Research activities on INCE/J RTV (Road Traffic Vibration)-Model

- Part: 2 Prediction of ground-borne vibration induced by traffic from cutting- and banking-structure roads -

Sunao KUNIMATSU[1]; Yasutoshi KITAMURA[2]; Akinori YOKOTA[3]; Hidenobu UCHIDA[4]; Masayuki SHIMURA[5]; Yasuyuki SANO[6]; Toshikazu OSAFUNE[7]; Hiroshi IWABUKI[7]; Riei ISHIDA[8]; Yoshihiro HIRAO[9]

[1] National Institute of Advanced Industrial Science and Technology, Japan

[2] Construction Engineering Research Institute Foundation, Japan

[3] Rion Co. Ltd., Retired, Japan; [4] Tobishima Corporation, Japan

[5] Civil Engineering and Eco-Technology Consultants Co. Ltd., Japan

[6] Aichi Institute of Technology, Japan; [7] Nippon Expressway Research Institute Co. Ltd., Japan

[8] Freelance, Japan; [9] Kobayasi Institute of Physical Research, Japan

ABSTRACT

In INCE/J, the prediction method of the first version of INCE/J RTV-Model named INCE/J RTV-Model 2003 for environmental impact assessment on ground-borne vibration induced by the road traffic was published for flat roads in 2003. L_{V10} (10 percentile-exceeded frequency weighted acceleration level) is used in the vibration evaluation for an environmental assessment in Japan. For this reason, the prediction in the model was based on a method to calculate the summation in decibel considering traffic volume within the defined time from the unit pattern which is the time history of vibration acceleration level at the prediction point when one vehicle runs on the road. The unit pattern could be calculated by using a simply empirical equation for the distance attenuation by Bornitz. In order to extend the previous model to a new applicable model for both cutting- and banking-structure roads, numerical simulations were performed. These results were summarized in this paper.

Keywords: Ground-borne vibration, Prediction method, Numerical simulation I-INCE Classification of Subjects Number(s): 40

1. INTRODUCTION

Environmental impact assessment law which performs an evaluation, a prediction by investigating environmental impact by large-scale development project beforehand was established in 1997 in Japan, and it is enforced in the local government by the regulations. L_{V10} (10 percentile-exceeded frequency weighted acceleration level) provided from the vibration level of vertical direction at the site boundary

1 s.kunimatsu@aist.go.jp
2 yktmr@port.kobe-u.ac.jp
3 yokota_akinori@biglobe.jp
4 Hidenobu_Uchida@tobishima.co.jp
5 shimura@kensetsukankyo.co.jp
6 sano-y@aitech.ac.jp
7 t.osafune.aa@ri-nexco.co.jp
8 ishida501@cronos.ocn.ne.jp
9 hirao@kobayasi-riken.or.jp

line of roadway is used for the evaluation in the vibration prediction concerning the running vehicle. For the prediction of L_{V10}, there was only a predicting equation proposed by PWRI (Public Works Research Institute) and the prediction equation has been used for the prediction. However the development of the predicting equation based on a physical background has been expected because the predicting equation was a statistical predicting equation. Therefore, in INCE/J, the prediction method of ground-borne vibration induced by traffic, INCE/J RTV-Model for flat roads was published in 2003.

In order to get knowledge to extend the previous model to a new applicable model for both cutting- and banking-structure roads, the unit pattern which is the time history of vibration acceleration level at the prediction point when one vehicle runs on the road is calculated by numerical simulation. In the RTV-Model 2003, the unit pattern can be calculated by using a simplified empirical equation for the distance attenuation proposed by Bornitz for the time change of the distance in a straight line between the prediction point and the reference point which are near to the position of the vehicle on the road. Only applicability of the unit pattern by simplified equation to the unit pattern by numerical simulation and the variable included in the simplified equation are discussed in this paper.

2. OUTLINE OF INCE/J RTV-Model 2003 AND SOME PROBLEMS TO BE CONSIDERED FOR THE EXTENSION

2.1 Outline of predicting equation proposed by PWRI

The predicting equation proposed by PWRI (PWRI equation) corresponds to flat, cutting-structure, banking-structure and elevated roads. The coefficient and the constant term of each factor of the predicting equation were determined by the multiple regression analysis using a large number of actual survey data which PWRI collected. In addition, this coefficient and constant term have been updated with the accumulation of actual survey data appropriately. Traffic volume, running speed, the number of the traffic lanes, the road surface roughness, the dominant frequency of the ground, road structure are included as the factors for the predicting equation of L_{V10}^{*} at reference point. L_{V10} in the prediction point is provided by subtracting the attenuation by the distance between the reference point and prediction point from L_{V10}^{*} at reference point.

For the cutting-structure, the banking-structure and ditch-structure, only height is considered as a correction value for L_{V10}^{*} by the road structure. In elevated roads, the constant of L_{V10}^{*} is changed by the condition that the number of bridge pier is one pier or more than one pier.

For flat roads, two types of viscous and sand ground are considered for getting the value of attenuation by distance. The reference point for flat roads is the receiving point at 5 m from the outside traffic lane.

This predicting equation has advantage that L_{V10} is calculated easily, but it is not possible to examine influence of the traffic volume according to the traffic lane in this equation because it cannot perform energetically-possible addition.

