# NONDESTRUCTIVE EVALUATION OF RAILWAY BRIDGE SUBSTRUCTURES BY PERCUSSION TEST

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The paper describes the conventional nondestructive evaluation of railway bridge substructures by percussion test. By the percussion test, the natural frequency of the bridge substructure can be measured with high accuracy and was applied to many railway bridge substructures in Japan. Importantly, it was confirmed that the natural frequency of the bridge piers decreased with the damage of the structure and increased with the reinforcement. The system of the percussion test includes iron ball to apply an impact force to the bridge substructure, velocity sensor to measure the free vibration of the bridge substructure and data acquisition system to record the free vibration. The detailed procedure in the percussion test is introduced in this paper. For the practical evaluation of the performance of the bridge substructures, a criterion of the natural frequency of the bridge substructures obtained from the result of the regression analysis with many field data was presented. Finally, an application of the percussion test to the Bridge over the Chikuma River was reported and the evaluation of the bridge substructures was conducted in this paper.

***Key Words :*** *percussion test, bridge substructure, natural frequency, free vibration*

## 1. INTRODUCTION

A foundation of bridge pier was constructed under the ground; therefore visual inspection is very difficult after natural hazard including an earthquake or flood. In the past, a performance of railway bridge substructures was evaluated on the basis of dynamic settlement, frequency and amplification of vibration when a train is passing, in addition to the static measurement of an inclination or settlement of the bridge pier. If the above measuring results exceed the tolerances or show time-dependent tendency, the performance of the bridge substructures is suspected. However, the above measuring results generally depend on the weight and passing velocity of the train; therefore the measuring results vary widely and are insufficient to evaluate the performance of the bridge substructures.

Alternatively, a new testing method to measure a natural frequency of the bridge substructures subjected to an impact force was proposed in 1986 (Nishimura 1986). This testing method is referred to as the Impact Vibration Test. By the Impact Vibration Test, it was confirmed that the natural frequency of the bridge substructures could be measured and decreased with the damage of the structure and increased with the reinforcement. This Impact Vibration Test becomes standard method to evaluate the performance of the railway bridge piers in Japanese railway companies and many filed data accumulated over 20 years. Accumulated field data was classified under the type of foundations, height of the piers and the weight of the superstructures. On the basis of the above classified data, criteria of natural frequency obtained from regression analysis were proposed on each foundation (i.e., spread foundation, pile foundation, caisson foundation). These values are considered to be standard values of existing bridge substructures. In practice, the performance of bridge pier can be simply evaluated to compare the above criterion and natural frequency of the actual measurement. This paper describes the details of the Impact Vibration Test and introduces an actual work to evaluate the performance of railway bridge substructure in Japan.

## 2. IMPACT VIBRATION TEST

Figure 1 shows the flow chart of the Impact Vibration Test according to the Railway Technical Research Institute (RTRI) design code (RTRI 2007). An iron ball is hanged from the top of the bridge pier, if available, by using the bridge side walk. A velocity sensor was set on the top of the bridge pier to measure the vibration of the pier. The measuring direction of the velocity sensor is the same as that of the dumped impact force. The iron ball is operated by an inspector on the ground with the rope. The inspector pulls the rope to hit the iron ball to the bridge pier as shown in Figure 2. The bumped impact force makes the bridge pier to vibrate in free. This free vibration is measured using the velocity sensor and a spectral analysis is carried out to determine the natural frequency of the bridge pier. The performance of the bridge pier is evaluated to compare the measured natural frequency with the proposed criteria or previously measured natural frequency.

Figure 3 shows examples of time histories of the bumped impact forces. The maximum bumped impact force in each case is 500 N. Figure 3a shows an ideal pulse wave having no contact duration, which is practically impossible. Figure 3b and 3c show practical bumped impact forces modeled with a sinusoidal wave having frequencies of 100Hz and 50Hz. In practice, the iron ball was wrapped with rubber because of the protection of the concrete surface of the bridge pier. Without wrapped-around rubber, the concrete surface was damaged due to the dumped impact force. Due to the above wrapped-around rubber, the contact duration between the iron ball and bridge pier becomes longer showing Figure3b and 3c. Figure 4 shows Fourier spectrum of example time histories of bumped impact forces showing Figure 3. Amplitude of the Fourier spectrum of the ideal pulse wave becomes constant as shown in Figure 4a. On the other hand, the amplitude of the Fourier spectrum of the practical bumped impact forces modeled with the sinusoidal wave decreases with increasing the frequency as shown in Figure 4b and 4c. This means that it is very important to apply the bumped impact force with the minimum contact duration between the iron ball and bridge pier to keep the Fourier amplitude on the frequency. From the practical experience in Japan, a natural frequency of the bridge pier is generally less than 20 Hz. This indicates that the Impact Vibration Test is practically available if the constant amplitude in the Fourier amplitude ranging up to 20 Hz was confirmed after measuring the time history of the bumped impact force.

