EVALUATION OF THE VIBRATION CHARACTERISTICS OF THE PLATFORM SHED ON THE RAILWAY VIADUCT

Kazuaki IWASAKI¹, Atsushi HAYASHI², Chihiro TAKAHASHI³, Kazuhiro KOYANAGI⁴

ABSTRACT

In the 2011 off the Pacific coast of Tohoku Earthquake, much damage was caused to the structures on railway viaducts even in regions where the structural frame of the buildings in the surrounding area was not heavily damaged. In order to clarify this factor, firstly microtremor measurements were carried out at platform shed on railway viaduct. Based on the frequency analysis of the measurement result and the system identification result, it was found that the structural characteristics can be evaluated by two mass system model, and the vibration parameters can be accurately estimated by the system identification. Next, a frame model of the platform shed on the railway viaduct was prepared, and the behavior at the time of the earthquake was estimated. Normally, the natural period of the structure at the time of earthquake is longer than the natural period of the microtremor measurement due to the nonlinearity of the structural frame. Therefore we proposed an evaluation method of the natural period at the time of earthquake by the natural period of microtremor measurement. Based on these evaluations, we examined the relation between the extent of damage on the platform shed on the railway viaduct over the 2011 off the Pacific coast of Tohoku Earthquake and the earthquake ground motion. As a result, by considering the amplification of the seismic ground motion as two mass system model, correlation with magnitude of damage was seen. From the above, we showed the possibility to estimate the behavior of earthquake behaviors on a platform shed on a railway viaduct by the method based on this research.

Keywords: Platform Shed; Railway Viaduct; Microtremor Measurement; System Identification; Modal Analysis;

1. INTRODUCTION

In the 2011 off the Pacific coast of Tohoku Earthquake, many damage occurred to structures on railway viaducts (Fig. 1) (East Japan Railway Co. 2011). In addition, despite the fact that the structural frame of the building in the surrounding area has not suffered serious damage, damage to the structural frame occurred in the platform shed on the railway viaduct.

In this research, firstly, vibration characteristics are evaluated by microtremor measurement of the platform shed on the railway viaduct. Furthermore, by structural analysis, we estimate vibration characteristics at the time of earthquake and attempt to estimate the factors that contributed to the damage at the time of the earthquake.

Figure 1. The damage of the structures on the railway viaducts

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1.1 Past Studies about Evaluation of Vibration Characteristics of Buildings

In order to evaluate vibration characteristics of buildings, a method using system identification is focused recently (for example Ikeda et al. 2014). System identification is a method of evaluating the characteristics of the system by observing the output when there is external input to the system. Although earthquake motion or forced vibration is used as external input, there are problems with observation frequency and ease of implementation. Therefore, it is studied to use microtremor that are easy to observe as external input, however it is necessary to consider the influence of the small signal/noise (SN) ratio. In this research, we evaluate vibration characteristics of a platform shed on a railway viaduct by using system identification which is studied on buildings.

1.2 About a Platform Shed on a Railway Viaduct

As shown in Fig. 2, generally a platform shed on railway viaduct consists of a steel framed platform shed on a reinforced concrete railway viaduct. In addition, a platform shed is joined to a railway viaduct by exposed column bases. A heterogeneous composite structure which greatly differs in mass and rigidity like this is a structural form not seen elsewhere. Furthermore, in a platform shed on a railway viaduct designed in the past, a lower railway viaduct is designed with the design standard of the railway structure, an upper platform shed is designed separately by the design standard of the building are doing. For this reason, there is a possibility that structural characteristics as a coupled structure are not sufficiently considered.

![Figure 2. A platform shed on a railway viaduct](image)

2. EVALUATION OF VIBRATION CHARACTERISTICS OF A PLATFORM SHED ON RAILWAY VIADUCT BASED ON MICROTREMOR MEASUREMENT

2.1 Microtremor Measurement in the Platform Shed on the Railway Viaduct

In order to grasp vibration characteristics of a platform shed on a railway viaduct, the microtremor were measured with actual structures and the vibration characteristics of the low vibration level were evaluated.

