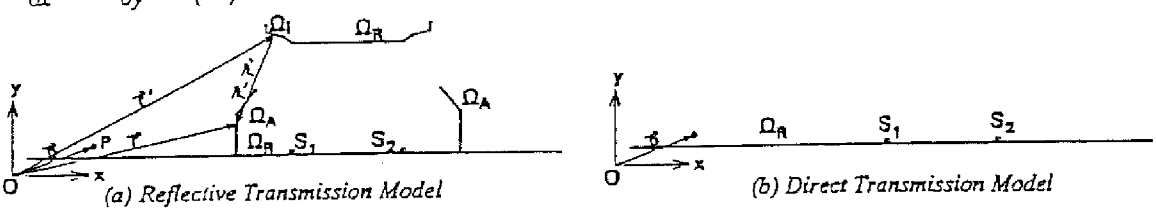
Double-decker road structures are seen in metropolitan cities, because road space can be effectively increased. In order to assess the noise from traffic on these structures, an efficient prediction method of road traffic noise containing multi-reflective noise is required. We have already proposed a numerical prediction method for this purpose using the Monte Carlo simulation (MCS) in our previous papers[1]. The MCS is highly suitable for calculating the values of equivalent continuous A- weighted sound pressure level $L_{Aeq}[dB]$, because it enable easy simulation of the direct transmission of multi-reflection waves [2]-[4]. However, the MCS is based on geometrical acoustics, and it is difficult to compute the diffracted transmission of multi-reflection waves. Therefore, when the space between the bottom of the girder supporting an upper road and the top of the noise barrier on the underling planar road is small, the numerical errors of $L_{Aeq}[dB]$ computed using the MCS increase. To overcome this drawback, the boundary element method (BEM)[5], [6] based on wave equations is applied for prediction of road traffic noise.

In this paper, a prediction method of road traffic noise along elevated tracks for the $L_{Aeq}[dB]$ computed using the BEM and method of the ASJ (Acoustical Society of Japan) Model-1998[7] is presented. Furthermore we compare the result of the BEM prediction with that of the MCS prediction and measurement.

ACOUSTICAL MODEL FOR A DOUBLE-DECKER ROAD BY BOUNDARY ELEMENT METHOD

As shown in Fig.1(a), the double-decker road structure with sound barriers located on both sides of the upper road is modeled as a two-dimensional problem. The equation of this problem is:

$$\frac{\partial^2\Phi(\bar{p})}{\partial x^2}+\frac{\partial^2\Phi(\bar{p})}{\partial y^2}=\left(\frac{\omega}{c}\right)^2\Phi(\bar{p}), \quad (1)$$



(a) Reflective Transmission Model *(b) Direct Transmission Model*

Fig.1 Boundary Element Model for a double-decker road

where $\Phi(\bar{p})$ is the magnitude of velocity potential at any field point $P(\bar{p})(\bar{p}=(x,y))$ and ω/c is the wave number (with ω the circular frequency and c the speed of sound). Equation (1) is termed the Helmholtz equation. In Fig.1(a), according to the ASJ Model-1998[7], two sound sources S_1 and S_2 are located on the road surface. Each source is a pressure source and their incident field is defined by the following equation:

$$\overline{P_0}=-jAH_0^{(2)}\left(\frac{\omega\zeta}{c}\right), \quad (2)$$

where $\overline{P_0}$ is the pressure at a distance ζ from the axis of the source, $A(=1.0[Pa])$ is the pressure on a cylinder of unit radius $(\zeta=1.0[m])$, and $H_0^{(2)}(\ )$ is the Hankel function of second type and zero order. The pressure P_0 is in inverse proportion to frequency ω. In the BEM model, we assume that the reverberations into the space which has two small openings have a great influence on the noise from traffic on the double-decker road structures. Therefore, we only consider the sound sources S_1 and S_2 on the under road (but considering sound sources on upper tracks in the calculation