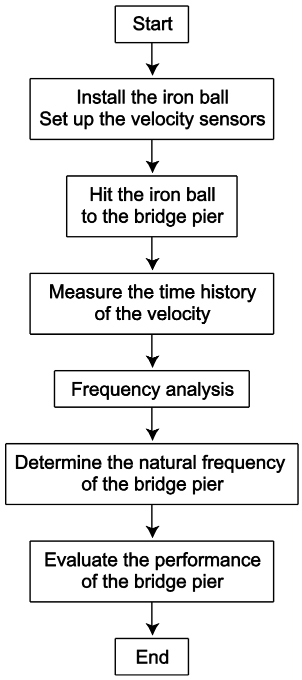


Fig. 1 Flow chart of the conventional percussion test.

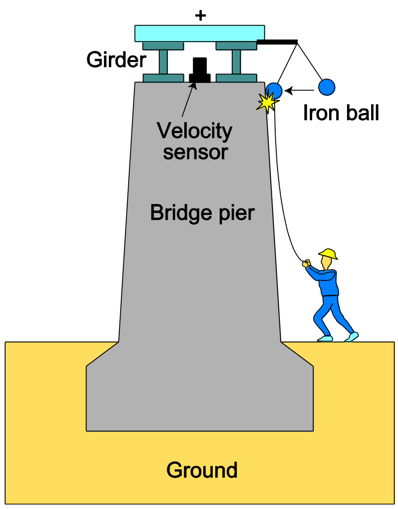


Fig. 2 Typical percussion test.

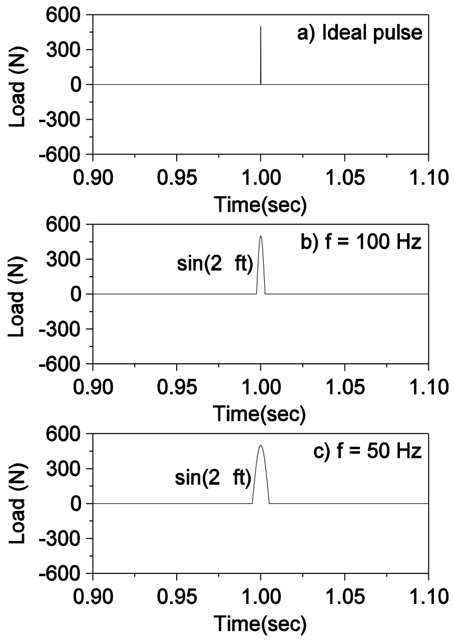


Fig. 3 Time histories of the imaginary impact forces: a) ideal impact force, b) impact force with smaller contact duration, and c) impact force with longer contact duration.

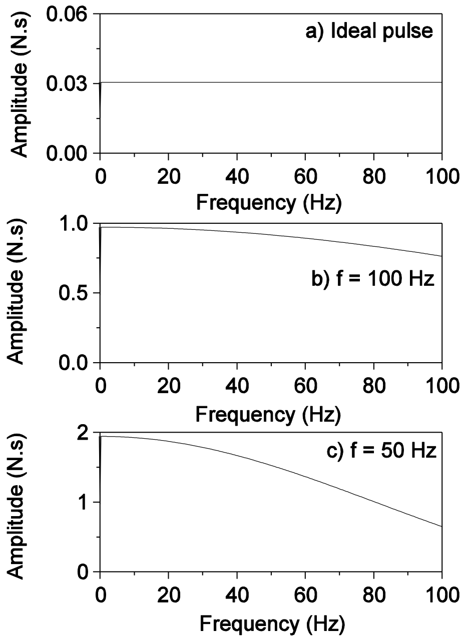


Fig. 4 Fourier spectrum of the time histories of the imaginary impact forces: : a) ideal impact force, b) impact force with smaller contact duration, and c) impact force with longer contact duration.

Fig. 6 Overview of the Bridge over the Chikuma River on the Bessho Line.