2.2 Outline of INCE/J RTV-Model 2003

In RTV-Model 2003, the applicability of the simplified equation based on the Bornitz equation was examined for the layered ground with six kinds of representative ground constitution by comparison with distance attenuation properties of the ground vibration to propagate from fixed point vibration source. As a result, it was recognized that the simplified equation was applicable enough on the ground where propagation speed of the S-wave became gradually fast towards a depth direction. On the other hand, the applicability worsened on the ground including the layer that propagation speed of S-wave was slow under the surface layer, but it was deemed that the simplified equation was applicable though the predicted vibration acceleration level became a little slightly bigger in case of the range of frequency such as the ground-borne vibration induced by road traffic. However, in RTV-Model 2003, the time history of vibration acceleration level calculated by the simplified equation for the straight-line distance between point source and prediction point changing with time was considered to be the unit pattern based on the knowledge obtained from observation experience because a simulation technology of the ground-borne vibration induced by road traffic in consideration of the vehicle travel did not develop in those days (1).

Because the equation development and the predictive calculation for RTV-Model 2003 were presented in inter-noise 2006 (2,3), the detailed description is omitted in this paper. The predictive calculation is carried out by the flow shown in Figure 1 roughly. At first, it is determined whether the ground can be modelled as the half infinity ground to use the simplified equation based on the Bornitz equation. The reference point is the point 1m away from the traffic lane center and the vibration acceleration level at the reference point is calculated by giving road surface roughness, equivalent thickness of pavement, running speed, constant of vehicle classification (two type of vehicle; heavy and small vehicle) and constant of ground classification (three type of ground; loam, sand gravel and alluvium) as parameters. The simplified equation is used as the relative distance attenuation equation assuming that the vibration acceleration level at the reference point is the reference value. Therefore, the reference point moves with the vehicle as discrete point source, and the reference value corresponding to vibration source is given at the reference point near vibration source. On the other hand, the reference point in PWRI equation is the receiving point at 5 m from the outside traffic lane as mentioned above. From the point of view concerning the reference point, the prediction procedure in RTV-Model 2003 is different from that in PWRI equation greatly.

In RTV-Model 2003, it becomes basic to calculate the unit pattern of the vibration acceleration level by the run of one vehicle which is considered as moving point sources and the value of its time integration. The addition of the energy depending on traffic volume is carried out for the result and the equivalent vibration acceleration level as time average is calculated. Furthermore, this equivalent vibration acceleration level is converted into equivalent vibration level into L_{V10} (Ref. Figure 1, Figure 2).

