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Practical Evaluation Method of Input Loss of Rigid-Frame Viaducts with Piles

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Abstract

Past studies have shown that the input loss effect associated with the dynamic interaction of ground-foundation systems can be reproduced in large-scale group-pile foundations. However, only few studies have investigated the input loss effect on structures such as the single-column, one-pile rigid-frame viaducts commonly observed in Japan which are not expected to provide the group-pile effect due to a longer distance between the piles than the normal one.Therefore, we examined the input loss effect of rigid-frame viaducts. In addition, we proposed a simplified static analysis method for evaluating the response of structures while taking into consideration the input loss effect, and examined the applicability of the method proposed. The scope of the research and the results are summarized below.

(1) A dynamic linear analysis by means of two-dimensional lumped-mass models was conducted to examine the input loss effect of one-column, one-pile rigid-frame viaducts. It was found out that rigid-frame viaducts that have wide inter-pile spacing and therefore are not expected to provide the group-pile effect can still produce input loss, and the input loss effect becomes greater as the difference in rigidity between the ground and the piles becomes larger.

(2) Reduction of structural response associated with input loss is significant at low frequencies.

(3) In order to take the input loss effect into consideration in the structural response evaluation, methods were proposed for calculating effective input coefficients by means of a seismic deformation method and for calculating response spectra based on the random vibration theory. The applicability of these methods proposed was verified through comparison with dynamic analysis.

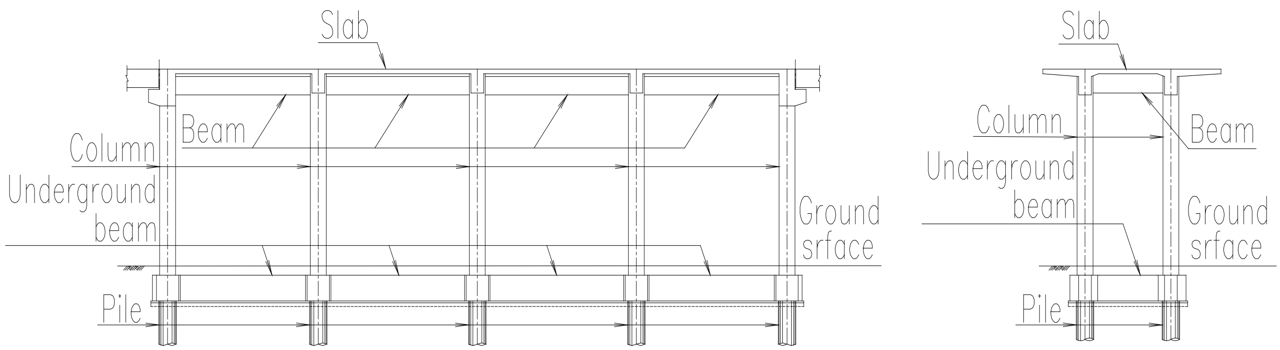
Keywords: Input loss, Effective input motion, Kinematic interaction

1. Introduction

Many of the viaducts in Japan utilize the rigid-frame structure as shown in Fig. 1, in which the slabs, columns, cross and longitudinal beams are rigidly joined. From the time when they were first introduced as a railway structure in the early 1900s, rigid-frame viaducts proved to be superior to other structural forms due to the low construction cost and greater seismic capacity in earthquake-prone Japan. Many rigid-frame viaducts in Japan have a pile foundation to cope with the country’s geological conditions. It is widely known that input loss, which reduces the seismic ground motion absorbed into the structure, is generated in structures supported by a pile foundation. In comparison with a free field, seismic ground motion absorbed into a structure supported by a pile foundation is reduced since the ground motion caused by the earthquake is limited due to the existence of the foundation. (e.g. [1,2]) Numerous experimental and analytical studies (e.g. [3,4]) have been conducted on the input loss of group-pile and other large-scale foundations, by which the input loss effect on pile foundations has been verified. On the other hand, only few studies have been conducted on the input loss effect of rigid-frame viaducts that have a wide space between the piles and thus are not expected to provide the group-pile effect.

In Japan, static analysis methods are often used in aseismic designing to simplify the design process, in which the impact of inertia force on seismic ground motion is evaluated using nonlinear response spectrum methods. [5,6] Although static analysis methods are capable of evaluating the seismic response of structures in a simple manner, they require separate detailed studies for response evaluation in which input loss is taken into consideration. Therefore, input loss is not considered normally in the design process to avoid analytical complexity and instead to attach importance to evaluation on the safe side. However, more reasonable aseismic designing can be achieved by considering the input loss effect. It is therefore desirable that a static analysis method should be developed so that it is possible to evaluate the seismic response of structures in a simple manner while taking input loss into consideration.

