Special edition paper

Development of a Method of Analytically Considering Ground Vibration



Misa Taniguchi* Yasuo Watanabe* Mitsuru Shimizu*

Problems of ground vibration along Shinkansen routes are expected to increase with faster Shinkansen speeds. We thus have proposed a simplified model on excitation by structures and vibration propagation to the surrounding ground at running of trains. For bridge structures on pile foundations in soft ground for which ground vibration was often pointed out, we studied an analysis method and vibration control work. In this study, we thus examined applicability of that method to spread foundations in relatively firm ground, scrutinized conditions such as the material and size of the vibration control work and proposed an effective vibration control work.

●Keywords: Ground vibration control, Vibration control work, Continuous underground wall, Axisymmetric model

1 Introduction

Transmission of vibration from the structures to the ground at running of trains is expected to be larger with increased Shinkansen speeds. However, methods to evaluate such ground vibration and to choose vibration control work that can effectively reduce the vibration have still not been clearly proposed.

In the past, we have proposed an evaluation technique for effectiveness of vibration control work performed near structures (continuous underground wall)[1] in soft ground areas for which ground vibration was often pointed out. Based on the measurement results of actual ground vibration, we examined whether this technique is also applicable to relatively firm ground. Furthermore, for the choice of effective vibration control work in such ground, we made analytical consideration of different materials, wall thicknesses and depths of the vibration control work. This article will report the study results.

2 Ground Vibration Control

Ground vibration is, as shown in Fig. 1, vibration from the force applied to the structures when a train passes a viaduct and propagated through the piers and the ground to a certain point. Ground vibration control is classified as 1) control near the vibration source, 2) control on the propagation path, and 3) control at the vibration receiving point. Railway operators can easily take measures only within the railway property. The measures in 1) above, such as empty trenches and vibration isolation walls (continuous underground walls) along the viaducts are thus effective.

Fig. 2 shows the concept of vibration reduction by a vibration isolation wall. The incident wave propagated from the vibration source consists of the wave that diffracts around the wall and the wave that penetrates the wall. For the wave that penetrates the wall, it is known that material of the vibration isolation wall that is harder or softer than the ground enhances the effect of isolating the vibration. We thus selected concrete as the harder material and expanded polystyrene (EPS) as the softer material of the vibration control work.

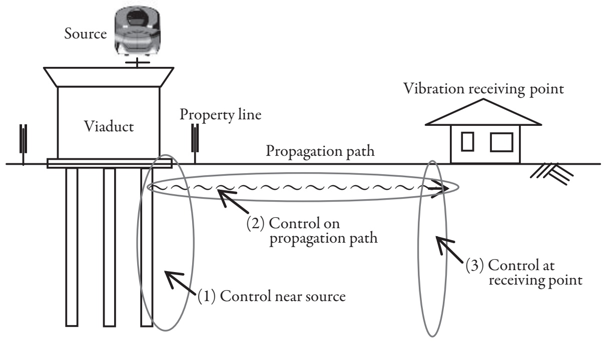

Fig. 1 Vibration Control on the Ground

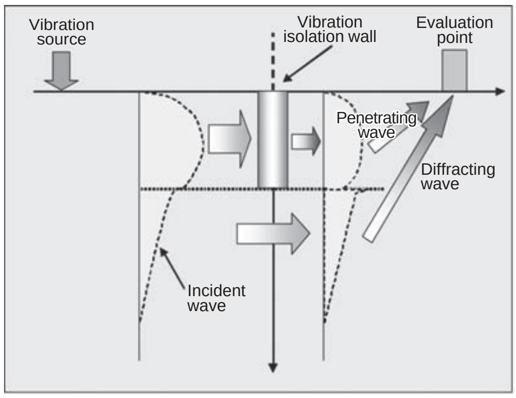

Fig. 2 Concept of Vibration Reduction by Vibration Isolation Wall

3 Verification of Analysis Method

3.1 Overview of Analysis Method

As shown in Fig. 3, vibration at a certain point is a combination of waves of different phases from multiple piers as a train moves. Vibration thus varies by ground layer state and train speed. Here, we modeled four piers for which train vibration is assumed to affect the measurement points and performed analysis.