In order to eliminate the influence of train vibration as much as possible at the platform shed on the railway viaduct, we measured microtremor at the time without train operation. Measurements were carried out at 16 stations shown in Table 1 at the railway viaducts and the platform sheds with different structure heights and structural types.

For the measurement of microtremor, simultaneous measurements were made at three points, the foundation of the railway viaduct, the foundation of the platform shed, and the top of the platform shed, using the three component velocimeter or accelerometer. Recording of measurement data was continuous data of about 30 minutes at a sampling frequency of 100 Hz or 200 Hz.
Table 1. 16 Stations measured microtremor

<table>
<thead>
<tr>
<th>Sta.</th>
<th>Member of Shed Column</th>
<th>Structural Type of Shed</th>
<th>Height of Shed [m]</th>
<th>Structural Type of Viaduct</th>
<th>Height of Viaduct [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>4.0</td>
<td>RC Moment Frame</td>
<td>8.4</td>
</tr>
<tr>
<td>B</td>
<td>Steel Column</td>
<td>Moment Frame</td>
<td>7.9</td>
<td>RC Moment Frame</td>
<td>17.2</td>
</tr>
<tr>
<td>C</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>4.0</td>
<td>RC Moment Frame</td>
<td>22.0</td>
</tr>
<tr>
<td>D</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>5.1</td>
<td>RC Moment Frame</td>
<td>16.0</td>
</tr>
<tr>
<td>E</td>
<td>Steel Column</td>
<td>Moment Frame</td>
<td>5.4</td>
<td>RC Moment Frame</td>
<td>8.2</td>
</tr>
<tr>
<td>F</td>
<td>Steel Column</td>
<td>Moment Frame</td>
<td>6.6</td>
<td>RC Moment Frame</td>
<td>17.0</td>
</tr>
<tr>
<td>G</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>4.2</td>
<td>RC Moment Frame</td>
<td>8.3</td>
</tr>
<tr>
<td>H</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>4.0</td>
<td>Steel Moment Frame</td>
<td>7.5</td>
</tr>
<tr>
<td>I</td>
<td>Steel Column</td>
<td>Moment Frame</td>
<td>7.8</td>
<td>RC Moment Frame</td>
<td>13.0</td>
</tr>
<tr>
<td>J</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>6.2</td>
<td>RC Moment Frame</td>
<td>6.8</td>
</tr>
<tr>
<td>K</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>3.7</td>
<td>RC Moment Frame</td>
<td>13.8</td>
</tr>
<tr>
<td>L</td>
<td>Steel Column</td>
<td>Moment Frame</td>
<td>4.0</td>
<td>RC Moment Frame</td>
<td>10.8</td>
</tr>
<tr>
<td>M</td>
<td>Steel Build Box</td>
<td>Moment Frame</td>
<td>3.2</td>
<td>RC Moment Frame</td>
<td>8.1</td>
</tr>
<tr>
<td>N</td>
<td>H-Shaped Steel</td>
<td>Weak Axis Moment Frame</td>
<td>5.2</td>
<td>RC Moment Frame</td>
<td>6.0</td>
</tr>
<tr>
<td>O</td>
<td>Steel Column</td>
<td>Moment Frame</td>
<td>6.3</td>
<td>RC Moment Frame</td>
<td>9.4</td>
</tr>
</tbody>
</table>

2.2 Estimation of Natural Period by Frequency Analysis

From the time history data of microtremor synchronously measured at station D, transfer functions of the platform shed and the railway viaduct were determined for each of the parallel direction of the track (X direction) and the perpendicular direction to the track (Y direction). For the analysis, the portion of the recorded data, which is less influenced by vibrations such as trains and works, was cut out and used. In order to calculate the natural period, a small section of 20.48 seconds was cut out from the obtained recorded data. Fourier transform was performed for each section, an ensemble mean value of Fourier spectrum was calculated, and a transfer function was obtained from the spectral ratio (Fig. 3). Furthermore, the primary natural period was obtained from the peak of the transfer function.
Figure 3. The transfer functions of Station D