/6

of the equivalent continuous A-weighted sound pressure level $L_{Aeq}[dB]$). The boundary surface Ω is made up of two parts Ω_R and Ω_A as indicated in Fig.1(a) ($\Omega=\Omega_R\cup\Omega_A$). The boundary conditions of Ω_R and Ω_A are defined by acoustic impedance $Z(\bar{r},\omega)$ as:

$$Z(\bar{r},\omega)=\frac{1+R(\bar{r},\omega)}{1-R(\bar{r},\omega)}\rho c, \tag{3}$$

with the pressure reflective ratio $R(\bar{r},\omega)$:

$$\alpha(\bar{r},\omega)=1-|R(\bar{r},\omega)|^2, \tag{4}$$

where $\alpha(\bar{r},\omega)$ is the absorption coefficient. We assume that the boundary surfaces Ω_R are rigid surfaces. Such as the bottom of upper tracks, road surfaces and ground surfaces, therefore, the absorption coefficient of Ω_R is $\alpha(\omega)=0$. On the other hand, the absorption ratio of absorbent-material surfaces Ω_A is $\alpha(\omega)=0.8$ according to the absorption coefficient by the reverberation method. In this problem, $Z(\bar{r},\omega)$ are real. These impedance boundary conditions $Z(\bar{r},\omega)$ are associated with the Helmholtz equation (1), and the following results is obtained:

$$\frac{j\omega\rho}{Z(\bar{r},\omega)}\Phi(\bar{r},\omega)-\frac{\partial\Phi(\bar{r},\omega)}{\partial\bar{n}}=0. \tag{5}$$

This equation is called Robin Condition[5], [6]. For the calculation by the BEM, equation (1) using the 2D Green function $G(\bar{r}-\bar{r}',\omega)$ from Green's third identity[5], [6] and Sommerfeld Radiation Conditions can be transformed into the boundary integral equation as:

$$\sum_{i=1}^{N}\sum_{i'=1}^{N}H_{i,i'}\Phi(\bar{r}'_{i},\omega)=\sum_{i=1}^{N}\sum_{i'=1}^{N}G_{i,i'}\frac{\partial\Phi(\bar{r}'_{i},\omega)}{\partial\bar{n}} \tag{6}$$

by discretization of the boundary integral equation. In equation (6), $H_{i,i'}$ and $G_{i,i'}$ are boundary integrals associated with the Neumann Condition and Dirichlet Condition, $\bar{r}$ and $\bar{r}'$ are vectors of any observation and source point and N is the number of the discretized boundary element mesh. In the BEM mesh, the length of one element is 1/6 of the minimum wavelength. If either $\Phi(\bar{r}',\omega)$ or $\partial\Phi(\bar{r}',\omega)/\partial\bar{n}$ is defined, on substituting equation (5) into equation (6), we obtain:

$$\Phi(\bar{p},\omega)=\int_{\Omega}\left[\Phi(\bar{r},\omega)\frac{\partial G(\bar{p}-\bar{r},\omega)}{\partial\bar{n}}\right]d\Omega-\int_{\Omega}\left[G(\bar{p}-\bar{r},\omega)\frac{\partial\Phi(\bar{r},\omega)}{\partial\bar{n}}\right]d\Omega \tag{7}$$

at any observation point $P(\bar{p})$. In this expression (7), $\bar{r}$ is any point on the boundary surface. For each frequency, the values of $\Phi(\bar{p},\omega)$ can be calculated by using equation (7). The pressure value $\overline{P(\bar{p},\omega)}[Pa]$ and the sound pressure level $L_P(\bar{p},f)[dB]$ are obtained at the observation point $P(\bar{p})$ by results of solving equation (7):

$$\overline{P(\bar{p},\omega)}=j\omega\rho\Phi(\bar{p},\omega), \tag{8}$$

$$L_P(\bar{p},f)=20\log\left|\frac{\overline{P(\bar{p},f)}}{P_0}\right| \quad (f=\omega/2\pi), \tag{9}$$

where $P_0[Pa]$ is the standard sound pressure. In this paper, the sound pressure levels $L_{P,1}(\bar{p},f)$ and $L_{P,2}(\bar{p},f)[dB]$ at the observation point $P(\bar{p})$ generated from sound sources S_1 and S_2 are computed using the BEM model for frequencies ranging from 100 to 1000 $[Hz]$ with a linear step of $20[Hz](=\Delta f)$ [8]. For those sound pressure levels the $L_{P,1}(\bar{p},f)$ and $L_{P,2}(\bar{p},f)[dB]$ computed, A-weighted, spectrum of road traffic noise indicated by equation (10) [7]:

$$W_C(f)=-10\log\left[1+\left(\frac{f}{2000}\right)^2\right][dB] \tag{10}$$

and revision for cylindrical sources $W_S(f)$ $(=10\log(f/100))$ $[dB]$ are considered; therefore, $L^*_{P,1}(\bar{p},f)$ and $L^*_{P,2}(\bar{p},f)[dB]$ are obtained:

$$L^*_{P,k}(\bar{p},f)=L_{P,k}(\bar{p},f)+W_C(f)+W_A(f)+W_S(f)[dB] \quad (k=1,2). \tag{11}$$