## 3. CASE HISTORY

### (1) Layout and fonts for the front matters

The Chikuma River named in Nagano prefecture is named as the Shinano River in Niigata prefecture. The total length of the Chikuma River and the Shinano River is 367 km and the longest in Japan. The discharge at average of the Chikuma River and the Shinano River is 518 $m^3$/s. The Bridge over the Chikuma River on the Bessho Line was constructed in 1924 as shown in Figure 5 and 6. The superstructure is Pratt truss, the longest span is 44.88 m and the total length of the bridge is 224.17 m. Four caissons were constructed to support the above superstructures. Four caissons and bridge piers A, B, C and D as shown in Figure 5 were constructed by plain concrete. Figure 7 shows a schematic figure of the bridge pier and caisson. The heights of the pier and the caissons are 6.045 m and 7.62 m, respectively. Riverbed in each pier was also superimposed in Figure 7. Deposit of the ground is gravel and sand. The average N value by the standard penetration test becomes 42, indicating the ground having high stiffness and strength.

The change of the riverbed was also superimposed in Figure 5. In 1924, the riverbed was almost flat and could sufficiently support four caissons. However, due to construction of dams and soil-erosion control works in the upper stream, downstream sediment transport decreases. This causes the decreases of the

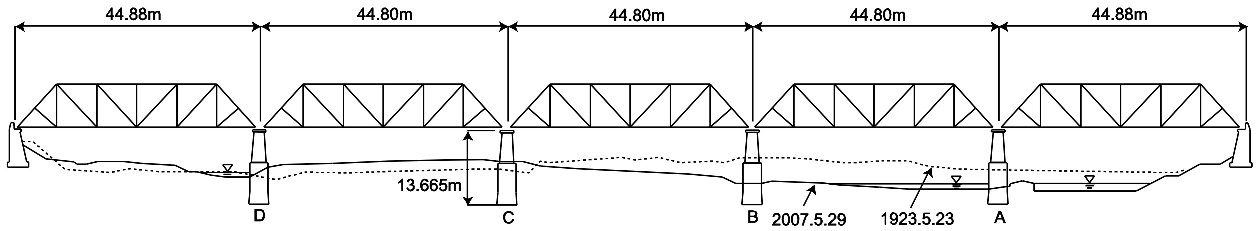


Fig. 5 The Bridge over the Chikuma River on the Bessho Line.

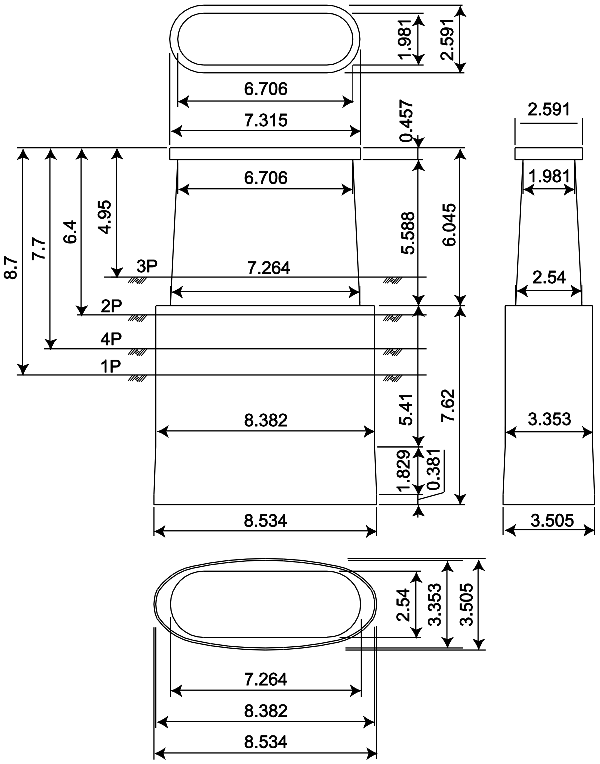


Fig. 7 Schematic figure of the pier and caisson.

Fig. 8 Setting of the impact vaibration test.

riverbed, especially around 1P and 2P as shown in Figure 5. Due to the bed-degradation, the bearing capacities of the caissons were considered to decrease more or less. To evaluate the performance of the substructures under the bed-degradation, the Impact Vibration Test was carried out for the bridge substructures, as shown in Figure 8.

**(2) Result of the impact vibration test**

Figure 9a shows a time history of the velocity measured at the top of the pier A subjected to the impact force using 30 kg iron ball. As mentioned before, the riverbed around the pier A is the lowest among others. This indicates that the natural frequency of the pier A can be expected to be lower than that of other piers. From the above time history of the velocity as shown in Figure 9a, a spectral analysis was carried out to identify the natural frequency. Figures 9b and 9c show Fourier and phase spectrums. The maximum amplitude of 7.69 Hz was obtained at the resonance in accordance with the result of the phase spectrum in which the resonance occurred at the phase of 180 in degrees. Similarly, Figures 10 to 12 show the time histories of the velocity and results of the spectral analysis of the piers B, C and D. For the all of the piers, the natural frequency was identified from the results of the Impact Vibration Test as shown in Table 1.