According to the transfer function shown in Fig. 3 (a)(c), the natural period of the platform shed is 0.31 second in the X direction and 0.35 seconds in the Y direction, therefore the rigidity differs depending on the direction. This is considered to be particularly influenced by the direction of the strong axis and weak axis of the column. According to the transfer function shown in Fig. 3 (b)(d), the natural period of the railway viaduct is 0.27 seconds in the X direction and 0.29 seconds in the Y direction, and the influence of directional orientation is relatively small as compared with the platform shed.

Similarly, for the other 15 stations, we calculated the natural period. The relationship between the height of the railway viaduct and the height of the platform shed and the natural period of each is shown in Fig. 4. Regarding the railway viaduct, it can be approximated by the same approximate expression regardless of direction. On the other hand, the platform shed stiffness and structural form of the material is different depending on the direction. From this fact, approximate expressions were calculated by classifying them into a strong axis moment frame, a weak axis moment frame, and a single column structure.

2.3 Estimation of Vibration Characteristics by System Identification

To estimate modal parameters from microtremor records, we use time domain system identification.
System identification is carried out by multi-input-multi-output ARX model (Saito 1998). The 163.84 seconds acceleration records that are obtained from low noise records of microtremor measurement are used as input or output of the system identification. The degree order of the model is changed from 1 to 50, the order that AIC (Akaike Information Criterion) (Akaike 1974) becomes the minimum value is adopted. The observed records and the model output are shown in Fig. 5, which are in good agreement with each other, therefore a numerical model approximating from the system identification be able to evaluate vibration characteristics of structures.

Next, assuming that the structure is a two mass system model as shown in Fig. 6, the modal parameters up to the second order are estimated from the ARX model parameters obtained by the system identification by the following equation (Saito 1998).

\[
f_j = \frac{\log |p_j|}{2\pi \Delta t} = \sqrt{(\log |p_j|)^2 + (\arg p_j)^2} \\
h_j = \frac{-\log |p_j|}{2\pi f_j \Delta t} \\
\beta u_j = \Re \left[ 2 x_j \left( \frac{1-h_j^2}{T(2\pi f_j h_j - \text{sign}[3|p_j|]2\pi f_j (1-2h_j^2))} \right) \right] \tag{1}
\]

Using a two mass system model based on the estimated modal parameters, vibrations of top of the railway viaduct and top of the platform shed are estimated by modal analysis from vibration of the microtremor record on the ground surface. These estimated vibrations are roughly consistent with observation records as shown in Fig. 7. From this, it is considered that the modeling based on a two mass system model using estimated modal parameters is approximately valid.
Figure 7. Comparison of the microtremor measurements and the modal analysis

For other 15 stations in addition, system identification is carried out in the same way and the modal parameters are estimated. The natural periods found from the Fourier spectrum ratio shown in 2.2 are compared with the natural periods calculated from the ARX model (Fig. 8). In both railway viaducts and platform sheds, the natural periods calculated from the ARX model are consistent with the natural periods found from Fourier spectrum ratio.

About the platform sheds, the relationship between the identified natural periods and the damping coefficients are shown in Fig. 9. With the evaluation formula shown in the past study (AIJ 2000) is also shown in the Fig. 9, the damping coefficients evaluated this study are generally smaller than this evaluation formula. In this evaluation formula, in addition to microtremor measurements, various data are included, such as the results of exciter experiments, whereas in this report it is attributable that the damping coefficients are evaluated by only low small vibration based on microtremor measurements.
Fig. 10 shows the relationship between the natural period ratio (the ratio of the natural period of the platform shed to the natural period of the railway viaduct) and the amplification factor $A_2$. When to consider that the mass ratio (the ratio of the mass of the platform shed to the mass of the railway viaduct) is small, the amplification factor $A_2$ is expressed by the equation (4) by the stimulation function up to the second order identified.