In ground vibration analysis, we first model a pier and its surrounding ground by the axisymmetric finite element method ("axisymmetric FEM") as shown in Fig. 4. On the modeled current ground, we analyzed vibration to obtain the transfer function between the pier and the nodal points on the ground

*Frontier Service Development Laboratory, Research and development Center of JR East Group

surface. Next, using ground vibration measurement data measured when a train passes, we figured out the pier excitation force of each of four piers by inverse calculation of their transfer functions. Then, applying pier excitation force to the model that took into account the newly developed vibration control work, we obtained the time history of the vibration acceleration that is transmitted from the piers to the measurement points and the vibration level. Finally, we compared those to the values before applying the new vibration control work to evaluate the effect of the new work.

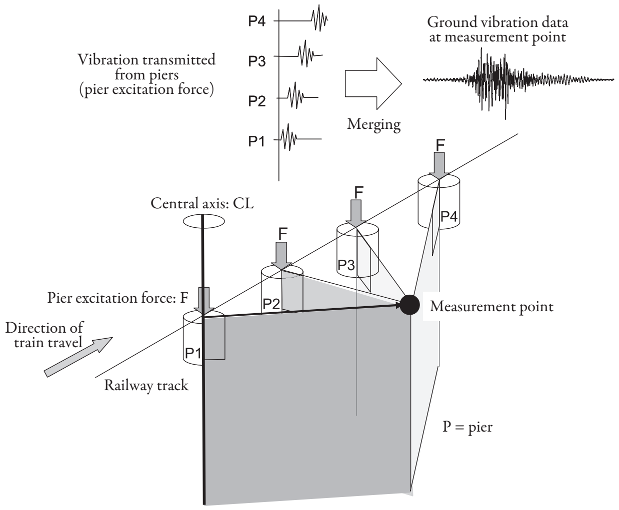

Fig. 3 Image of Ground Vibration Propagation

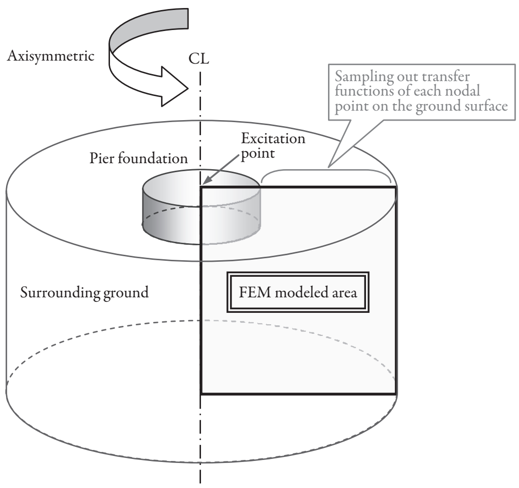

Fig. 4 Concept of Axisymmetric FEM

3.2 Ground Vibration Measurement

At a Tohoku Shinkansen viaduct with a spread foundation, we measured ground vibration when the test train of the specifications listed in Table 1 passed there. The ground vibration measurement data is, as shown in Fig. 5, data of the three components in the direction longitudinal to the track (X direction), direction perpendicular to the track (Y direction) and vertical direction (Z direction) simultaneously measured for approx. 16 seconds at intervals of 5/10,000 seconds at three points 12.5 m, 25.0 m and 50.0 m from the track center. Fig. 6 shows an example of the measured ground vibration waves.