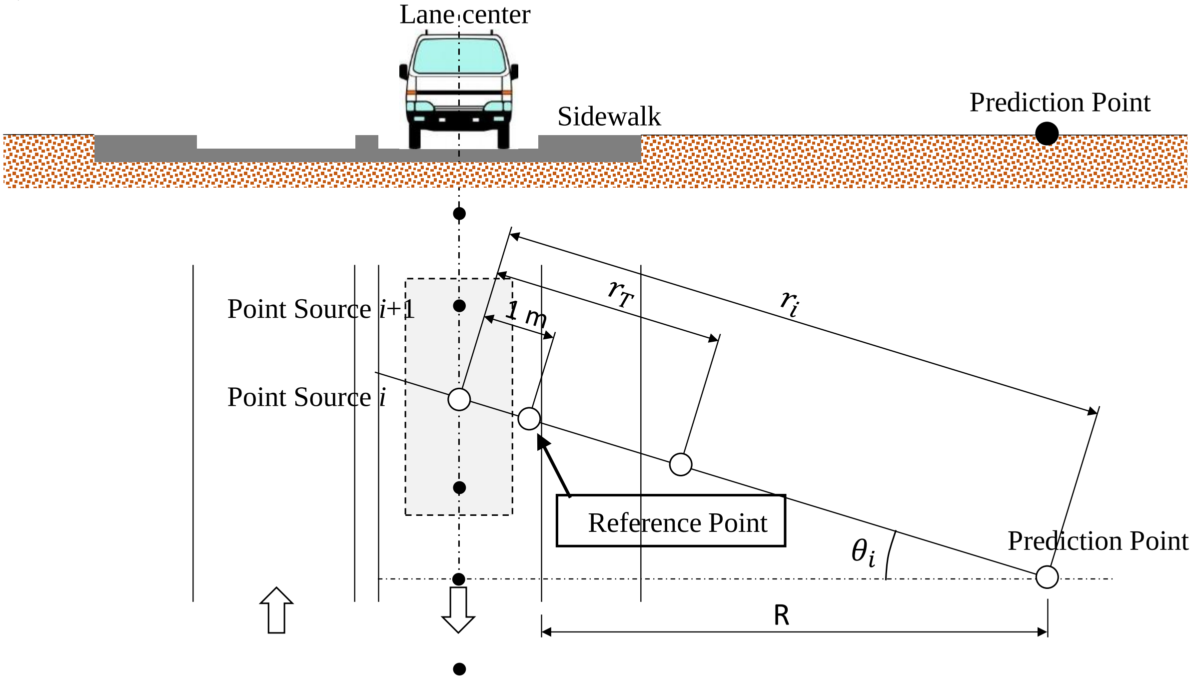


Figure 1 – Conceptual diagram of RTV-Model 2003

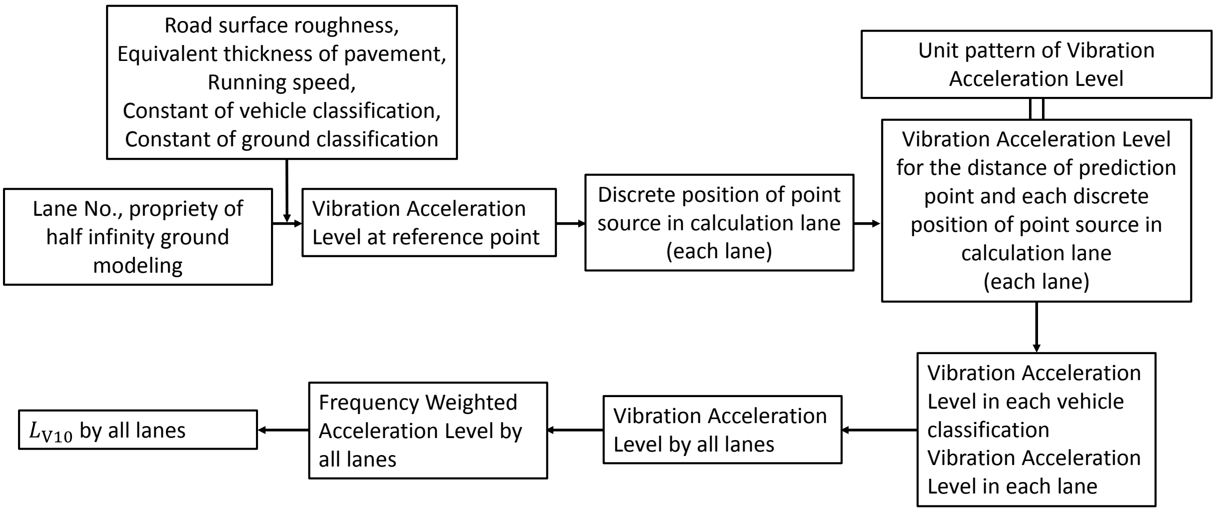


Figure 2 – The flow chart of the predictive calculation by RTV-Model 2003

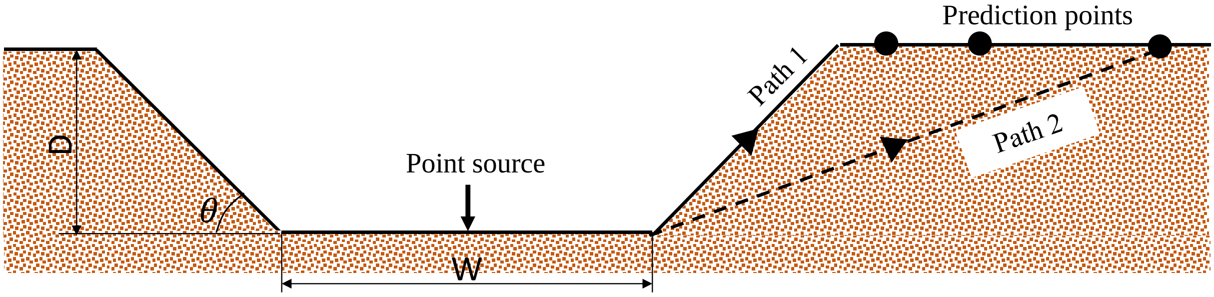
2.3 Some problems to be considered for the extension to cutting- and banking-structure roads from flat roads

Figure 3 shows schematic view of a cutting-structure road and a banking structure road.

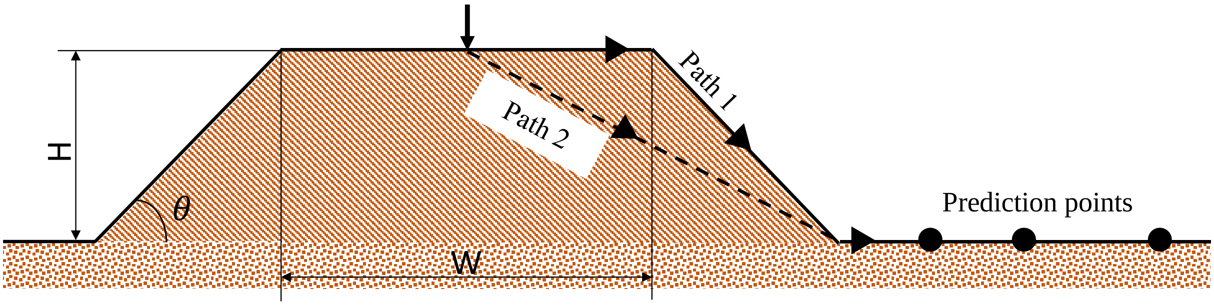
When it is tried that the predictive method of the flat road is extended to a cutting-structure and a banking-structure roads, the problems that should be considered include the following mainly.

2.3.1 Wave propagation path

In the application of the simplified equation, the examinations about the way of thinking of the propagation distance by the difference of the geometric shapes from the position of the vehicle considered to be moving point source to the prediction point and the attenuation with distance (geometric and internal attenuation) are necessary. In the propagation path, two paths shown in Figure 3 are considered as a simple propagation path. Path 1 is a path propagating along the ground surface and Path 2 is a shortest path through the ground arriving at the prediction point from an exciting force.



(a) Cutting-structure road



(b) Banking-structure road

Figure 3 – Relations with the propagation path and the propagation distance for RTV-Model

2.3.2 Properties of banking material

The case that is different from the material properties of original ground in the properties of banking material is usually thought about to build banking on the original ground. As for this, it is related to the setting of the value of the internal attenuation coefficient of the simplified equation based on the Bornitz equation.

About these, the examinations were performed by calculating the unit pattern from the numerical simulation result that assumed a vehicle travel moving source.