With this for a background, we started our development work by analyzing the input loss effect of rigid-frame viaducts. Specifically, dynamic analysis was carried out using two-dimensional lumped-mass models to examine the input loss effect of rigid-frame viaducts. Next, we developed a simple static analysis method for evaluating the seismic response of structures while considering the input loss effect and examined the validity of the method through comparison with dynamic analysis.



(a) Side view
(b) Cross-sectional view

Fig. 1 Rigid-frame viaduct

2. Input loss effect of rigid-frame viaducts

Input loss effect can be evaluated using the effective input coefficient η, which is the ratio of the seismic response of the pile head to that of the free field. This means that the input loss effect can be evaluated by seismic response analysis using the models of the free field and structures.

In our study, dynamic analysis was conducted using lumped-mass models to clarify the input loss effect of rigid-frame viaducts as discussed below.

2.1 Analytical models

The lumped-mass models of rigid-frame viaducts used in our study, shown in Fig. 2 (a), featured the reinforced concrete piles, with the pile bottoms supported and the pile tops rigidly joined to the underground beams. Two types of ground were used to analyze the impact of the ground conditions on input loss: multi-layer ground (Type A) shown in Fig. 2 (b) and single-layer ground (Type B) shown in Fig. 2 (c). Ground reaction was evaluated using Formula (1) normally used in designing railway structures in Japan [7] and Formula (2) [8] that was proposed by Vesic based on the elastic beam spring theory.

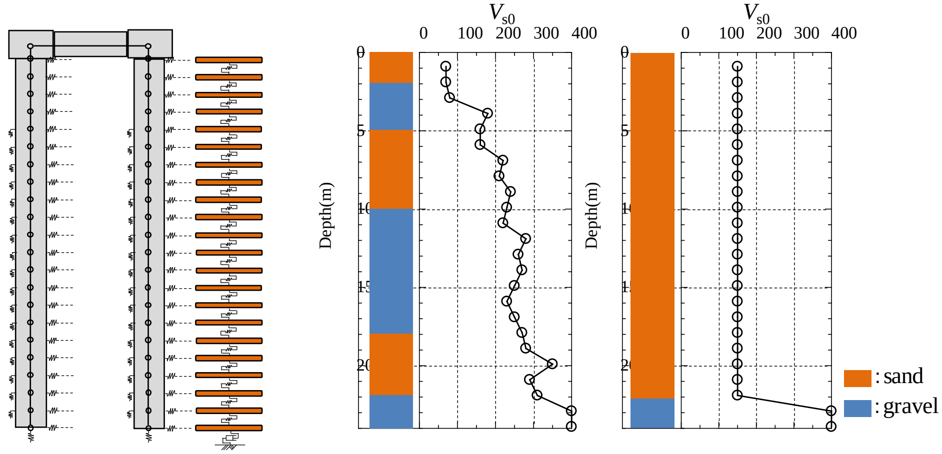
$$kh = 3.6\rho_{gk} E_d B^{-3/4} \tag{1}$$

where E_d is the deformation modulus of the ground and ρ_{gk} is the correction factor for the duration of action, which was set at 1.0 in our study.

$$kh = 0.65 \frac{Es}{(1-\upsilon_s^2)B} \cdot \sqrt[12]{\frac{Es \cdot B^4}{Ep \cdot Ip}} \tag{2}$$

where kh is the ground reaction coefficient; B, the pile diameter; E_P, Young's modulus of the pile; I_P, the second-order moment of the pile; E_s, Young's modulus of the ground; and ν_s, Poisson's ratio of the ground.

The structures were modeled using beam elements while the interaction between the ground and the foundation was modeled using spring elements. Sufficiently large free field was selected for modeling so that it would not be affected by the response of the structures. To extract the kinematic components of dynamic interaction, the piles and footing were made massless to eliminate any impact of inertia-generated interaction. Table 1 shows the specifications of the structure models and the analytical cases used in our study. The attenuation constant of the ground and that of the structures were both set at 3% at both 1 Hz and 10 Hz based on Rayleigh damping.