Table 1 Specifications of Test Train

Train No.	Vehicle series	Number of cars	Car length	Velocity
9855B	E954	8 cars	25 m	314 km/h

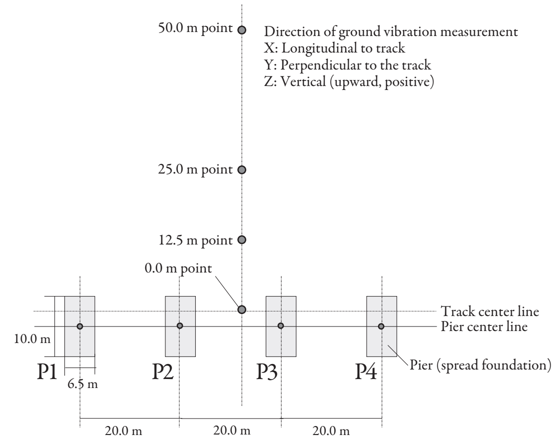

Fig. 5 Plan of Ground Vibration Measurement Point

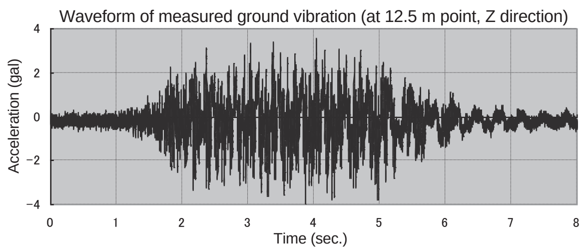

Fig. 6 Example of Measured Ground Vibration Wave

3.3 Development of Analysis Model

3.3.1 Modeling of Piers

The viaduct we used in this study has piers on spread foundations of earth covering of approx. 5 m. The actual piers are rectangular (solid line), so we modeled them as axisymmetric circles (shaded). The radius of the modeled footing R is the radius of a circle that has a plane area equal to that of the footing, and the radius of the modeled pier column r is the value that is R reduced by the distance from the front of the pier column to the end of the footing L. Fig. 7 shows an image of the modeled pier.

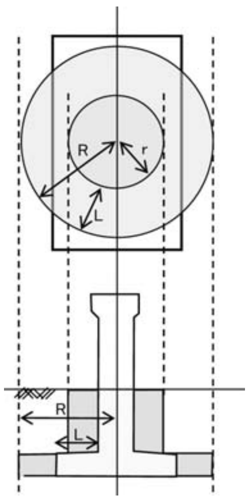

Fig. 7 Image of Modeled Pier (upper: plan, lower: cross section)

3.3.2 Modeling of Ground

The ground at a depth of 3 m or more under ground level (GL) of the point surveyed this time was mainly of diluvial sand with a standard penetration resistance N-value of 30 or more. We thus applied the ground constant shown in Table 2 as the value for analysis in modeling. As ground strain by a passing train is assumed to be minute, we applied the PS logging results to the ground constant without making changes, and set the attenuation constant h at 2.0% for the piers (reinforced concrete, RC) and at 3.0% for the ground. The ground constants are as follows.

(a) Shear rigidity G was assumed from $G = \rho Vs^2$.

(b) Shear wave velocity Vs was assumed from $Vs = 80\ N^{1/3}$ for sand and $Vs = 100\ N^{1/3}$ for clay [Aseismic Standard 4.3].

Table 2 Ground Constant in Analysis

Layer type	Layer thickness (m)	Weight per unit volume γ (kN/m³)	Shear rigidity G (MN/m²)	Poisson's ratio ν
Ts	0.60	15.0	15.0	0.490
Dc	0.90	15.0	22.0	0.490
Ds1	1.50	16.1	23.6	0.497
Ds2-1	3.00	17.5	64.2	0.492
Ds2-2	1.90	17.8	95.7	0.489
Ds2-3	0.90	15.8	92.7	0.488
Ds2-4	3.75	20.2	129.0	0.488
Ps	—	20.1	128.0	0.488

*Ts: Top soil or pavement, Dc: Diluvial clay layer, Ds1: Diluvial sand layer 1, Ds2: Diluvial sand layer 2, Ps: Gravel

3.3.3 Vibration Analysis Model

The method of vibration analysis was viscoelastic FEM that axisymmetrically modeled the foundation of the piers and the surrounding ground and took attenuation into account.

(1) Modeled area

We set the width of the analysis model at approx. 100 m, assuming the distance where analytically there is no effect by the boundary on the farthest piers at the ground vibration measurement points. The depth of the model was set at approx. 70 m, roughly 2/3 the width.