3. NUMERCAL SIMULATION METHODS OF THE GROUND-BORNE VIBRATION INDUCED BY TRAFFIC IN CONSIDERATION OF THE VEHICLE TRAVEL

3.1 Modeling of the dynamic grounding load to be caused by a running vehicle

The power spectrum $S_Q(p)$ (p : circular frequency) of dynamic grounding load by interaction of the vehicle and the road surface irregularity is provided by multiplying the frequency response function of grounding load of the vehicle and the power spectrum of road surface irregularity. Using the power spectrum of dynamic grounding load, the time history of the grounding load $Q(t)$ is expressed by the equation (1) as superposition of harmonic vibration load.

$$Q(t) = \sum_{j=-\mathrm{N}, j\neq 0}^{j=\mathrm{N}} \left(\sqrt{S_Q(\bar{p}_j) \cdot \Delta p_i} \, e^{i\varphi_j} \right) \cdot e^{i\bar{p}_j t} \quad (1)$$

Here, $\bar{p}_j$, φ_j are the circular frequency and the phase in the j th section when a limited frequency domain is divided into N section. By discretizing like equation (1), the ground vibration solution for the moving harmonic vibration load of single frequency $\bar{p}_j$ with the load amplitude $\sqrt{S_Q(\bar{p}_j) \cdot \Delta p_j e^{i\varphi_j}}$ is calculated and the ground-borne vibration induced by one vehicle is obtained by superposing the solution for the frequency component of the N section. The power spectrum (ISO/DIS 2631, 1972) published by ISO is used for the power spectrum of the road surface irregularity. The uniform random numbers are used for the phase of the equation (1) because the power spectrum by ISO contains no information on the phase angle.

If it is considered the spatial frequency of road profile to 2.0 c/m, the maximum frequency of the dynamic grounding load to occur becomes 33.3 Hz for the vehicle speed 60 km/h and 44.4 Hz for the vehicle speed 80 km/h.

3.2 Thin layer element solution for the moving harmonic vibration load of single frequency

Suppose that ground surface is flat and consider the case that harmonic vibration load of the single frequency runs at constant speed on x-axis. At this moment, the vibration load is expressed with the Dirac delta function.

If Fourier transform with respect to space x, y and finite Fourier transform with respect to time t for motion equation are performed, motion equation becomes the ordinary differential equation on space z. Then if the ground is discretized by thin layer to z-axis direction, and the Galerkin method is applied for thin layer elements, the simultaneous linear equation on displacement in frequency ω_n —wave number k_x, k_y domain is provided

At first, using vibration load being expressed with the Dirac delta function, the inverse Fourier transform with respect to wave number k_x is carried out. Next, the displacement solution of the closed form is provided if frequency ω_n is fixed and the orthogonality characteristics of the eigenfunction are applied for the motion equation with respect to k_y. Furthermore, the displacement solution in the real space is found if the displacement solution provided by a previous step is superposed for frequency ω_n. The time history of vibration acceleration level (the unit pattern) is provided by the displacement solution being converted into the vibration acceleration level (Ref. Figure 4).

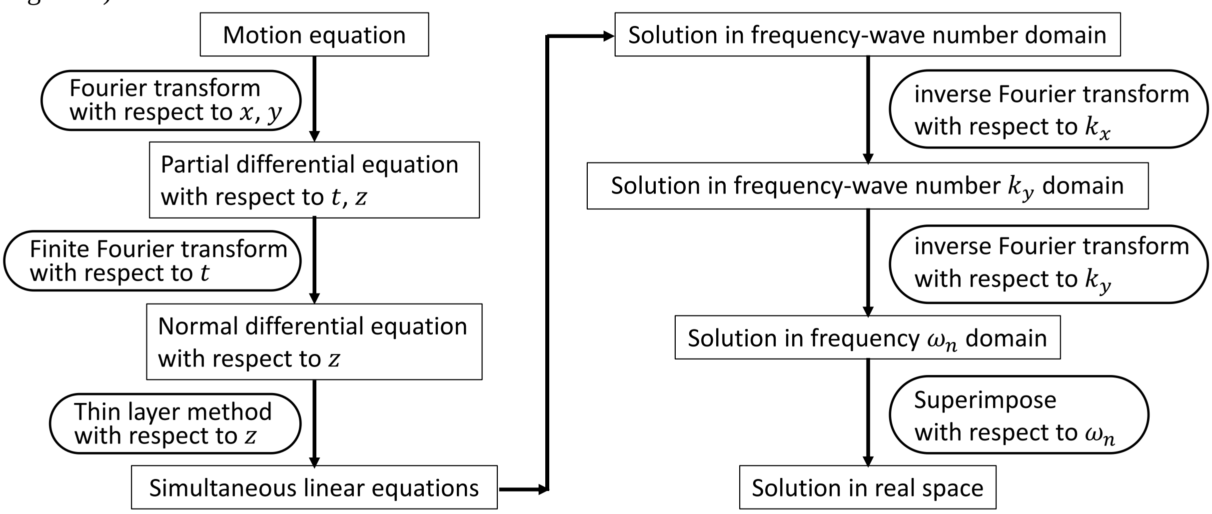


Figure 4 – The calculation flow about thin layer element solution

3.3 Boundary element solution for the moving harmonic vibration load of single frequency

If Fourier transform with respect to space x, y, z and finite Fourier transform with respect to time t for motion equation are performed, the simultaneous linear equation on displacement in frequency —wave number domain is provided. After the inverse Fourier transform with respect to wave number k_x is carried out using vibration load being expressed with the Dirac delta function, the provided displacement solution is resolved partial fraction, and the reverse Fourier conversion with respect to wave number k_y, k_z is performed. The displacement and stress fundamental solutions of closed form for infinite elastic body are derived by applying residue theorem of complex integration to the results.