Using $L^*_{P,1}(\bar{p},f)$ and $L^*_{P,2}(\bar{p},f)[dB]$ for the frequencies $f_{i''}[Hz]$ indicated in equation (12):

17

$$f_{i''}=f_{min}+\Delta f(i''-1)\ \ (i''=1,2,\cdots M)[Hz], \tag{12}$$

the sound pressure level $\overline{L_{P,k}}(\bar{p})$ for the sound sources S_1 and S_2 is obtained:

$$\overline{L_{P,k}}(\bar{p})=10\log\left[\sum_{i''=1}^{M}10^{\frac{L_{P,k}(\bar{p},f_{i''})}{10}}\Delta f\right][dB], \tag{13}$$

where M is the number of frequencies (M=46) for calculating $\overline{L_{P,k}}(\bar{p})$. Similarly, for the BEM model of the planar road displayed in Fig.1(b), by computing the sound pressure levels $\overline{L_{P,1}^{'}}(\bar{p}),\overline{L_{P,2}^{'}}(\bar{p})[dB]$ at the observation point $P(\bar{p})$ insertion loss $\Delta L_{P,k}(\bar{p})[dB]$ between the direct transmission model and the reflective transmission model is obtained as:

$$\Delta L_{P,k}(\bar{p})=\overline{L_{P,k}}(\bar{p})-\overline{L_{P,k}^{'}}(\bar{p})\ \ [dB]\ \ (k=1,2), \tag{14}$$

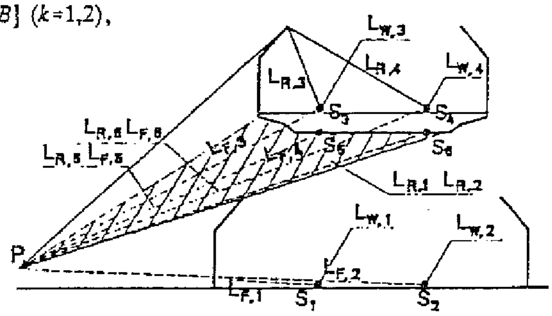


Fig.2 models of noise propagation for double-decker road structures

A CALCULATION METHOD OF SOUND PRESSURE LEVEL FOR DOUBLE-DECKER ROAD STRUCTURE

In this prediction method, the road traffic noise is evaluated on the basis of the values obtained by combining the insertion loss $\Delta L_{P,k}(\bar{p})[dB]$ given by equation (14) with the equivalent continuous A-weighted sound pressure level $L_{Aeq}[dB]$ for the direct transmission model displayed in Fig.1(b) according to the ASJ Model-1998 [7]. As shown in Fig.2, taking six sound sources $S_{k'}(k'=1-6)$ into consideration, the unit pattern $L_{FS,k',i^*}^{'}(\bar{p})[dB]\ (k'=1-4)$, $L_{FB,k',i^*}^{'}(\bar{p})[dB]\ (k'=1-4)$ and $L_{Fstr,k',i^*}^{'}(\bar{p})[dB](k'=5,6)$ of each sound source is obtained as:

$$L_{FS,k',i^*}^{'}(\bar{p})=L_{WS,k'}^{'}-8-20\log\ l_{k',i^*}\ \ [dB]\ \text{for a passenger car}, \tag{15}$$

$$L_{FB,k',i^*}^{'}(\bar{p})=L_{WB,k'}^{'}-8-20\log\ l_{k',i^*}\ \ [dB]\ \text{for a large car}, \tag{16}$$

$$L_{Fstr,k',i^*}^{'}(\bar{p})=95.3-8-20\log\ l_{k',i^*}\ \ [dB]\ \text{for the noise from the upper track}, \tag{17}$$