For the piers, only the underground parts were modeled. Without modeling the aboveground part of the piers, the mass of that part is disregarded. There were no problems with the results, however, because the excitation force of that part is calculated in inverse calculation of pier excitation force and the total calculation is balanced.

(2) Element breakdown

As FEM is a discrete model, appropriate ground element breakdown pitch needs to be set to transmit shear waves in vibration analysis. Based on the following assumption, we set the shear wave velocity between Vs/(4f) and Vs/(6f) as a rough estimate for FEM element breakdown.

· The maximum frequency f was 50 Hz (maximum frequency at vibration measurement time interval of 5/10,000 sec).

· The minimum values of the width and height of the element to transmit the shear waves were approx. 1/4 to 1/6 the length of a wave.

(3) Boundary conditions

The boundary conditions of the analysis model of the ground on the pier side (left side) were "horizontally fixed and vertically free at vertical excitation" and "horizontally free and vertically fixed at horizontal excitation". The boundary conditions of the free ground side (right side) added the element of axisymmetric semi-infinite ground. This element setting defines the viscosity boundary to the free ground and the main analysis area. The bottom surface was set at the viscosity boundary that took account of the physical property values of the Ps layer on the lower surface of the model. On the upper surface of the pier, we set a constraint condition where the excitation point at the center of the upper surface of the modeled pier and other nodal points on the upper surface of the pier would cause the same displacement as that of the excitation point.

(4) Meshed diagram

Fig. 8 shows the meshed diagram we used in analysis of the current state taking account of the above-mentioned (1)–(3).

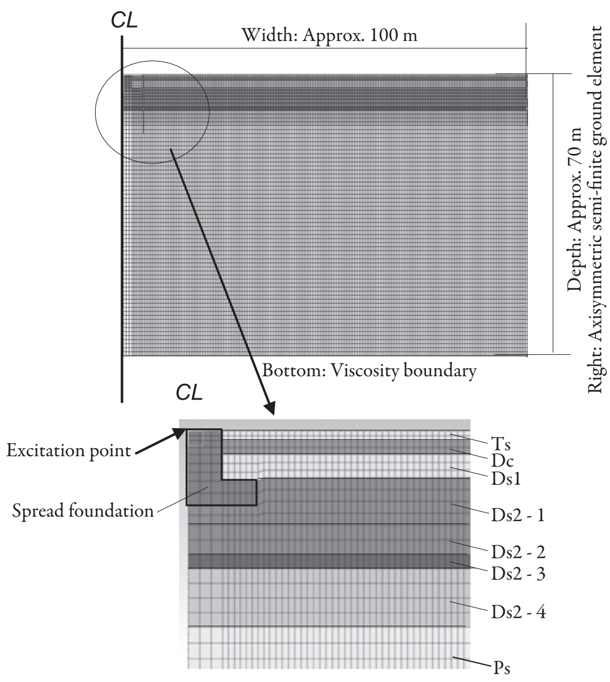

Fig. 8 FEM Meshed Diagram of Current Ground
(upper: whole domain, lower: enlargement of near pier)

3.4 Vibration Analysis of Current Ground

In vibration analysis of the current ground, transfer functions that fit the ground characteristics are sampled by applying appropriate waves to the center of the pier. Fig. 9 shows an image of waves input at the pier center being propagated to the nodal points on the ground surface and sampled as transfer functions. The individual transfer functions actually sampled show different characteristics depending on the distance from the vibration measurement point to the pier as shown in Fig. 10.