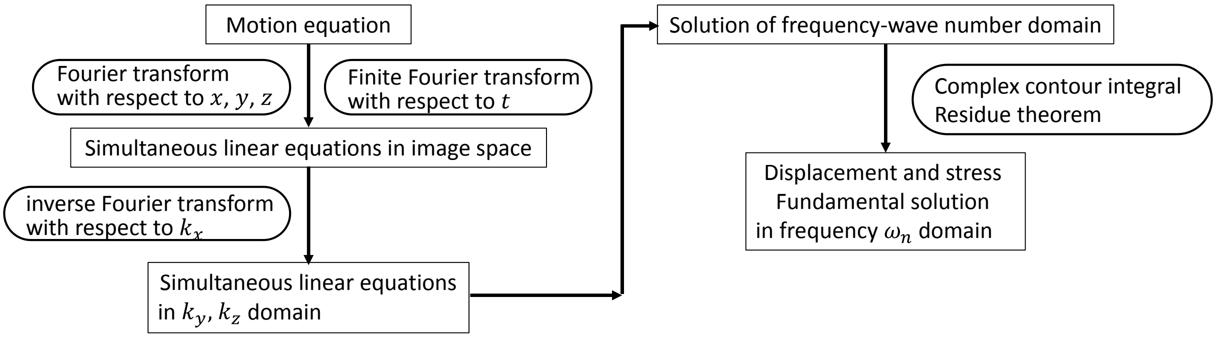


Figure 5 – The calculation flow about boundary element solution

A boundary element analysis is carried out using these fundamental solutions, and the displacement solution in the real space is found by superposing the displacement solution of a provided frequency domain. The time history of vibration acceleration level (the unit pattern) is provided by the displacement solution being converted into the vibration acceleration level (Ref. Figure 5).

3.4 Numerical method for flat road

Thin layer element method is applied for the flat roads. The quadratic shape function is used for the displacement function. The thickness of the thin layer element is considered to be variableness for the exciting frequency, and it is set to 1/5 of wavelength. In addition, the set of the boundary of the finite depth is necessary, and the depth of bottom end is considered to be variableness for the exciting frequency, and it is set to 1.5 times of the wavelength.

3.5 Numerical method for cutting-structure road

Boundary element method is applied for the cutting-structure roads. The linear shape function is used for the displacement function. The size of the boundary element is considered to be variableness for the exciting frequency, and it is set to 1/10 of wavelength. The finite fictitious ground surface is inserted into infinite elastic ground to realize the actual ground surface. The finite length of the ground surface is considered to be variableness for the exciting frequency, and it is set to the distance of one wavelength from the farthest prediction point.

For shortening of the calculation time, the cutting-structure is considered to be symmetry for the running path of the vehicle, and the analysis model is reduced in consideration of symmetric property on the one side.

3.6 Numerical method for banking-structure road

The hybrid method which applies a boundary element method to the part of banking and a thin layer element method to the part of original ground is adopted. As for the element size in the boundary element method, the same condition as a cutting-structure road is adopted. Also, as for the thickness of thin layer element and the depth to the bottom end, the same condition as a flat road is used.

4. COMPARISON OF THE RESULTS BY NUMERICAL SIMULATION AND THE RESULTS BY SIMPLIFIED PREDICTION

4.1 Flat road

The unit pattern by the simplified equation in RTV-MODEL 2003 was not inspected by using the numerical simulation results, because a simulation technology of the ground-borne vibration induced by a moving load did not develop in those days.

In this paper, the inspection of a unit pattern used in RTV-MODEL 2003 is carried out using a simulation technology of the road traffic vibration in consideration of the run of the vehicle. In the Figure 6 and Figure 7, the unit pattern by the simplified equation is compared with the unit pattern by the numerical simulation for the flat road of loam and sand gravel ground. The value shown in Table 1 was used for the material constant of the ground, and the vehicle speed was set to 60 km/h. Power spectrum of the ISO (1972) was used for the road surface irregularity, and the degree of the irregularity was assumed with a spectrum level of the boundary of “Goodness and Usually”.

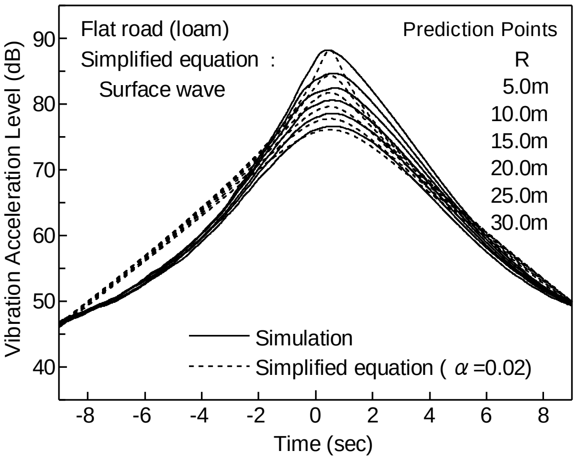


Figure 6 – Flat road (loam)

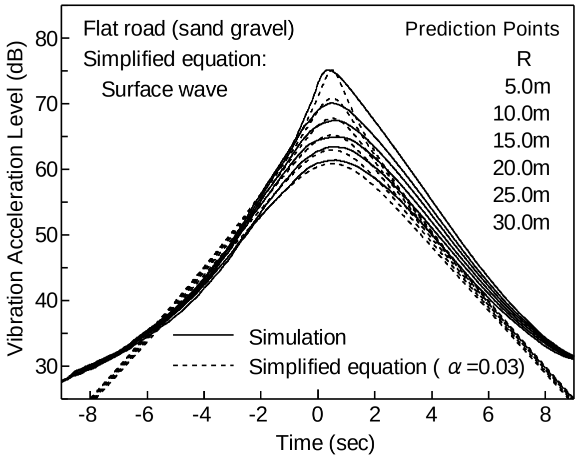


Figure 7 – Flat road (sand gravel)

Table 1 – Material constants of the ground used for numerical simulation (Except banking-structure roads)

Road structures	V_s (m/s)	N value (ref.)	Density (t/m^3)	Poisson’s ratio	Damping constant
Flat (loam)	130	3	1.4	0.3	0.02
Flat (sand gravel)	200	10	2.0	0.35	0.04
Cutting	200	10	1.8	1/3	0.02

Here, the unit pattern by numerical simulation was provided by the unit pattern of the power average of the unit pattern that tried 100 times using random numbers in the phase information of the road surface irregularity. In addition, two unit patterns were compared by matching the peak level of the unit pattern of prediction point No.1 (5 m point) by the simplified equation with the peak level of the unit pattern by the simulation because the unit pattern by the simplified equation is found at a relative level. The prediction points were set at intervals of 5 m in 5 m – 30 m.