where, l_{k',i^*} is a distance between a separate point source in the i^*th for source $S_{k'}(k'=1-6)$

$$l_{k',i^*}=\sqrt{l_{k',0}^2+(i^*\cdot\Delta l)^2}\ \ (i^*=0,1,2,\cdots,m) \tag{18}$$

where $L_{WS,k'}^{'}[dB]$ and $L_{WB,k'}^{'}[dB]$ are sound power levels for sound sources $S_{k'}(k'=1-4)$ according to the ASJ model-1998 [7] as:

$$L_{WS,k'}^{'}=46.7+30\log V_{S,k'}\ \ [dB]\ \text{for a passenger car}, \tag{19}$$

$$L_{WB,k'}^{'}=53.2+30\log V_{B,k'}\ \ [dB]\ \text{for a large car}. \tag{20}$$

Combining the insertion loss $\Delta L_{P,k'}(\bar{p})[dB]$ $(k'=1-2)$ presented in the preceding section with the unit patterns $L_{RB,k',i^*}(\bar{p})$ and $L_{RS,k',i^*}(\bar{p})$ $(k'=1-2)$, unit patterns which take multi-refractive sound into consideration are obtained at the observation point $P(\bar{p})$:

$$L_{RS,k,i}^{'}(\bar{p})=L_{FS,k,i}^{'}(\bar{p})+\Delta L_{P,k}(\bar{p})\ \ [dB]\ \ (k=1,2)\ \text{for a passenger car}, \tag{21}$$

$$L_{RB,k,i}^{'}(\bar{p})=L_{FB,k,i}^{'}(\bar{p})+\Delta L_{P,k}(\bar{p})\ \ [dB]\ \ (k=1,2)\ \text{for a large car}. \tag{22}$$

The unit patterns for the sound sources $S_{k'}(k'=3-6)$ are obtained according to the ASJ Model-1998 as:

$L'_{RSk'j}\cdot(\bar{p})=L'_{FSk'j}\cdot(\bar{p})+\Delta L_{Dk'j}\cdot(\bar{p})+\Delta L_{Gk'j}\cdot(\bar{p})+\Delta L_{Mk'j}\cdot(\bar{p})$ $[dB]$ for a passenger car, (23)
$L'_{RBk'j}\cdot(\bar{p})=L'_{FBk'j}\cdot(\bar{p})+\Delta L_{Dk'j}\cdot(\bar{p})+\Delta L_{Gk'j}\cdot(\bar{p})+\Delta L_{Mk'j}\cdot(\bar{p})$ $[dB]$ for a large car and, (24)
$L'_{Rsr,k'j}\cdot(\bar{p})=L'_{Fsr,k'j}\cdot(\bar{p})+\Delta L_{Dk'j}\cdot(\bar{p})+\Delta L_{Gk'j}\cdot(\bar{p})+\Delta L_{Mk'j}\cdot(\bar{p})$ $[dB]$ for the noise from the upper track, (25)

where $\Delta L_{Dk}(\bar{p})$ denotes refractive reduction and $\Delta L_{Gk}(\bar{p})$ excess attenuation over the ground. Therefore, the equivalent continuos A- weighted sound pressure level $L_{Aeq}(\bar{p})[dB]$ at the observation point $P(\bar{p})$ is:

$$L_{Aeq}(\bar{p})=10\log\left[\sum_{k'=1}^{4}\left\{\frac{\overline{N_S}\cdot\Delta l}{\bar{l}T}\left(2\sum_{i'=1}^{m}10^{\frac{L'_{RSk'j}\cdot(\bar{p})}{10}}+10^{\frac{L'_{RSk',0}(\bar{p})}{10}}\right)\right\}+\frac{\overline{N_B}\cdot\Delta l}{\bar{l}T}\left(2\sum_{i'=1}^{m}10^{\frac{L'_{RBk'j}\cdot(\bar{p})}{10}}+10^{\frac{L'_{RBk'j}(\bar{p})}{10}}\right)\right.$$
$$\left.+\sum_{k''=5}^{6}\left[\frac{\overline{N_B}\cdot\Delta l}{\bar{l}T}\left(2\sum_{i'=1}^{m}10^{\frac{L'_{Rsrk''j}\cdot(\bar{p})}{10}}+10^{\frac{L'_{Rsrk'',0}(\bar{p})}{10}}\right)\right]\right][dB], \qquad (26)$$

where $\overline{N_S}$ and $\overline{N_B}$ are respectively, the numbers of passenger cars and large size cars per 3600 [sec] and $T(=3600[\text{sec}])$ is the integration time.

