Evaluation of the Damping Properties of Railway Structures

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The running safety of railway vehicles in seismic conditions is evaluated by using the generally adopted damping constant of railway structures, which is generally 5 %, because there are only a few measured examples of damping constants. However, if the damping constant is lower, vehicle running safety declines proportionately. The authors evaluated the damping constants of many railway structures by vibration measurement. This paper proposes a method for estimating the damping constant of railway structures. Furthermore, the effects of structural damping on the behavior of high-speed trains were studied by combining structural analysis and simulations of vehicle dynamics. A method was then proposed to identify structures presenting a risk in terms of vehicle running safety during earthquakes.

Keywords: damping constant, railway structures, natural period, vehicle running safety

1. Introduction

It is common knowledge that damping properties are important for evaluating the safety of structures or the running safety of railway vehicles during earthquakes. Differences in structural damping constants may explain the wide variation in structural damage resulting from the massive 2011 off the Pacific coast of Tohoku Earthquake [1]. Consequently it is very important to evaluate damping properties to identify at-risk railway structures which will require special attention during seismic assessment.

In this paper, ‘damping properties’ means the damping constants of whole structures in the main vibrational mode during earthquakes. Some research [2, 3, 4] has been conducted to evaluate the modal damping constants of long-span bridges, using seismic observations. However, they were only case studies in which damping properties were not the main focus. On the other hand, there is other research [5, 6, 7, 8, 9, 10, 11] on the damping constants of bridges which uses a statistical approach based on past measurement results. Nevertheless, there is still no adequate method for evaluating damping properties at present, because measurement methods differ and the number of measurement examples is low compared to the many types of structure and a wide variety of ground conditions.

The authors took microtremor measurements [12] on railway a wide array of reinforced concrete bridges and viaducts, under varying ground conditions. The damping constants and natural periods of these structures were then evaluated. Results showed that there was a positive correlation between the damping constant and ground deformation [13].

This study proposes an estimation method of damping constants of railway structures based on the past research [13]. Furthermore, effects of the structural damping on behavior of the high-speed train were studied by combining the structural analysis and vehicle dynamics simulation. A method was then proposed to extract at-risk structures in terms of running safety during earthquakes.

2. Outline of the damping constant calculation based on microtremor measurements

2.1 Methods for measuring and calculating the damping constant

Figure 1 shows methods for measuring and calculating the damping constant. High sensitive velocity measuring devices were installed and microtremors were measured to clarify the vibration characteristics of structures. The devices were installed on the upper side of the structure in a free field. The measurement time was set to 20 minutes per site. The sampling frequency was set to 200 Hz. The time histories of the microtremor in the free field ($z(t)$) and the upper side of the structure ($x(t)$) were obtained.

Fourier transform was applied to the measurement data and the ratio of the Fourier amplitude spectrum on the upper side of the structure ($x(f)$) to that on the free field ($z(f)$) was calculated. The ratio of the Fourier amplitude spectrum obtained from the above represents the structured frequency response function against input ground motion. Then, the time history data were divided into data of 20.48 seconds and the Fourier amplitude spectrum was calculated from each divided data set, excluding the data including noise in the analysis. Average values of the frequency response function obtained from the measurement data (Red line in Fig. 1) were defined as the measurement results.

Then, it is known that the main vibrational mode during earthquakes is initiated at the first natural frequency of the frequency response function and the whole structures are vibrated in the same direction in the mode [13]. This means that the frequency response function at around the first natural frequency can be approximated by the theoretical solution of the transfer function $H(f)$ of the single degree of freedom system.

Therefore, the damping constant h and the natural frequency f_0 can be evaluated by fitting the organized measurement results to the transfer function (Blue dotted line

Fig. 1 Outline damping constant calculation based on microtremor measurements

in Fig. 1) of the single degree of freedom system (Curve fitting method).

2.2 Railway structures used for measurement

136 railway structures of varied design and built on different types of ground were used for taking measurements, as shown in Fig. 2. The legends G1-G7 and corresponding legends in Fig. 2 indicate ground classifications as defined in the Japanese seismic design code [14] for railway structures and the number of measurements for each ground classification.