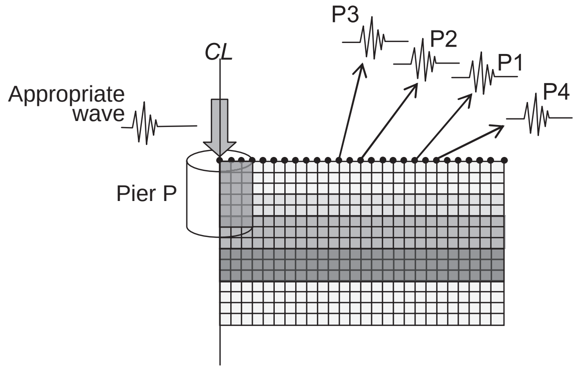

Fig. 9 Image of Sampling of Transfer Functions

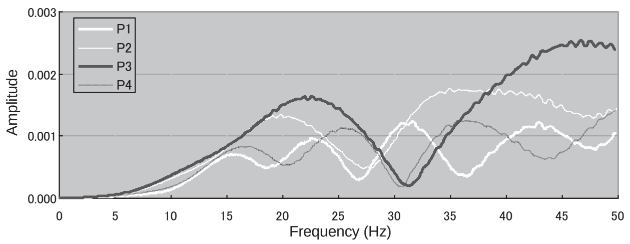

Fig. 10 Transfer Functions of Ground Vibration Measurement Point (at 12.5 m point, Z direction)

3.5 Calculation of Pier Excitation Force

Using transfer functions and ground vibration measurement data according to the distance from the center of each of the four piers to the measurement points, we made inverse calculation of pier excitation force at the pier centers taking into account train speed and phase difference. In the analysis, we made axial correction because we found some deviation of initial values in the vibration measurement data. Fig. 11 shows an example of the obtained pier excitation force shown in the Fourier spectrum.

Fig. 12 shows the time history waveforms (in the direction longitudinal to the track) of the pier excitation force calculated from the ground vibration measurement data at the 12.5 m point, 25.0 m point and 50.0 m point. The waveforms of the pier excitation force found from the ground vibration measurement data at the 12.5 m point and 25.0 m point are similar to each other. Those waveforms indicate the situation before, during and after the passing of the train. We excluded from the application to the analysis pier excitation force calculated from ground vibration measurement data at the 50.0 m point because that pier excitation force could not represent excitation force at the passing of the train.

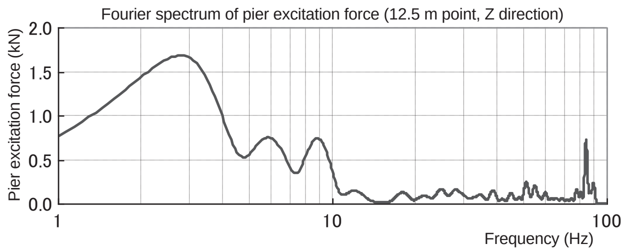

Fig. 11 Fourier Spectrum of Pier Excitation Force

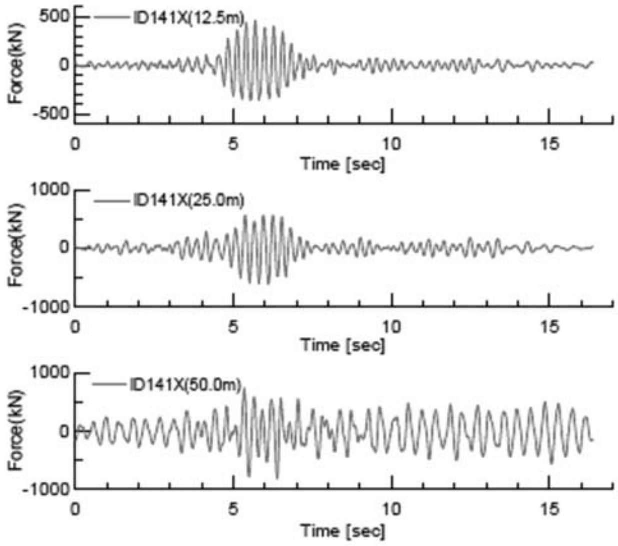

Fig. 12 Time History Waveform of Pier Excitation Force (direction longitudinal to track)

3.6 Calculation of Vibration Level

Vibration level at the measurement points was calculated using the pier excitation force that was inversely calculated from the ground vibration measurement data at the 12.5 m and 25.0 m points we determined reliable in the previous paragraph. Table 3 lists the differences between the calculated vibration level ("calculated value 12.5" and "calculated value 25.0") and the vibration level calculated from actual ground vibration measurement data ("measurement value"). The places with remarkably large differences were shaded. Looking at those, we found that the measurement data at the 12.5 m point had a