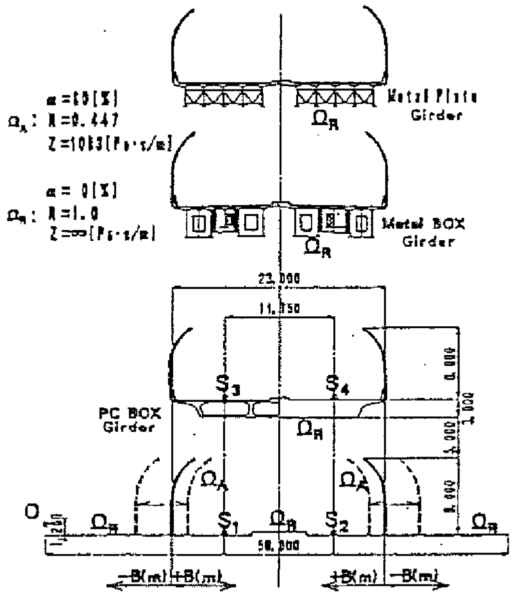


Fig.3 Analytical models for double-decker road (bottom of upper track is flat, I-beam and box)

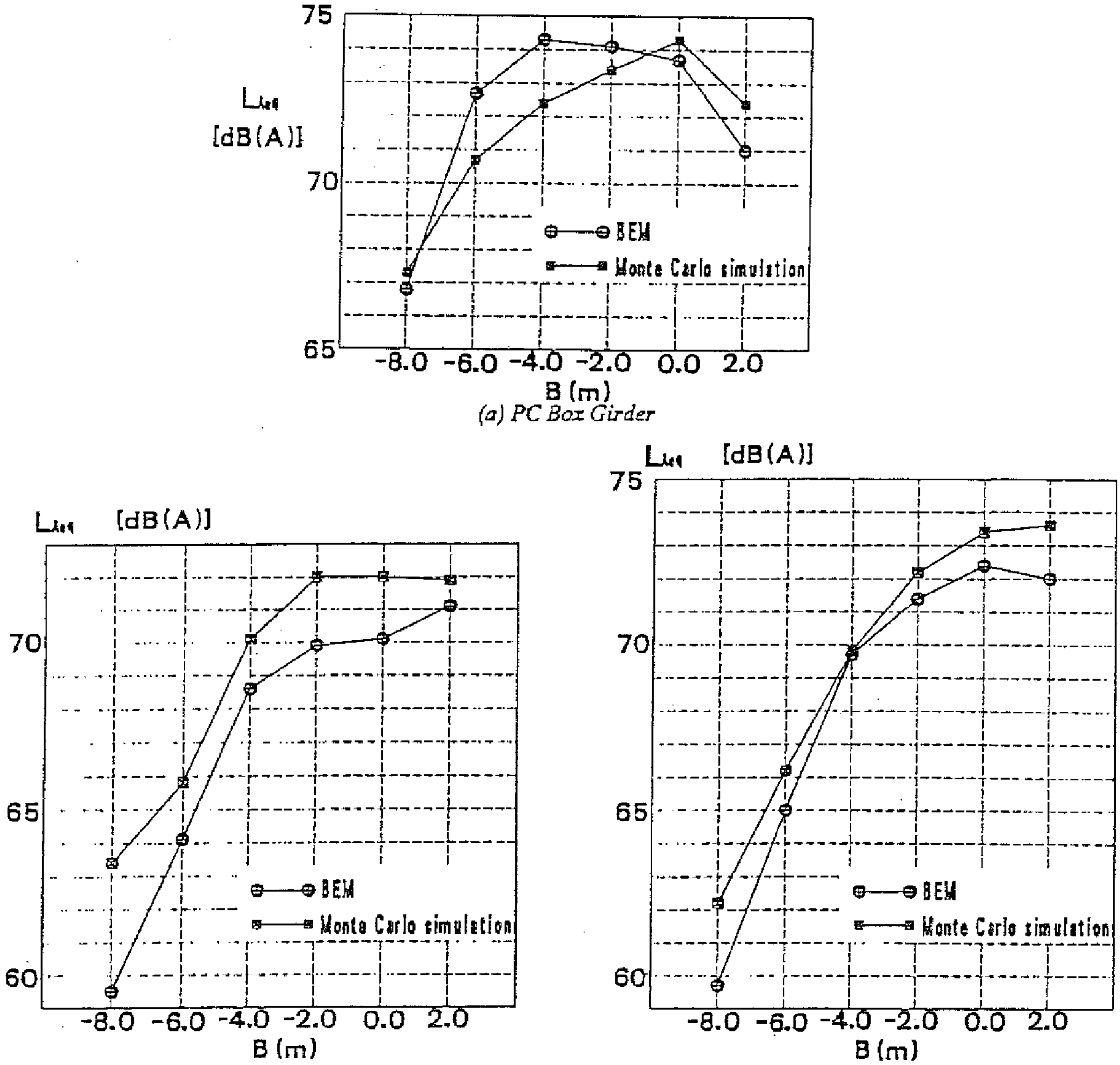
INFLUENCE OF SOUND BARRIER POSITION ON SOUND PRESSURE LEVELS (COMPARISON BETWEEN BEM AND MCS VALUES FOR L_{Aeq})