2.3 Damping constant calculation results

The amplitude ratio α is defined as the ratio of the amplitude of the upper side of the structure to that of the lower side (Fig. 3). The amplitude ratio $\alpha=0$ means that there is no ground displacement, in other words, there is only relative displacement between the upper and lower parts of the structure. By contrast, the amplitude ratio $\alpha=1$

Fig. 3 Amplitude ratio α of the amplitude of the upper side to that of the lower side of the structure

means that there is no relative displacement between the upper and the lower part of the structure, and only ground displacement occurs, i.e. the amplitude ratio α is related to the contribution to ground displacement. Figure 4 shows the relationship between damping constants and amplitude ratios. As a result, there is a positive correlation between the

Fig. 2 Structural types used for measurement

Fig. 4 Relationship between the amplitude ratio α and the damping constant h

damping constant and the amplitude ratio. It means that the damping constants are high when α is large (the contribution to ground displacement is large) because of the large contribution of radiational damping, and the damping constants are low when α is small (the contribution of the ground displacement is small) because of the large contribution of material damping.

3. Method for estimating the damping constant based on the ratio of the structural period to the ground period

Figure 5 shows the relationship between the damping constant h calculated by the microtremor measurement and the ratio T_s/T_g of the structural natural period T_s to the ground one T_g . The damping constants are low in the range of $T_s/T_g > 1$. On the other hand, the damping constants vary widely for all the values from the high ones to the low ones in the range of $T_s/T_g \leq 1$. This trend also appeared in the past studies [15, 16]. In the range of $T_s/T_g \leq 1$, the structure and ground were both vibrated, so the radiational damping (several tens of percent) and the internal damping (a few percent) were expected to have an effect (Fig. 6(a)). By contrast, in the range of $T_s/T_g > 1$, only the structure was vibrated, so the contribution of the radiational damping was small (Fig. 6(b)). This mechanism is determined by the T_s and T_g which include the effect of the ground conditions and the type of structure. Therefore, it is possible to evaluate the measurement results regardless of the ground conditions and the structural types.

This study proposes the following equation (1) for estimating the damping constant based on measurement results.

$$h = \begin{cases} 0.05 & (T/T_g \leq 1) \\ 0.05(T/T_g)^{-0.7} & (T/T_g > 1) \end{cases} \quad (1)$$

where T means the structural elastic natural period T_s or the equivalent natural period T_{eq} in evaluating the vehicle running safety.

Figure 7 shows the comparison between the measurement results and the line estimated by the equation (1). The estimated line was set at a 5 % damping constant in

Fig. 5 Relationship between the damping constant and the ratio of the structural natural period to the ground one

Fig. 6 Concept of damping exerted for the respective period ratios

Fig. 7 Comparison between the measurement results and the estimated line

the range of $T_s/T_g \leq 1$ where the radiational damping and the internal damping were making a contribution. On the other hand, the estimated line was set to evaluate the average values of the measurement results roughly in the range of $T_s/T_g > 1$ where the contribution of the radiational damping is small.

4. Quantification of the relationship between the damping constant and running safety

For this chapter, a number of structural analyses and vehicle dynamic simulations were conducted, and the relationship between the maximum response of the structure and the vehicle running safety was quantified.

4.1 Outline of analyses

4.1.1 Structural analyses

The bridge or the viaduct was modeled to have one linear single degree of freedom system as shown in Fig. 8 in the structural analyses. Surface ground motion was input to this model and absolute displacement at the top of the structure was evaluated. Various damping constants h

Fig. 8 Linear single degree of freedom for structural analyses

(0.5, 1.0, 2.0, 3.0, 4.0, 5.0, 10, 20 %) and equivalent natural periods T_{eq} (at 0.1 second intervals from 0.1 seconds to 2.0 seconds) were set in the analyses. For the input ground motions, the 22 waves whose predominant periods were different, were selected from the observed records and seismic design motions.

4.1.2 Vehicle dynamic simulations

The time histories of absolute displacement at the top of the structure were input to the vehicle dynamic simulations. A Vehicle Dynamics Simulator (VDS) [17] was used for this simulation. Figure 9 shows the analytical model for railway vehicle dynamics simulation for a single-car train. The vehicle model was a high-speed Shinkansen vehicle (bolsterless bogies). The vehicle model consisted of a single carbody, two bogie frames and four wheelsets. Each of these seven rigid bodies had six degrees of freedom, and each of the rails supporting the eight wheels had its own independent two degrees of freedom. For a single-car train, therefore, the analytical model had 58 degrees of freedom in total. The rigid bodies were connected by springs and damping components such as bolster springs, axle springs, lateral dampers, yaw dampers (anti-hunting dampers), lateral stoppers, traction devices and so on. The contact forces between the wheels and the rails were calculated using the contact model based on Kalker's theory. Further, the motion of the wheels could be calculated even if they lifted from the rail surface. Regarding vibration of tracks, the respective portions of the rails under the eight wheels were assumed to vibrate simultaneously with the same waveform.