$$A_2 = A'_2/A'_1 = \sqrt{\frac{2\beta u_2^2}{1 + 2\beta u_1^2}}$$

(4)

Although there are variations due to the influence of unsteady vibration such as wind and walking, when the natural period ratio approaches 1, the amplification factor $A_2$ tends to increase due to resonance. In Fig. 10, the amplification factors $A_2$ by the modal analysis are shown in accordance with the mass ratio of the second layer to the first layer is set to 1%, 5%, and 10%. Although the mass ratio differs depending on the station, as the result of the survey, it is recognized as about 1 to 10% by mass ratio to railway viaduct in most stations. It is considered that the amplification factors $A_2$ of the ARX model by the microtremor records correspond with the amplification factors by the modal analysis.
3. ESTIMATION OF EARTHQUAKE VIBRATION CHARACTERISTICS OF THE
PLATFORM SHED ON THE RAILWAY VIADUCT

3.1 Structural Performance of the Platform Shed on the Railway Viaduct by the Frame Model Analysis

For the platform shed on the railway viaduct in station D, it is modeled by frame model as shown in Fig. 11. The static nonlinear analysis is performed by the distribution of seismic forces in the height direction according to the provisions of the Building Standards Law. Fig. 12 shows the horizontal seismic coefficient-displacement relationship about the railway viaduct and the platform shed. The equivalent natural period $T_{eq}$ obtained from the stiffness of the elastic limit is shown in Table 2. In comparison with the natural periods obtained from microtremor in Chapter 2, the equivalent natural periods are 2.3 times longer for the railway viaducts and 1.7 times longer for the platform sheds. Since the natural periods at the time of the earthquake are different from the natural periods obtained from the microtremor, in order to estimate the vibration at the time of earthquake, it is necessary to properly evaluate the nonlinearity of the structures.

![Frame Model of Platform Shed](image)

Figure 11. The frame model of the platform shed on the railway viaduct in station D

![Seismic Coefficient vs Displacement](image)

Figure 12. Relation between the seismic coefficient and the displacement
Table 2. Estimated natural periods of station D

<table>
<thead>
<tr>
<th>Natural period obtained from microtremor [s]</th>
<th>Natural period obtained from frame model analysis [s]</th>
<th>Magnification</th>
</tr>
</thead>
<tbody>
<tr>
<td>The platform shed</td>
<td>0.32</td>
<td>0.55</td>
</tr>
<tr>
<td>The railway viaduct</td>
<td>0.31</td>
<td>0.73</td>
</tr>
</tbody>
</table>

3.2 Estimation of Seismic Vibration Characteristics based on Microtremor Measurement Results

Regarding the natural period of the railway viaduct general section, the relationship between the microtremor natural frequency $f_0$ and the equivalent natural frequency $f_{eq}$ is shown by the following equation in the past study (Tokunaga 2015).

$$f_{eq} = 0.41f_0$$ (5)

Based on equation (5), the equivalent natural period is 2.4 times longer than the microtremor natural periods. This is due to the nonlinearity of nonstructural members and materials, and it almost agrees with the result of 3.1 verified at station D. From this fact, it is considered that the natural period of the railway viaduct at the time of the earthquake is increased by about 2.4 times longer than the natural period obtained from the microtremor.

The platform shed is an elastic behavior in Fig. 12 (b), however it is different from the natural period obtained from the microtremor. In order to evaluate this factor, static linear analysis of the frame model is carried out for the platform sheds in station I, J and O. About the platform shed of each station, the column base condition is set as two cases of pin and fixed.

Fig. 13 shows a comparison between the analysis value and the measurement value. The analysis natural periods with the column base fixed are close to the microtremor natural period. This is because the column base condition is nearly fixed in the amplitude region of the microtremor. The natural periods with the column base pin are about 1.8 times longer on the average than those with the base fixed, which is basically in agreement with the result of 3.1. At the time of earthquake, it is thought that the natural periods of the platform shed approach the natural period with the column base pin.