(a) Rigid-frame viaduct (b) Type A (c) Type B

Fig. 2 Analytical models

Table 1 Analytical cases and pile specifications

Item	case1-1	case2-1	case1-2	case2-2
Ground type (Number of layers)	Type A	Type B	Type A	Type B
Number of piles (n)	2		2	
Pile diameter B (m)	1.0		1.0	
Inter-pile distance s (m)	5.0		3.0	
Pile length L (m)	21.0		21.0	
Young's modulus of the pile E_P (kN/m^2)	2.50×10^7		2.50×10^7	
Second-order moment of the pile I_P (m^4)	0.049		0.049	
Horizontal ground reaction coefficient k_h	Formula (1)		Formula (2)	

2.2 Analytical conditions

Analysis was carried out using a dynamic linear method. White noise, as shown in Fig.3, was used as the seismic wave input, which was applied from the location beneath the free field.

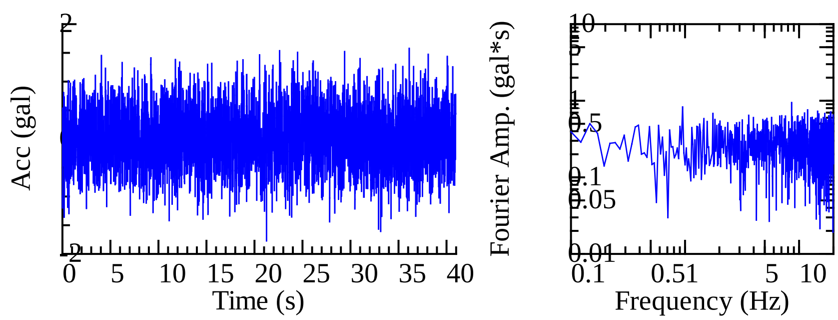


Fig. 3 Time history of seismic wave input and corresponding Fourier amplitude spectrum

2.3 Analytical results

Fig. 4 shows the calculated effective input coefficients for the four analytical cases. While staying at around 1.0 at the lowest frequencies, the effective input coefficients started to decline at around 1 Hz in Cases 1-1/1-2 and at around 2 Hz in Cases 2-1/2-2, indicating that even rigid-frame viaducts with relatively greater inter-pile spacing can have an input loss effect. Examined from the viewpoint of the ground conditions, the effective input coefficients hit the bottom at around 6 Hz in Type A ground and at around 10 Hz in Type B ground. Furthermore, the cases calculated with Formula (2) indicate a decline starting at a lower frequency than the cases calculated with Formula (1). This can be explained as follows: near the ground surface, Type A ground is less rigid than Type B ground, and Formula (2) produces lower ground rigidity than Formula (1), resulting in higher pile rigidity relative to the ground. Consequently, the piles limit the ground motion more effectively to produce a greater input loss effect.

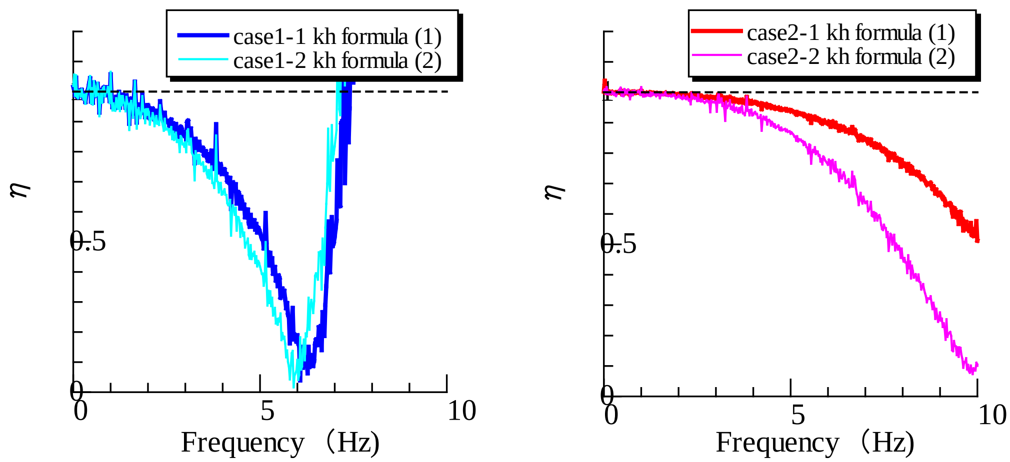


Fig. 4 Comparison of effective input coefficient η of

3. Simple method for calculating effective input coefficients

In the field of aseismic designing of railway structures in Japan, the response displacement methods, in which the ground and structures are modeled separately and the structure models are subjected to ground displacement, have been introduced [5] for evaluating the impact of ground displacement using the static analysis methods. Similarly to the nonlinear response spectrum methods, however, response evaluation using these methods requires separate detailed studies to take into consideration the input loss effect. Accordingly, these methods are normally ignored for the sake of simplifying the design process.