When the simplified equation is applied, the setting of the constant of the geometric attenuation n and internal attenuation coefficient of the ground α become the problem. In RTV-Model 2003, it is supposed it is the body wave (n=1.0) at the interval from the reference point 1 m away from the moving point source to 15 m and it is the surface wave (n=0.5) at the distance more than 15m. However, the way of thinking to be the body wave to 15 m is not adopted in this paper because it is thought that it is necessary to be considered based on much simulation results. Also, though internal attenuation coefficients from actual survey experience about the distance attenuation of the ground vibration are given for three kinds of ground (loam, sand gravel, and alluvium) in RTV-Model 2003, it is necessary to pay attention to not necessarily according with internal attenuation coefficient α in RTV-MODEL 2003 because the material constant of the ground in the simulation is one case as showed in Table 1 in Figure 6 and Figure 7.

In Figure 6 and Figure 7, the simplified equation was supposed to be the equation (n=0.5) only for surface waves and the suitable value of internal attenuation coefficient α was found by examining the compatibility of a general shape by a try and error method. The internal attenuation coefficient in the simplified equation that compatibility is good for a unit pattern by the simulation becomes the almost near value for α = 0.014 of the loam and α = 0.031 of the sand gravel in RTV-Model 2003. In addition, as for the shape around the peak of the unit pattern, the pattern by the simplified equation becomes narrower than a unit pattern by the numerical simulation. The width of the unit pattern around the peak by the simplified equation may become narrow, and the shape less agrees more if supposed to be a body wave to 15m in RTV-Model 2003.

4.2 Cutting-structure road

In the numerical simulation model, only one case of D=3 m in the depth, W=11 m in the width of the base of the cutting-structure, 60km/h in the vehicle speed was assumed, and the two cases of the angle of the slope, 30 degrees and 90 degrees (as the approximation of ditch-structure) were examined. The material constant of the ground is shown in Table 1 and the road surface irregularity was set as well as the model of flat road. Path 1 and Path 2 shown in Figure 3 (a) were considered. It is supposed that a surface wave propagates along the ground surface from the vibration source to the prediction point in Path 1, and that a surface wave propagates along the ground surface from the vibration source to the foot of slope, and a body wave propagates through the underground from the foot of slope to the prediction points in Path 2.

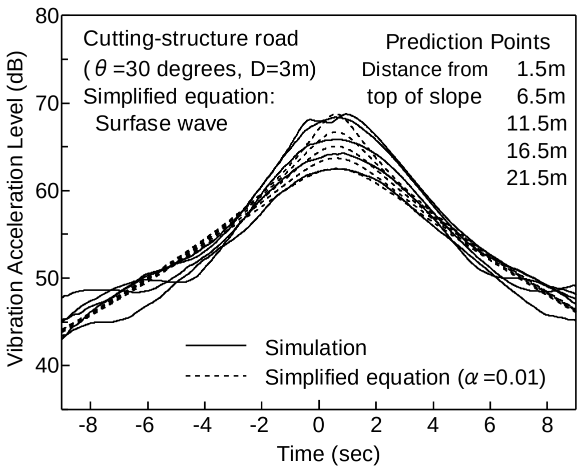


Figure 8 – Cutting-structure road (θ =30°, Path 1)

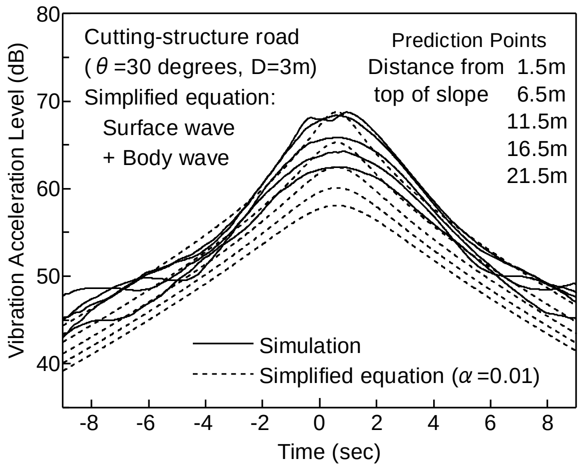


Figure 9 – Cutting-structure road (θ =30°, Path 2)

The results for the cutting-structure road with 30 degrees slope are shown in Figure 8 and Figure 9, and the results for the 90 degrees slope are shown in Figure 10 and Figure 11.

In the cutting-structure road with 30 degrees slope, it is understood that Path 1 of Figure 8 has better compatibility in comparison to Path 2 of Figure 9 for the shape of the curve of the unit pattern by the simplified equation and the attenuation situation for the distance of the peak level. On the other hand, though the unit pattern by the numerical simulation is slightly complicated in the 90 degrees slope and it is hard to match the pattern by the simplified equation, it is understood that Path 2 of Figure 11 has better compatibility in comparison to Path 1 of Figure 10 for the shape of the curve of the unit pattern by the simplified equation and the attenuation situation for the distance of the peak level.

