When a train runs at high speed, vibration is transferred from viaduct to piers and from piers to the ground using the piers as an oscillation source. This may consequently vibrate windows and doors of wayside buildings.

Furthermore, ground vibration control is one of the most important issues in achieving further speed increase of high-speed trains. Examples of ground vibration control work include one-time measures such as vibration isolation work and rigidity improvement of viaducts, but the effects of such work vary due to structure and ground conditions.

In light of these circumstances, we have undertaken development with an aim of establishing a streamlined design and construction method for highly effective ground vibration control work. We will report here on the results of the developed analysis method using a simplified model for structural oscillation and surrounding ground. We also verified that analysis method by test construction for that vibration control work.

Keywords: Ground vibration control, Streamlined design and construction method, Establishment of analysis method, Vibration control work

1 Introduction

When a train runs at high speed, vibration is transferred from viaduct to piers and from piers to the ground using the piers as an oscillation source. This may consequently vibrate windows and doors of wayside buildings.

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In light of these circumstances, we have undertaken development with an aim of establishing a design and construction method for highly effective ground vibration control work. This article will report on development results and give an overview of test construction.

2 Relation Between Ground Vibration and Structure Types

We surveyed locations and types of structures where ground vibration is indicated frequently. Fig. 1–3 show the survey results.

Results in Fig. 1–3 clarified that the structure that is more often pointed out with ground vibration is bridges (including viaducts and over-track bridges), and upper structures with ground vibration are more often girder structures rather than rigid-frame viaducts. We also found that ground vibration occurs more often on pile foundations than on spread foundations. Based on those findings, we decided to mainly focus on girder structure bridges with pile foundations in this study.

3 Overview of Studied Structures

We chose girder viaducts with pile foundations with a deep bearing layer (L = 30 m) as the subject of study. The intermediate layer is soft ground with very low N value less than 10. Fig. 4 shows the photos, and Fig. 5 shows the cross section plan and columnar section diagram of the site. JR East property at the site is very narrow since a road runs by the piers. There we measured actual vibration before and after work.
We analyzed the relation between vibration level and train speed. Fig. 7 shows measurement results before vibration control work. Here, vibration level is shown in comparative values with the vibration level of low speed trains (J+R train set) as 1. The analysis shows that vibration level can be classified by train set and train speed.

6.1 Analysis Method Overview
Three-dimensional analysis is often used to simulate characteristics in planar and depth directions for ground and structures. In usual three-dimensional analysis, however, an overly cumbersome and complicated analysis model means an increase in time and cost for analysis. Thus, we examined a simplified analysis method to be able to propose one where we can achieve analysis with accuracy equal to that of three-dimensional model analysis.

In the proposed analysis method, vibration analysis whereby a pier and its surrounding ground has been modeled by three-dimensional axisymmetric Finite Element Method (FEM) is carried out, then the level of vibration of that surrounding ground from four piers as the vibration source is calculated using a transfer function. That transfer function is found by calculation. Here, excitation force for four piers is input taking into account time difference caused by train speed. Combining analysis parameters such as foundation model shape and damping factor of the ground, calculation results and ground vibration measurement results are compared to select the appropriate modeling method for consideration of present conditions. Fig. 8 illustrates the analysis procedure.

<table>
<thead>
<tr>
<th>Analysis parameter</th>
<th>Setting conditions and setup values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Footing dimensions</td>
<td>Inscribed circle, only on the outbound line side</td>
</tr>
<tr>
<td>Pile modeling</td>
<td>With/without pile modeling</td>
</tr>
<tr>
<td>Damping factor of surface ground h (%)</td>
<td>2.5, 5, 7.5, 10, 12.5</td>
</tr>
</tbody>
</table>
6.2 Study of Analysis Method

Analysis parameters are model dimensions of footing, foundation pile modeling and damping factor of ground. Model dimensions of footing are of two patterns: inscribed circle of footing when regarding whole footing as the oscillation source, and center circle of outbound line when taking into account excitation force only from outbound track. Table 1 shows a combination of analysis parameters in FEM analysis. Fig. 9 shows image of modeling of footing.