Table 3 Comparison of Measurement Value and Calculated Value Vibration Levels (Overall Value)

		Vibration level calculated from measurement data	Vibration level at measurement points calculated from 12.5 m measurement data and difference		Vibration level at measurement points calculated from 25.0 m measurement data and difference	
		Measurement value (dB)	Calculated value 12.5 (dB)	Difference from measurement value (represented as a ratio (%))	Calculated value 25.0 (dB)	Difference from measurement value (represented as a ratio (%))
X direction	12.5 m	48.5	48.5	0.0	50.6	4.2
	25.0 m	48.7	48.9	0.3	48.7	0.0
Y direction	12.5 m	46.0	46.0	0.0	50.0	8.7
	25.0 m	43.9	41.7	5.0	43.9	0.0
Z direction	12.5 m	51.5	51.5	0.1	53.4	3.8
	25.0 m	46.6	46.5	0.3	46.6	0.0

smaller difference from the measurement value. We thus decided to apply ground vibration measurement data at the 12.5 m point to calculation of the vibration level after performing vibration control work.

4 Study on Vibration Control Work

4.1 Creation of Vibration Control Work Models

As vibration control work that can be done in the railway property, we examined 12 cases with different depth and wall thickness of concrete or EPS. Table 4 shows combinations of the vibration control work, Table 5 shows physical property values of each material needed for analysis, and Fig. 13 shows an example of a meshed diagram of the FEM model for vibration control work of 0.4 m wall thickness and 15 m depth.

4.2 Vibration Analysis of Vibration Control Work Models

As with the current ground, we performed vibration analysis of the vibration control work models by axisymmetric FEM to find the transfer functions of the nodal points on the ground surface. The actual vibration control work would be a continuous wall away from the piers by a certain distance, but the modeled vibration control work is a circle at a set distance from each pier as its center as shown in Fig. 14. The reason for that is because the work is axisymmetrically modeled in this analysis. Looking at the FEM cross section from the axisymmetric central axis (CL) to the 12.5 m point, we see offset between the actual work location and the modeled work location and a difference between the transfer functions of those. Thus, we set as a virtual measurement point the point (nodal point) where the distance from the front of the actual work location to the 12.5 m point L and that distance of the modeled work location (L) are equal. And we applied the transfer function at that virtual measurement point to perform vibration analysis.

4.3 Calculation of Vibration Level

As done on the current ground, we calculated time history of vibration acceleration and vibration level from the inverse calculated pier excitation force and the ground vibration measurement data at the 12.5 m point. We evaluated the effectiveness of each vibration control work according to the presence of a vibration reduction effect. Section 5 will show the evaluation results of the vibration control work.

Table 4 Combination of Vibration Control Work

Material	Wall thickness (m)	Depth (m)
Concrete	0.4 m	15 m
		30 m
		50 m
	0.8 m	15 m
		30 m
		50 m
EPS	0.4 m	15 m
		30 m
		50 m
	0.8 m	15 m
		30 m
		50 m

Table 5 Physical Property Values of Vibration Control Work

Type of work	Weight per unit volume γ (kN/m³)	Shear rigidity G (MN/m²)	Poisson's ratio ν	Attenuation constant h
Concrete	24.5	11132000	0.17	0.02
EPS	0.1	1400	0.10	0.02