In our previous paper, we calculated the reflective noise levels from upper tracks, under which there is a planar track using the Monte Carlo Simulation and clarified the noise particularities, using as parameters the positions of noise barriers along the underlying track. In this section, we calculate two reflective noise levels $L_{Aeq}[dB]$ from elevated tracks, under which there is a planar track using the Monte Carlo Simulation and the method presented in the preceding section, using as parameters the position of noise barriers along the underlying track (see Fig .3), and we compare these two results.

The double-decker road is modeled by three types of upper track structures shown in Fig.3. In these three models, the height of sound barriers on the under track is $8.0[m]$ and the space between the bottom of the girder supporting the upper track and the top of the noise barrier on the planar road is $D=5.0[m]$ (see Fig.3). We assume that the upper road and the under road are two - lane roads. The sound sources are located at the center line of each lane. For the sound sources S_1 and S_2 of the under road, the number of passenger cars per hour is $N_{CS}=1200$, the number of large cars per hour is $N_{CB}=300$ and the speed of vehicles is $V=60[km/h]$. For the sound sources S_3 and S_4 of the upper road, the number of passenger cars per hour is $N_{HS}=1600$, the number of large cars per hour is $N_{GB}=400$ and the speed of vehicles is $V=100[km/h]$. For the sound sources S_5 and S_6 from the upper track, the number of large cars

/9

the side surface Ω_A of the sources of sound barriers is α=0.8 and the boundary condition for the other surface Ω_R is α=0. Shown in Fig.4(a), (b) and (c), are the equivalent continuous A- weighted sound pressure levels $L_{Aeq}[dB]$ at the observation point O using as a parameter $B[m]$ the position of sound barriers along the under track. In Fig.4(a) and (c) (PC Box and Metal Box), it can be seen that the calculated values of $L_{Aeq}[dB]$ using MCS and BEM are in good agreement. In Fig.4(b) (Metal Girder), compared with the values using MCS, the values using BEM tend to be underpredicted by about 1~4$[dB]$. The results of BEM as well as the results using MCS show that road traffic noise decreases with setting back sound barrier on the planar road from the road.