Table 1 Current natural frequencies and ratio of the current natural frequency to the criteria of the potential natural frequency of the Bridge over the Chikuma River on Bessho Line.

| Pier | Natural frequency (Hz) | Ratio of the current natural frequency to the criteria of the potential natural frequency |
|---|---|---|
| A | 7.69 | 1.43 |
| B | 9.40 | 1.74 |
| C | 12.70 | 2.35 |
| D | 10.99 | 2.04 |

**(3) Criterion of the natural frequency**

As mentioned above, the performance of bridge substructures can be evaluated with the natural frequency obtained from the Impact Vibration Test with the spectral analysis. Ideally, it is the best way for the exact evaluation of the performance of the bridge substructures to compare the current natural frequency with that immediately after the construction. However, there is little case to measure such an initial natural frequency of the pier immediately after construction in general. Therefore, the RTRI proposed an experimental formula to calculate a potential natural frequency by the regression analysis on the basis of many field data. The field data of the actually measured natural frequency of bridge substructures include 362 for spread foundation, 129 for caisson and 135 for pile foundation. In this regression analysis, high sensitive parameters on the natural frequency were selected, such as a weight of the superstructure and a height of the pier. The proposed formula shows a high correlation coefficient, indicating an accurate estimation.

According to the RTRI design code, the potential natural frequency of bridge piers supported by caisson can be obtained as follows:

$$F = 11.83 \times \frac{N^{0.184}}{W_h^{\ 0.285} \times H_k^{\ 0.059}} \tag{1}$$

where $F$ is the criterion of the potential natural frequency; $N$, $N$ value of the ground obtained from the standard penetration test; $W_h$, a weight of superstructure; $H_k$, a height of the pier minus a height of slab at the top of the pier. In this case, the criterion of the potential natural frequency of the bridge piers supported by the caisson can be calculated as follows:

$$F = 11.83 \times \frac{42^{0.184}}{125^{0.285} \times (6.045 - 0.457)^{0.059}} \qquad (2)$$
$$= 5.39$$

Table 1 shows a ratio of the current natural frequency to the above criteria of the potential natural frequency. According to the RTRI design code, if the ratio is less than or equal to 0.70, the bridge substructures should be repaired as soon as possible. If the ratio is more than 0.70 and less than or equal to 0.85, the bridge substructures should be carefully observed. If the ratio is more than 0.85 and less than or equal to 1.00, the bridge substructures is considered to have a minor problem. If the ratio is more than 1.00, the bridge substructure has no problem. Consequently, the current bridge substructures have no problem and good performance as compared to the potential natural frequency.

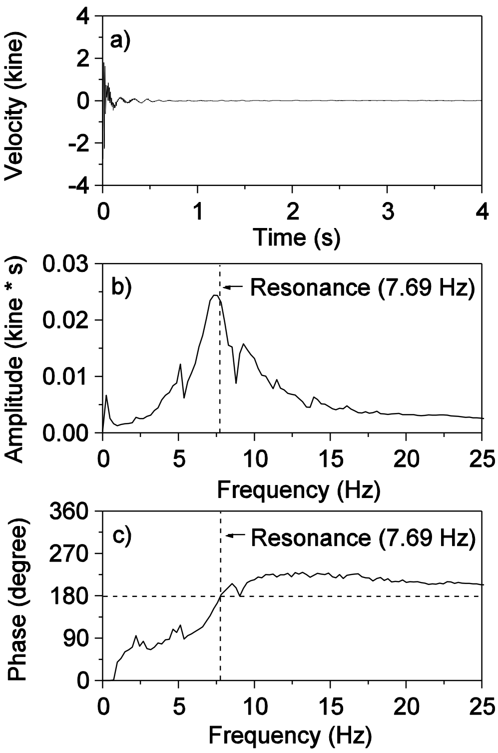


Figure 9 Result of the impact vibration test of the pier A and its foundation: a) time history of the velocity at the top of the pier A, b) Fourier spectrum of the time history of the velocity and c) phase spectrum of the time history of the velocity.