It should be noted that, it is revealed in Section 2 of this report that even for the rigid-frame viaducts, input loss can be generated from the relative difference between the rigidity of the piles and that of the ground. This effect can be reflected in aseismic designing by carrying out seismic response analysis using a consolidated lumped-mass model of the free field and structures. Other methods have also been proposed in the past studies for evaluating the seismic response of the ground and structures. (e.g. [9,10,11,12,13]) These methods, however, require complex modeling and physical property settings. For input loss evaluation, such methods as are often beeing used in the design process and simple are required.

We developed a simple method for calculating effective input coefficients and verified its validity through comparison with dynamic analysis, as discussed below.

3.1 Simple calculation method

Kinematic interaction, which is the dynamic interaction of a foundation-ground system during an earthquake, can be interpreted as interaction between the ground and pile foundation caused by natural ground vibration. Based on this assumption, it was believed that input loss could be evaluated by interpreting the eigenmodes obtained from the eigenvalues of each mode of the natural ground as the ground displacement, and subjecting the structure to this ground displacement. In this case, the concept can be widely applied to the design process by using the response displacement methods in evaluating the structure's response to ground displacement.

We propose the following method for calculating effective input coefficients using eigenvalue analysis and the seismic deformation method.

(i) Frequencies of the free field in each order mode and the individual eigenmodes are calculated by modeling the free field and analyzing the actual eigenvalues.

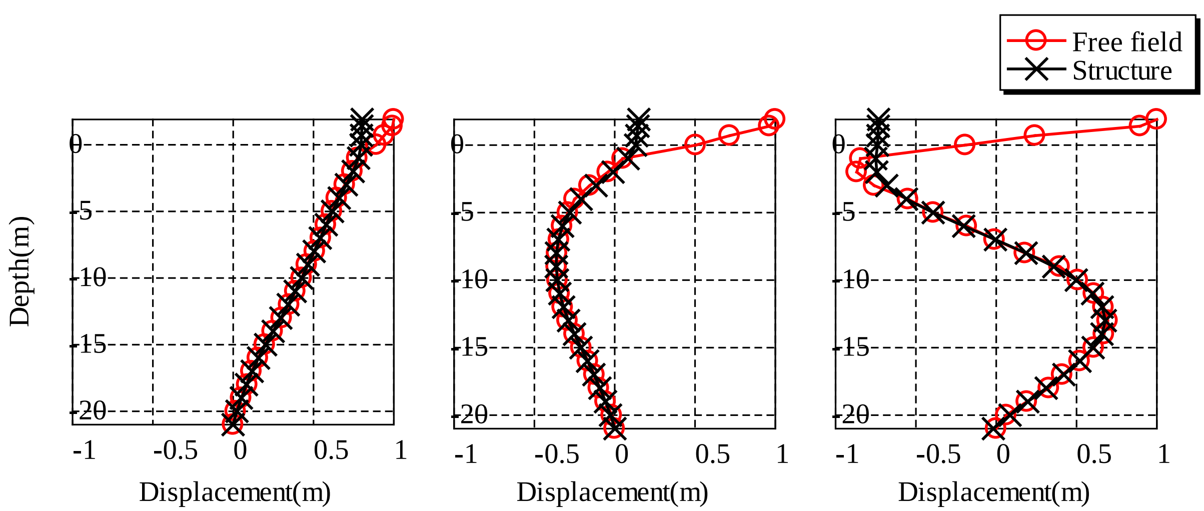
(ii) In the seismic deformation method, displacement of the structure is calculated by subjecting the structure to each eigenmode calculated by the eigenvalue analysis as the ground deformation. The maximum amplitude of each eigenmode is set to 1.0.

(iii) The displacement of structures calculated by the seismic deformation method is divided by the displacement of the free field. Then, effective input coefficients relative to the natural frequency of each order mode are calculated.