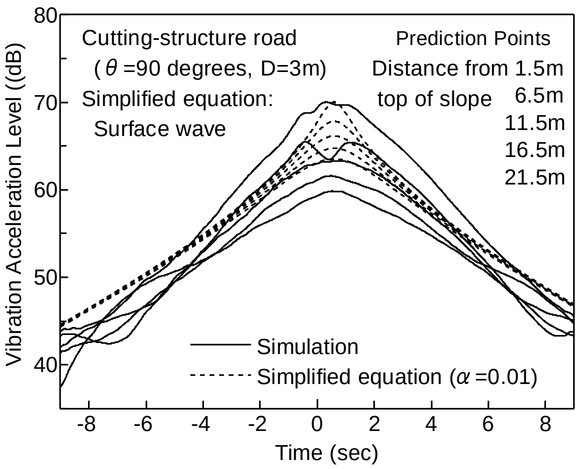


Figure 10 – Cutting-structure road (θ =90°, Path 1)

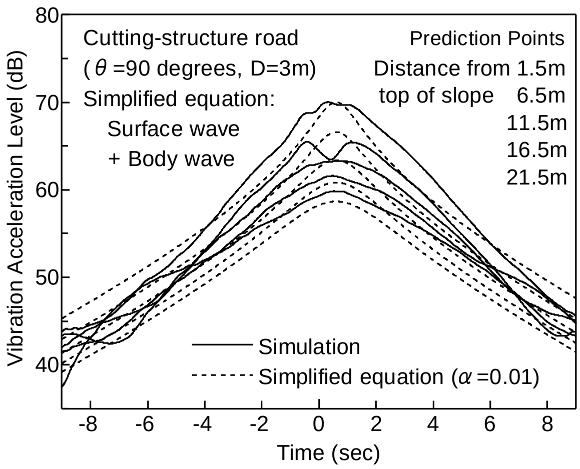


Figure 11 – Cutting-structure road (θ =90°, Path 2)

4.3 Banking-structure road

About the case of H=3 m in the height, W=11 m in the width of the crown of the banking-structure, 60 km/h in the vehicle speed and θ=30 degrees in the angle of the slope, the examination results for Path 1 and Path 2 in Figure 3 (b) are shown in Figure 12 and Figure 13. It is supposed that a surface wave propagates along the ground surface from the vibration source to the prediction point in Path 1, and that a body wave propagates through the underground from the vibration source to the foot of slope, and a surface wave propagates along the ground surface from the foot of slope to the prediction points in Path 2. The material constant of the ground used for the numerical simulation are shown in Table 2. The case different in the material constant of the original ground (the loam ground) is shown in table 2, but mentions it later about this.

It is understood that Path 1 of Figure 12 has better compatibility in Path 2 of Figure 13 for the shape of the curve of the unit pattern by the simplified equation. As the prediction points nears the foot of slope, the width of the unit pattern of Path 2 by the simplified equation becomes narrow in the Figure 13. From these results, it is better choice to adopt the unit pattern of Path 1 in the application of the simplified equation for banking-structure road.

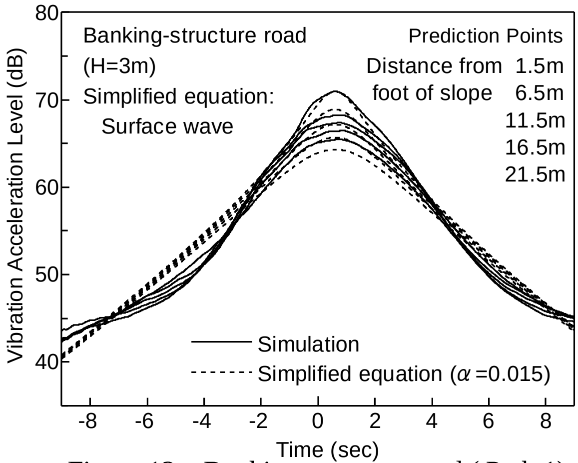


Figure 12 – Banking-structure road (Path 1)

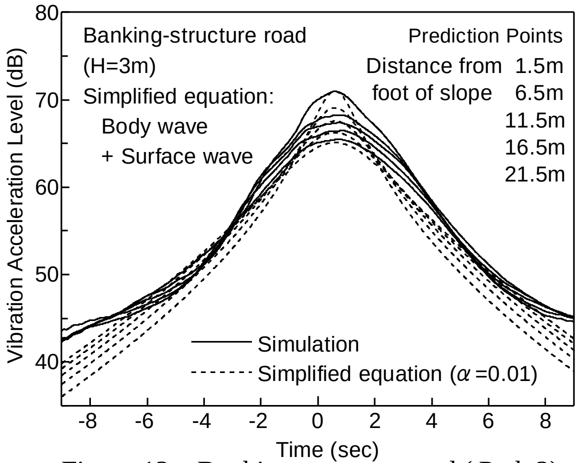


Figure 13 – Banking-structure road (Path 2)

Table 2 Material constant of the ground used for numerical simulation (Banking-structure roads)

Material constants	V_s (m/s)	N value (ref.)	Density (t/m^3)	Poisson's ratio	Damping constant
Banking material	200	10	1.8	1/3	0.02
(1)Original ground	200	10	1.8	1/3	0.02
(2)Original ground (loam)	130	3	1.4	0.3	0.02

For the case of H=5 m in the height, W=21 m in the width of the crown of the banking-structure, 80km/h in the vehicle speed, the degree of compatibility of the unit pattern by the simulation and the unit pattern of Path 1 by the simplified equation is shown in Figure 14 - Figure 16. For each case, the parameter except the value written down here is the same as the value used in Figure 12. The internal attenuation coefficient of the ground was set with α = 0.015 as well as the case of Figure 12. In all cases, the compatibility of the unit pattern by the simulation and the unit pattern by the simplified equation is good.

When the application of the simplified equation based on the Bornitz equation is thought for the flat road, the cutting-structures with 30 degrees slope and 90 degrees slope, the modelling the real ground as the ground with the homogeneous material constants is regarded as a meaningful approximate method. On the other hand, for the banking-structure road, it is thought that properties of banking material are different from the original ground to build the banking material on the original ground. Therefore, suppose that the original ground is the loam ground, the examination result concerning the compatibility of the unit pattern by the simplified equation is shown in Figure 17 when the material constant of the original ground is different from the constant in banking material. The material constants are shown in Table 2. The height and the width of the crown of the banking-structure and the vehicle speed are the same as the value used in Figure 12.