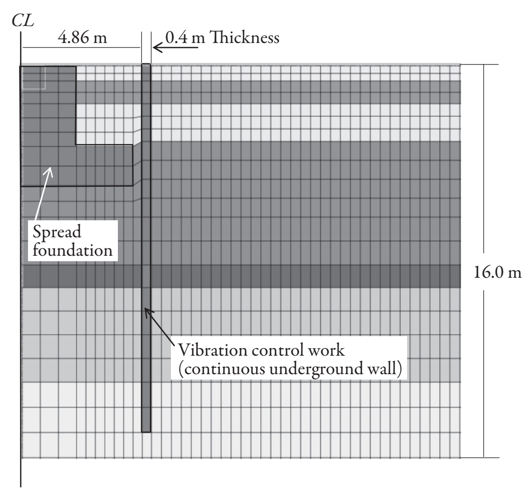

Fig. 13 FEM Meshed Diagram (Expansion near pier: taking into account vibration control work with wall thickness of 0.4 m and depth of 15 m)

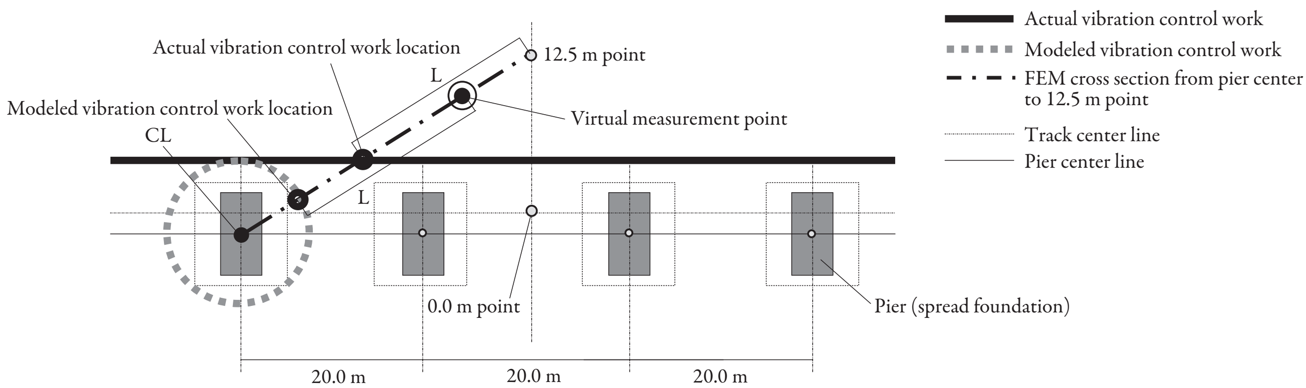

Fig. 14 Concept of Virtual Measurement Point

5 Evaluation of Vibration Control Work

5.1 Comparison between Material Types of Vibration Control Work

Fig. 15 shows the calculation results of the Fourier spectrum of vibration acceleration per direction. The dashed line is the "measurement value" before vibration control obtained from the ground vibration measurement data, and the solid line is the "calculated value" after vibration control is performed.

In Fig. 15 (a) where vibration control work was a concrete continuous wall, we could find a vibration reduction effect in the direction longitudinal to the track and the vertical direction within the 4 Hz to 10 Hz range at which vibration is perceivable to humans. That was despite some "calculated values" rising in the direction perpendicular to the track and thus vibration reduction effect could was expected. In Fig. 15 (b) with EPS continuous wall vibration control work, we could find no effective result as the "calculated value" was large.

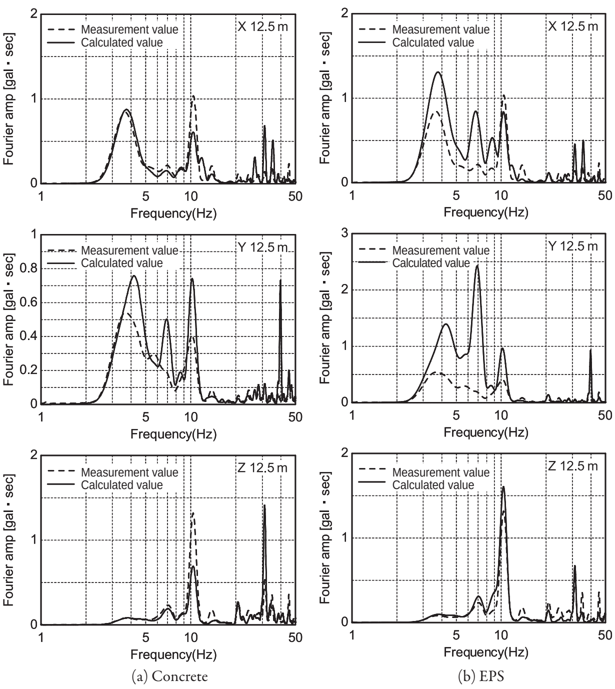

Fig. 15 Fourier Spectrum of Vibration Acceleration (upper: longitudinal to track, middle: perpendicular to track, lower: vertical)