3.2 Applicability of the simple method

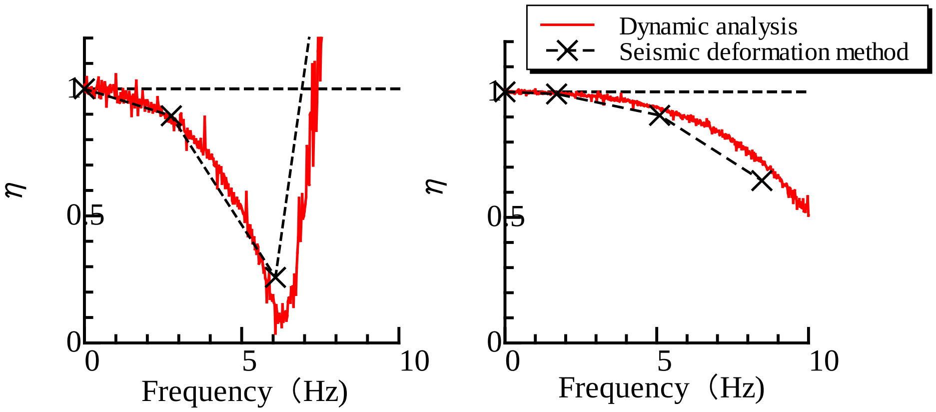
We selected Cases 1-1 and 2-1 mentioned in Section 2 for which Formula (1) was used for the following analysis. In the analysis, calculations were made for the first- to third-order modes following the (i) to (iii) proposals as the impact of high-order modes was considered insignificant in designing structures. In addition, effective input coefficients in the 0–10 Hz range were calculated by forming a linear profile of effective input coefficients for the natural frequencies of each order mode that were calculated in (iii). The effective input coefficient at 0 Hz was set to 1.0.

Fig. 5 shows the displacement of the free field and that of the structure in the first- to third-order modes of Case 1-1, calculated as per (i) and (ii) proposed above. In the figure, input loss is indicated where the displacement of the structure does not follow that of the free field, which in Case 1-1 is significant in the softer layer near the ground surface. This is attributable, as discussed in Section 2, to the rigidity of the piles which has become relatively higher than that of the ground. It has also been shown that the higher the order of the mode is in which the wavelength is shorter, the less the pile foundation follows the ground in displacement. As a result the input loss effect becomes the greater. Fig. 6 shows the calculated effective input coefficients based on (i) and (iii) proposed above and, for comparison, those based on the dynamic analysis discussed in Section 2. As shown in the figure, the calculated effective input coefficients based on the seismic deformation method resemble fairly well those that are based on the dynamic analysis, which verifies that the method can accurately evaluate the input loss effect.



(a) First-order mode (b) Second-order mode (c) Third-order mode

Fig. 5 Amplitude of free ground and piles in each mode of Case 1-1



(a) Case 1-1 Type A (b) Case 2-1 Type B

Fig. 6 Comparison of effective input coefficients

4. Simple method for evaluating response spectrum while taking into consideration input loss effect

To evaluate the response of structures by applying the effective input coefficients proposed in Section 3 to the static analysis, it is necessary to calculate the response spectra while taking into consideration the input loss effect. Normally, this is achieved by multiplying an effective input coefficient by the Fourier spectrum of surface seismic motion, them applying inverse Fourier transform to the multiplication results to obtain damped seismic motion input, and finally calculating the response spectra in the time domain. This method, however, involves complex calculation operations. To simplify the response spectrum calculation while taking into consideration the effective input coefficients, it is preferable to predict the response spectra in the frequency domain rather than to seek solutions in the time domain.

Based on the above, a simple method for evaluating the response of structures while considering the input loss effect was proposed based on the random vibration theory,and by comparison with the step - by - step integration method, the applicability of the proposed method and the impact of the input loss effect of rigid-frame viaducts on the response of structures were clarified.

4.1 Method for calculating the response spectra based on the random vibration theory

The random vibration theory handles vibration using the power spectra and root mean square value (RMS), and evaluates the maximum response of structures by obtaining the peak factors based on probabilistic response evaluation. [14] The root mean square value is an index indicating the average size, and can be expressed by using Formula (3) representing the square root of the product of the square of the transfer function of the absolute acceleration of a one-degree-of-freedom system and the acceleration power spectrum density of the seismic ground motion.

$$\sigma_a(\omega_0, h) = \sqrt{\int_{-\infty}^{\infty} \left| H_a(\omega_0, h, \omega) \right|^2 \cdot G_a(\omega) d\omega} \tag{3}$$

where $G_a(\omega)d\omega$ is the acceleration power spectrum density of the seismic ground motion and $H_a(\omega_0, h, \omega)$ is the transfer function of the absolute acceleration of a one-degree-of-freedom system. In Formula (4), ω_0 is the fundamental circular frequency of structures and h is the attenuation constant of structures.