Fig. 9 Analytical model for vehicle dynamics simulation

4.2 Method for evaluating vehicle running safety

Lateral displacements of the wheels relative to the rails were applied to evaluate critical vehicle running safety during an earthquake. When the lateral displacement reached ± 70 millimeters, it was considered that derailment would occur. The location of the wheels under these critical conditions is shown in Fig. 10.

In this study, the absolute displacement at the top of the structure caused by the input ground motion whose maximum acceleration was 100 gal, multiplied by the scaling factor β , was applied to the vehicle dynamics simulation. Then, derailment occurring or not occurring was determined according to the method described above, and applied to the vehicle response. The limit scaling factor regarding running safety β_{lim} can be evaluated for each damping constant. β_{lim} means the maximum scaling factor for which derailment does not occur. The ratio γ of the limit scaling factor $\beta_{lim}(h\%)$ of a damping constant h to $\beta_{lim}(5\%)$ of a 5 % damping constant can be calculated by the following equation.

$$\gamma(h\%) = \frac{\beta_{lim}(h\%)}{\beta_{lim}(5\%)} \quad (2)$$

When γ is lower than 1, the margin of the vehicle running safety is relatively low compared to when the damping constant is 5 %. In this study, the parameter γ is used to evaluate the effect of the damping constant on vehicle running safety.

Fig. 10 Wheel location under critical conditions

4.3 Relationship between structural response and damping constant

Figure 11(a) shows the relationship between the equivalent natural period and the maximum absolute acceleration

(a) Maximum absolute acceleration

(b) Ratio of the maximum absolute acceleration of damping constant h to that of 5 % damping constant

Fig. 11 Relationship between the maximum absolute acceleration and equivalent natural period

tion of the structure for the respective damping constants. Figure 11(b) shows the ratio of the maximum absolute acceleration of damping constant h to that of a 5 % damping constant against the equivalent natural period.

The structural response at the same equivalent natural period fluctuates greatly depending on the damping constant. When the damping constant is low, the width of the increase or decrease of the maximum absolute acceleration at some equivalent natural period is large. On the other hand, when the damping constant is high, this width is relatively small because the structural response is reduced and smoothed.

4.4 The relationship between the derailment limit value and the damping constant

There are two factors considered to affect derailment. First, that structural response grows because of lower damping constants. Second, that the derailment limit value increases because of lower damping constants. The structural response factor was evaluated in the preceding section, this section therefore deals with the second. For this purpose, the limit values of derailment SI [18] stipulated in “Design Standards for Railway Structures and Commentary (Displacement limits)” [19] are calculated for various damping constants. SI is calculated by integrating the velocity response spectrum $S_v(h, T)$ over the period T as shown in the equation (3).

$$SI = \int_{0.1}^{2.5} S_v(h, T) dT \quad (3)$$

Figure 12(a) shows the relationship between the minimum limit value SI for 22 waves and the equivalent natural period for the respective damping constants. Figure 12 (b) shows the ratio of the minimum limit value SI of damping constant h to that of a 5 % damping constant against equivalent natural period.

This figure means that the variation of SI depending on the change of the damping constant is about $\pm 10\%$ and this variation is smaller than that of the structural response depending on the change of the damping constant. Further, unlike the structural response, the tendency for the damping constant to increase or decrease does not always coincide with a similar tendency in the limit value.

Fig. 12 Relationship between the minimum limit value SI and the equivalent natural period

4.5 Relationship between the derailment limit value and the damping constant

From the preceding sections 4.3 and 4.4, it is considered that the effect of the damping constant on vehicle running safety depends mainly on the fact that structural responses grow due to lower damping constants. Therefore, the dependence of the ratio γ of the limit scaling factor regarding vehicle running safety on the damping constant is evaluated.