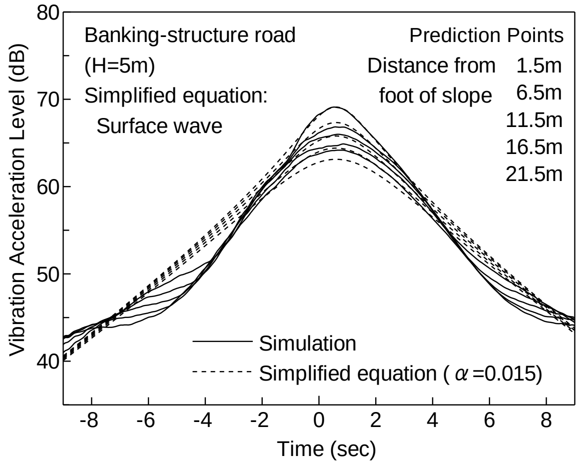


Figure 14 – Banking-structure road (Influence of the height)

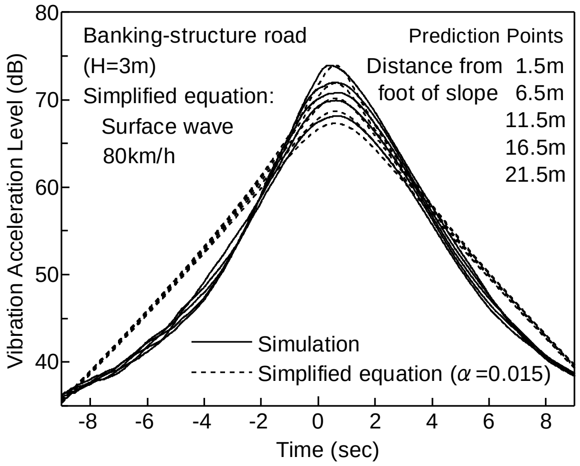


Figure 15 – Banking-structure road (Influence of the vehicle speed)

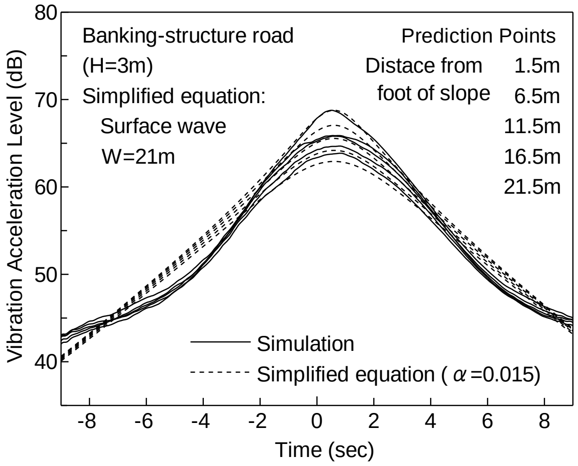


Figure 16 – Banking-structure road (Influence of the width of crown)

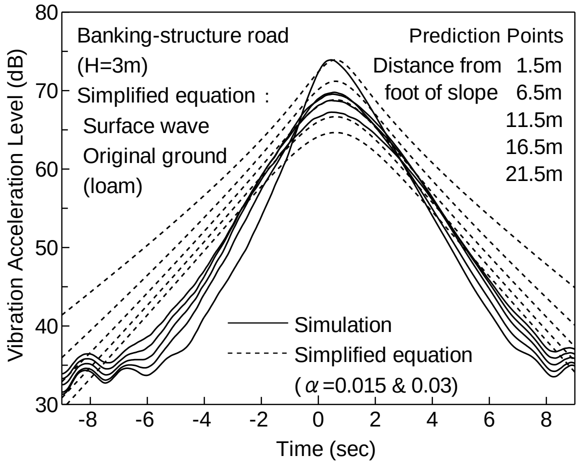


Figure 17 – Banking-structure road (Influence of the properties of banking material)

When the material constants of the original ground and the banking material are different, the compatibility by the simplified equation is not so good. The decrease ratio in peak level for the distance is improved if supposed to be $\alpha = 0.02$ the internal attenuation coefficient of the original ground, but the compatibility worsens in the shape of the pattern because the shape of the rise and decay of the unit pattern by the simplified equation broadens.

In the cases that the properties of banking material are different from the original ground, the examination that changes conditions is more necessary.

5. CONCLUSION

In order to extend the INCE/J RTV Model 2003 for flat road to a new applicable model for both cutting- and banking-structure roads, numerical simulations in consideration of the run of the vehicle were performed. The propagation path, the constant of geometrical damping and the internal attenuation coefficient were examined from the comparison of the both unit patterns. The inspection by the actual survey is necessary about the validity of the model in future and it is planned.

REFERENCES

1. Technical Committee of INCE of Japan, J. INCE/J, Road Traffic Vibration Prediction Model (INCE/J RTV-Model 2003), 2003, 28(3), pp.207-216.
2. Uchida H, Yokota A, Sano Y, Naruse H. Prediction model “INCE/J RTV-Model 2003” for ground vibration caused by road traffic -Part 1: Outline of the prediction model-. Proc INTER-NOISE 2006; 3-6 December 2006; Hawaii, Japan 2006.
3. Sano Y, Miyake T, Uchida H, Naruse H. Prediction model “INCE/J RTV-Model 2003” for ground vibration caused by road traffic -Part 2: Procedure for calculation-. Proc INTER-NOISE 2006; 3-6 December 2006; Hawaii, Japan 2006.