5.2 Comparison Between Wall Thickness and Depth of Vibration Control Work

Fig. 16 shows graphs plotted with the vibration level before and after vibration control work was done (overall value), and it compares the effects per thickness and depth of the work.

In the vertical direction, "calculated values" were smaller than "measurement values," meaning that the work could reduce vibration level in each case. Among those, wider and deeper work showed greater reduction effect. In the direction longitudinal and perpendicular to the track, the vibration level became larger after vibration control work with EPS continuous walls, while the vibration reduction effect was almost equal before and after work with concrete continuous walls.

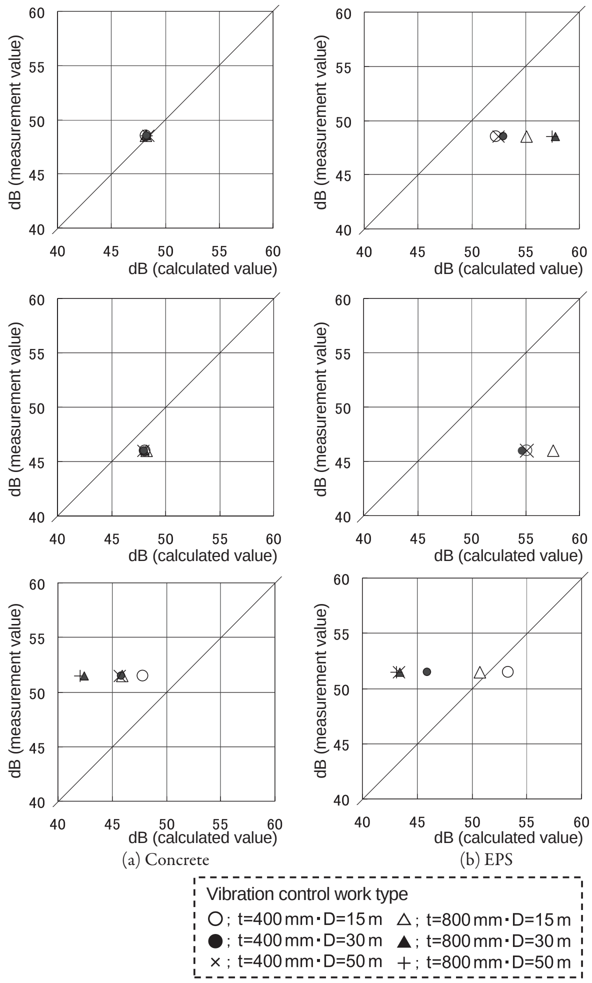

Fig. 16 Comparison of Vibration Levels (Overall Value) (upper: longitudinal to track, middle: perpendicular to track, lower: vertical)

6 Conclusion

The study results confirmed that the analysis method of ground vibration we had proposed for soft ground can also be applied to vibration analysis of spread foundations on relatively firm ground. As a result of the study, we were able to propose the following two points, and we are conducting further research based on those.

(1) Ground vibration measurement data

For calculation of pier excitation force, using the ground vibration measurement data measured at the 12.5 m point gives the most reproducible results.

(2) Effective vibration control work

Concrete is a better material for vibration control work. We can say that making the work thicker and deeper is more effective, although we see considerable variation in the effectiveness in terms of scope, wall thickness and depth of the work.

Reference:

1) Kazuhiro Nakade, Akiyuki Watanabe, "Development of Design and Construction Method for Highly Effective Ground Vibration Control Work," JR East Technical Review, No. 14 (2009)