Figure 13 shows the relationship between the ratio γ of the limit scaling factor regarding vehicle running safety defined in the equation (2) and the equivalent natural period for the respective damping constants. This figure shows that the vehicle running safety reduces relatively in all the period bandwidths when the damping constant is less than 5 %. The tendency of γ to increase or decrease is approximately opposite to the tendency of the structural response to increase or decrease with a low damping constant (Fig. 11(b)), which means that the dependence of the structural response on the damping constant affects vehicle running safety.

From the above results, if the damping constant of the structure and the equivalent natural period are given, it is possible to estimate the relative safety margin for vehicle running safety in case of a 5 % damping constant, which is set in the design standard.

Fig. 13 Relationship between the ratio of the limit scaling factor regarding vehicle running safety of various damping constants to that of 5 % damping constant and the equivalent natural period

5. Extraction method of the structures to be cautioned during an earthquake

Following the results in section 4, it is possible to evaluate the maximum response of the structure and vehicle running safety when the damping constant and the equivalent natural period are given. Further, due to results in 3, it is possible to evaluate the damping constant of the structure by using the natural period of the structure and the ground.

This section presents the method for estimating conditions to increase or decrease the maximum structural response and vehicle running safety. First, the range of 0.1-2.0 seconds is set for the equivalent natural period and the ground period, and the damping constant can be estimated from the equation (1). Next, the maximum structural response and the ratio of the limit scaling factor regarding vehicle running safety can be estimated by using the equivalent natural period and the estimated damping constant given in Fig. 11 and Fig. 13.

Figure 14 and Fig. 15 show the estimated results of the maximum absolute displacement and the ratio of the limit scaling factor regarding vehicle running safety respectively corresponding to a given structural equivalent natural period and a given ground natural period. These figures show a rate of change of the response, due to the response, in case of the 5 % damping constant assumed in seismic design.

Here, the rate of change of the absolute acceleration response is shown in Fig. 14 and the ratio of the limit scaling factor regarding running safety is shown in Fig. 15. However, it should be noted that the maximum value of the structural response and the minimum value of the ratio of the limit scaling factor are calculated for 22 input ground motions as described in Fig. 11 and Fig. 13. Further, it should be noted that Fig. 14 and Fig. 15 show the results on the safety side because the upper limit value of the damping constant of the structure was set as 5 %, as shown in Fig. 7 despite the higher damping constant in the range of $T_s/T_g < 1$. Figure 14 and Fig. 15 were prepared to prevent failure in extracting at-risk structures, given that the purpose of this study was to carry out the primary screening of at-risk structures focusing on low damping constants.

The absolute acceleration response was amplified to over 1.0 as shown in Fig. 14. On the other hand, vehicle running safety was reduced to less than 1.0 as shown in

Fig. 14 Maximum absolute displacement for the structural equivalent natural period and the ground natural period (against the value in case of a 5 % damping constant)

Fig. 15 Ratio of the limit scaling factor regarding vehicle running safety for the structural equivalent natural period and ground natural period against the value in case of a 5 % damping constant

Fig. 15. These figures show that structures with longer equivalent natural periods constructed on ground with shorter periods can produce a relative weakness. From these figures, it is possible to extract at-risk structures which have relatively large structural responses and thus reduced vehicle running safety. It should be mentioned that the structural equivalent natural period and the ground natural period required for the estimation can be estimated not only according to the method described in section 2, but also by using a simple method based on structure height and ground conditions [20].

6. Conclusions

This paper proposes a method for estimating the damping constants of railway structures. Furthermore, effects of the structural damping on behavior of the high-speed train were studied by combining the structural analysis and vehicle dynamics simulation. A method was then proposed to extract at-risk structures in terms of vehicle running safety during earthquakes. The results obtained were as follows.

- (1) It was confirmed that the larger the ratio T_s/T_g of the structural natural period T_s to the ground one T_g is, the lower the damping constants are. A method was then proposed to estimate damping constants h from the ratio T_s/T_g .
- (2) A method was proposed to estimate the relative safety margin for the vehicle running safety in case of the damping constant 5% assumed in the design standard based on the results of numbers of the structural analyses and vehicle dynamics simulations.
- (3) Combining the estimation method of the relative safety margin and that of the damping constant mentioned in (1) and (2) above, a method was proposed to identify at-risk structures during earthquakes, where the structural responses and the reduction of the vehicle running safety were relatively large.

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