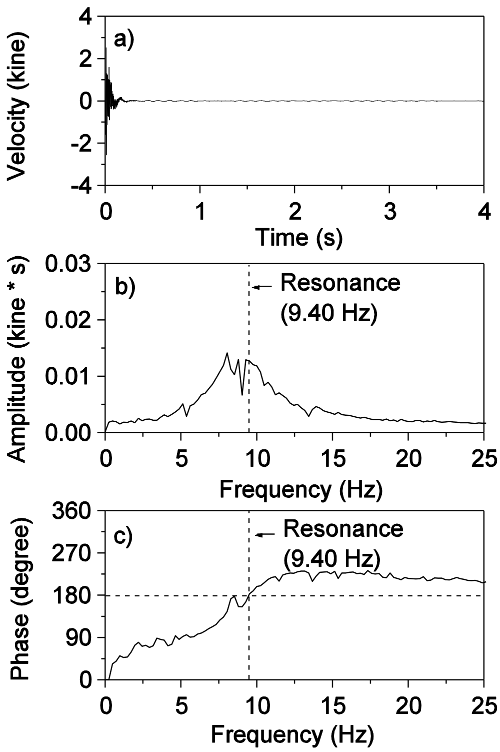


Figure 10 Result of the impact vibration test of the pier B and its foundation: a) time history of the velocity at the top of the pier B, b) Fourier spectrum of the time history of the velocity and c) phase spectrum of the time history of the velocity.

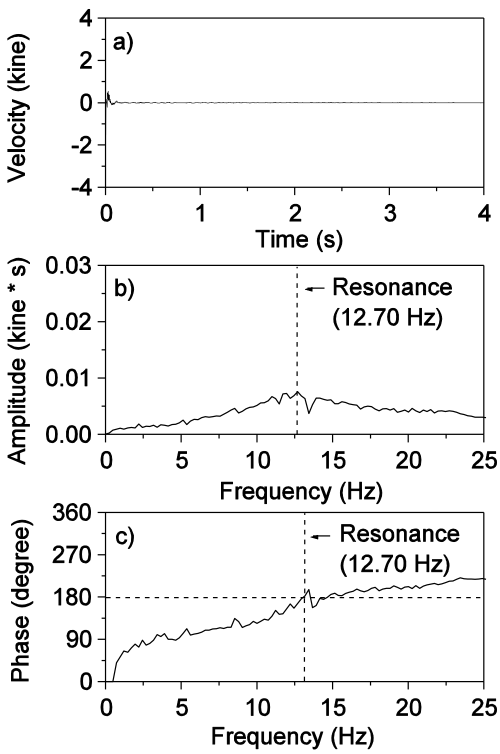


Figure 11 Result of the impact vibration test of the pier C and its foundation: a) time history of the velocity at the top of the pier C, b) Fourier spectrum of the time history of the velocity and c) phase spectrum of the time history of the velocity.

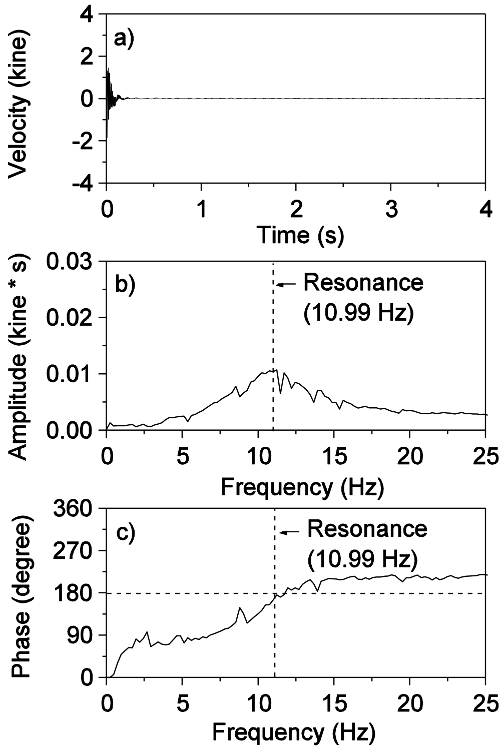


Figure 12 Result of the impact vibration test of the pier D and its foundation: a) time history of the velocity at the top of the pier D, b) Fourier spectrum of the time history of the velocity and c) phase spectrum of the time history of the velocity.

## 4. CONCLUSION

The paper describes a practical technique to evaluate the performance of bridge substructures by using the Impact vibration test. In order to estimate the natural frequency of the substructure, a spectrum analysis was conducted with a time history of the free vibration as compared to a criterion natural frequency obtained from the regression analysis in the basis of the many field data. This technique has an advantage of nondestructive, quick and accurate evaluation. The impact vibration test is applicable to the evaluation of the performance of structures having a natural frequency less than about 20 Hz. Another practical technique is necessary to develop for the evaluation of the performance of structures having the natural frequency more than 20 Hz. This will be reported elsewhere in the near future.

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