6.3 Study Results of Analysis Method

We verified accuracy of the analysis method using ground and structure conditions by comparing actual measurement values and calculated values. Fig. 10–13 show analysis results. The evaluation technique is shown by relative evaluation with the average of measurement values as 1. In these figures, X direction shows the vibration level in the direction of tracks, and Z direction shows that in the vertical direction. Vibration level in track longitudinal direction in Fig. 10 and 11 uses the damping factor as the parameter for comparison. The review results clarified that actual values and calculated values have good agreement in the analysis case with a damping factor of 2.5%. Fig. 12 and 13 show the review results when using the foundation model as the parameter and a damping factor of 2.5%. But we could not find clear tendencies in those analysis results with the foundation model as the parameter. Considering the modeling of ground in actual analysis work, simplified modeling at a certain accuracy level is demanded. Thus, for ground and structure conditions as in this study, we chose modeling with inscribed circle-shape footing, without pile modeling and with damping factor of surface ground being h = 2.5%.
We examined the ground vibration control work using the analysis model obtained by the proposed analysis method. Based on the determination that the optimal shape of vibration control work is wall width 50 cm, length 40 m and depth 15 m, we carried out actual construction. Fig. 14 shows construction overview. Since the control work had to be planned to be within JR East property, construction would be done in narrow space. Based on the consideration of construction methods, we decided to use the Espiler method. The Espiler method is a construction method that is applicable to construction in spaces with low overhead clearance such as under viaducts. Since it is a displacement construction method where drilling and filling are simultaneously carried out so the bored hole is always filled up, we thought it would affect surrounding ground much less. Fig. 15 shows an overview of the Safety-Piler method. The Safety-Piler method uses a backhoe-based construction machine with an auger attachment. That machine drills with the auger to build in-ground cement-made piles with by spraying liquid grout while soil on the site is displaced.

Since construction in vibration control work had to be done within JR East property, construction would be done near existing structures. Thus, we carried out impact analysis with an aim of forecasting surrounding ground behavior in construction and setting control values for actual work. In that analysis, we estimated displacement, deformation or load increase of existing structures by actual construction, and compared acceptable values of that displacement and deformation to acceptable values for existing structures based on bearing force. Based on those comparison results, we set control values for actual construction. Fig. 16 illustrates impact analysis flow for existing structures.
The control values at construction time are determined using the measurement control value of tracks by comparing values of displacement or deformation of existing structures or values of increased load with those of displacement or deformation of tracks.

In order to understand behavior of existing structures and surrounding ground caused by construction, we made measurements of in-ground displacement. Fig. 17 shows an overview of measurements. We measured in-ground displacement during construction using a multistage clinometer near the vibration control work. And, to measure change of pore water pressure of the surrounding ground by the construction, we also attached a pore pressure meter for measurement. Fig. 18–21 show measurement results for in-ground displacement. Since an earthquake occurred during construction, we re-measured initial values before and after the earthquake to exclude displacement by the earthquake and factors other than piling. Fig. 18 and 19 show measurement results before the earthquake and Fig. 20 and 21 show those after the earthquake. Measured values are shown per depth (shallow and deep). The measurement results clearly demonstrate that displacement occurred near the ground surface after the earthquake. As piling was carried out near the in-ground displacement gauge at that time, we can attribute that displacement largely to load action of heavy equipment. Next, we compared in-ground displacement distribution near the in-ground displacement gauge at piling to the amount of displacement that was calculated in the FEM analysis in "8. Analysis of Impact of Construction in Vibration Control Work". Fig. 22 shows comparison results. The results illustrate large effect by heavy equipment near structures. We thus should take into account in-ground stress by heavy equipment as lateral pressure.
By the analysis method explained in "6. Proposal of Analysis Method", we reviewed analysis results and measurement results after the construction vibration control work. Fig. 23 shows the overview of vibration measurement after the vibration control work. In order to identify the effect of the vibration control work, we made measurement on two traverse lines in the direction of the normal line; traverse line V with vibration control work and traverse line G without that.

Fig. 24 shows an image of the analysis model after vibration control work. We modeled footing and actual vibration insulation work into an axisymmetric model with the footing at the center, then compared the vibration measurement results to the vibration level at the 12.5 m point that was calculated in that model with ground model and excitation force explained in the proposed analysis method. Figs. 25–27 show comparison results. Evaluation is relative with average of vibration level measurement results on traverse line G as 1. X direction, Y direction and Z direction are vibration level in track longitudinal direction, direction at right angle to the track, and vertical direction respectively.

Comparison results in Figs. 25–27 illustrate that vibration level of both calculated values and actual measurement values at the point with vibration control work was reduced in X, Y and Z directions when compared to vibration level at the point without vibration control work. Furthermore, as actual measurement values and calculated values are plotted largely symmetrically to the 1:1 line, our method using that axisymmetric model could be verified as being appropriate.

Based on the verification results, we were able to propose an analysis method using a simplified axisymmetric model for design and construction for ground vibration control. Now we are proceeding with analysis using an accurate three-dimensional model to check consistency with simplified model analysis.