(a) PC Box Girder

(b) Metal Plate Girder

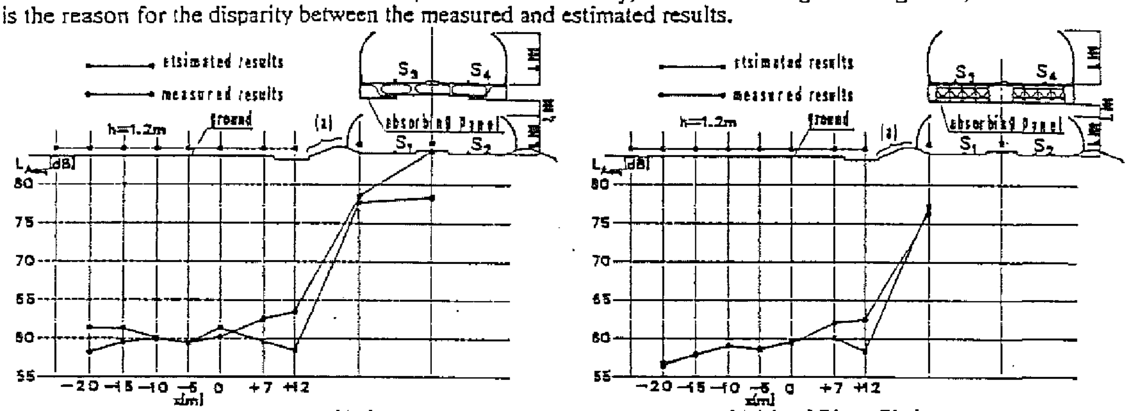
(c) Metal Box Girder

Fig.4 Equivalent continuous A-weighted sound pressure levels L_{Aeq} using BEM and MCS

COMPARISON BETWEEN ESTIMATE AND MEASURED VALUES OF SOUND-PRESSURE LEVELS L_{Aeq}

We measured the equivalent continuos A- weighted sound pressure levels L_{Aeq} for two types of actual double-decker roads shown in Fig.5. At the same time, we measured traffic volumes and the running speed of vehicles in order to compare with values calculated using the BEM. In Fig.5(a) and (b), the height of sound barriers on the under road is 6.0$[m]$, the height of sound barriers on the upper road is 8.0$[m]$ and the space between the bottom of the girder supporting the upper track and the top of the sound barriers on the under road is about 2$[m]$. The difference between

Fig.5(a) and (b), is the width of the absorbing panels placed under the elevated track. For the estimation of the equivalent continuous A-weighted sound pressure levels L_{Aeq}, the road traffic condition represented by sound sources S_1 and S_2 is a traffic volume of N_{GS}=750 passenger cars and N_{GB}=370 large cars per hour and a running speed of V=64[km/h] from the measured results. Similarly, one of the sound sources S_3 or S_4 represents a traffic volume of N_{HS}=1296 passenger cars and N_{HB}=504 large cars per hour and a running speed of V=80[km/h]. Furthermore, the boundary conditions of the absorbing panels placed under the upper track and in the sound barriers (Ω_A) is an absorption coefficient of α=0.8 in the BEM models. The pavement of the under road is porous asphalt, in the BEM models, the boundary condition of the pavement is an absorption coefficient of α=0.23. For others surfaces, such as rigid surfaces, the boundary condition is an absorption coefficient of α=0. Shown in Fig.5(a) and (b), are the equivalent continuous A-weighted sound pressure levels $L_{Aeq}[dB]$ of the measured results and estimated results using BEM plotted at points 1.2[m] above the ground. In both the double-decker road structures considered, the results measured and estimated using BEM are almost in agreement; however, for observation points x=7[m] and 12[m], the results of BEM tend to over predict the $L_{Aeq}[dB]$. For the ground located at the observation side of the barriers, the boundary condition for the BEM models is defined for a reflective surface, however in actuality, there exist foliage on this ground, which we believe is the reason for the disparity between the measured and estimated results.



(a) PC Box Girder (b) Metal Plate Girder

Fig.5 L_{Aeq} from double-decker road structures along the absorbing panel placed under the upper tracks

CONCLUSIONS

Our conclusions are summarized as follows:
1)Combining sound pressure levels using BEM with the method based on the ASJ Model-1998, enables the calculation of the equivalent continuous A- weighted sound pressure levels L_{Aeq}. 2)In the assessment of sound barrier position for double-decker road structures, the results using the MCS and the BEM are almost in agreement. Furthermore, not only the MCS but also the BEM predictions showed the effect of setting back the sound barrier on the planar road from the road for the decrease of road traffic noise. 3)An agreement between the measured results and estimated results using the BEM, was obtained.

Issues to be resolved in the case of the BEM prediction method are summarized as follows:
1)We need to confirm whether the prediction method using BEM can be applied to cases other than that mentioned above. 2)It takes considerable time to calculate by using the BEM, this prediction method requires to be reduced the time for an calculation.

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