![Figure 13. Comparison between the microtremor natural period and the analysis natural period](image)

Fig. 14 shows the relationship between the height and the natural period of the platform shed. It is understood that the natural period of the platform shed is longer than the approximate equation of the Building Standard Law. This is thought to be due to the fact that the number of nonstructural members such as walls is smaller than that of general buildings.

Therefore, the natural period of the platform shed obtained from the microtremor shows the vibration characteristic as the fixed column base; it is necessary to consider the fixation degree of the column base in order to estimate the vibration characteristics at the time of earthquake. When the column base is a
pin, the natural periods are about 1.8 times longer than the natural periods obtained from the microtremor. This is approximately in agreement with the result of 3.1 verified at station D.

![Graph showing the relationship between height and natural period](image)

**Figure 14. Relationship between the heights and the natural periods of the platform shed**

### 3.2 Evaluation of Earthquake Vibration Characteristics of the Platform Shed on the Railway Viaduct

We investigated the damage of the platform sheds on the railway viaducts at 13 stations influenced by strong vibrations in the 2011 off the Pacific coast of Tohoku Earthquake. The degrees of damage are set to 3 stages shown in Table 3. Although the relationship between the degree of damage and the SI value calculated from the nearest seismograph is shown in Fig. 15, there is no strong correlation between the degree of damage and the SI value.

<table>
<thead>
<tr>
<th>Degree of damage</th>
<th>Damage content</th>
</tr>
</thead>
<tbody>
<tr>
<td>III</td>
<td>Damaged on structural members</td>
</tr>
<tr>
<td>II</td>
<td>Damaged on non-structural members</td>
</tr>
<tr>
<td>I</td>
<td>No damage</td>
</tr>
</tbody>
</table>

**Table 3. The degrees of damage**

![Graph showing the relationship between degree of damage and SI value](image)

**Figure 15. Relationship between degree of damage and SI value**

Therefore, the microtremor natural periods are calculated from the result of Chapter 2, based on the relationship the height and the microtremor natural periods of both the railway viaducts and the platform shed. Furthermore, based on the result of Chapter 3, the equivalent natural periods are calculated from the microtremor natural periods. Using the obtained equivalent natural period, the amplification factors of the platform shed on the railway viaduct are calculated.

An index $SI_p$ considering amplification of earthquake ground motion due to railway viaducts is defined
by the following equation.

\[ SI_v = SI \times A \]

(6)

As shown in Fig. 16, the degrees of damage are more correlated with \( SI_v \) value than SI value. Especially, the \( SI_v \) value are smaller than the SI value at the small degree of damage. This is considered that the smaller amplitude by the railway viaduct influence the small damage of the platform shed at the area where the SI value is large and the degree of damage is small.

Therefore, it is highly probable that amplification caused by railway viaducts affected the damage on the platform shed on the railway viaduct in the 2011 off the Pacific coast of Tohoku Earthquake.

\[ \text{Figure 16. Relationship between degree of damage and } SI_v \text{ value} \]

4. CONCLUSION

In order to evaluate the vibration characteristics of the platform shed on the railway viaduct, we carried out microtremor measurements and structural analysis and obtained the following knowledge.

- The platform shed on the railway viaduct can evaluate the vibration characteristics by a two mass system model considered the rigidity and the mass of both the railway viaduct and the platform shed.
- The modal parameters required for two mass system model can be accurately estimated by system identification using the vibration record of the real structure.
- The natural periods obtained from microtremor of both the railway viaduct and the platform shed can be estimated from the respective heights.
- The natural period at the earthquake of both the railway viaduct and the platform shed can be estimated from the natural period obtained from the microtremor in consideration of the material nonlinearity and the joint fixation.
- There is a correlation between the degree of the damage of the platform shed on the railway viaduct in the 2011 off the Pacific coast of Tohoku Earthquake and the strength of the seismic motion considering the amplification of the railway viaduct.

5. REFERENCES


Damping in Buildings (2000). Architectural Institute of Japan