$$\left| H_a(\omega_0, h, \omega) \right|^2 = \frac{1 + 4h^2(\omega/\omega_0)^2}{\left\{1 - (\omega/\omega_0)^2\right\}^2 + 4h^2(\omega/\omega_0)^2} \tag{4}$$

To obtain the maximum acceleration response from the root mean square values of the acceleration response of a one-degree-of-freedom structure, the peak factors are required. According to Rosenblueth, when white noise representing the power spectrum density $G_a(\omega)$ of a one-degree-of-freedom system affects seismic ground motion, the maximum response value $Sa(\omega_0,h)$ can be expressed as follows[15]:

$$S_a(\omega_0,h)=\omega_0\sqrt{\frac{\pi G_a}{2h\omega_0}}\cdot\sqrt{1-\exp(-2h\omega_0 t_d)}\cdot\sqrt{2}\sqrt{0.424+\ln(2h\omega_0 t_d+1.78)} \tag{5}$$

where t_d is the duration of seismic ground motion (principal motion). With seismic ground motion of white noise, integration of Formula (3) produces:

$$\sigma_a(\omega_0,h)=\sqrt{\frac{\omega_0\pi G_a}{2h}} \tag{6}$$

Deleting $G_a(\omega)$ from Formula (5) and Formula (6) yields Formula (7):

$$S_a(\omega_0,h)=\sigma_a(\omega_0,h)\cdot\sqrt{1-\exp(-2h\omega_0 t_d)}\cdot\sqrt{2}\sqrt{0.424+\ln(2h\omega_0 t_d+1.78)} \tag{7}$$

In case of use of Formula (7), calculating $\sigma_a(\omega_0,h)$ by using Formula (3), but not Formula (6), eliminates the need to simulate seismic ground motion with white noise. In that case, the following peak factor p is used:

$$p=\sqrt{2}\sqrt{0.424+\ln(2h\omega_0 t_d+1.78)} \tag{8}$$

In the following equations, $S_a^{org}(\omega_0,h)$ is the original response spectrum and $S_a^{\mathrm{mod}}(\omega_0,h)$ is the response spectrum with input loss taken into consideration.

$$S_a^{org}(\omega_0,h)=\sigma_a^{org}(\omega_0,h)\cdot\sqrt{1-\exp(-2h\omega_0 t_d)}\cdot\sqrt{2}\sqrt{0.424+\ln(2h\omega_0 t_d+1.78)} \tag{9}$$

$$S_a^{\mathrm{mod}}(\omega_0,h)=\sigma_a^{\mathrm{mod}}(\omega_0,h)\cdot\sqrt{1-\exp(-2h\omega_0 t_d)}\cdot\sqrt{2}\sqrt{0.424+\ln(2h\omega_0 t_d+1.78)} \tag{10}$$

Formula (9) and Formula (10) together produce the following response spectral ratio:

$$R=\frac{S_a^{\mathrm{mod}}(\omega_0,h)}{S_a^{org}(\omega_0,h)}=\frac{\sigma_a^{\mathrm{mod}}(\omega_0,h)}{\sigma_a^{org}(\omega_0,h)} \tag{11}$$

Using Formula (3), the following is obtained:

$$R=\sqrt{\frac{\int_{-\infty}^{\infty}\left|H_a(\omega_0,h,\omega)\right|^2\cdot\{\eta(\omega)\}^2\cdot G_a(\omega)d\omega}{\int_{-\infty}^{\infty}\left|H_a(\omega_0,h,\omega)\right|^2\cdot G_a(\omega)d\omega}} \tag{12}$$

where $\eta(\omega)$ is the effective input coefficient. In our proposed method, structural response is evaluated using Formula (12) while taking the input loss effect into consideration.

4.2 Structural response evaluation using our proposed method

Comparison was made between the elastic acceleration response spectrum produced by Formula (12) and that by a step-by-step, time-domain integration method, with the aim of examining the applicability of the proposed equation and the impact of the input loss effect on structures. Seismic ground motion (KOB waves) observed at the Kobe Marine Observatory during the 1995 Hyogo-ken Nanbu Earthquake, shown in Fig. 7, was used for the examination. The attenuation constant of structures was set to 5%. The input loss coefficient used was based on the results of Case 1-1 and Case 2-1 in Fig. 6, calculated using the seismic deformation method.

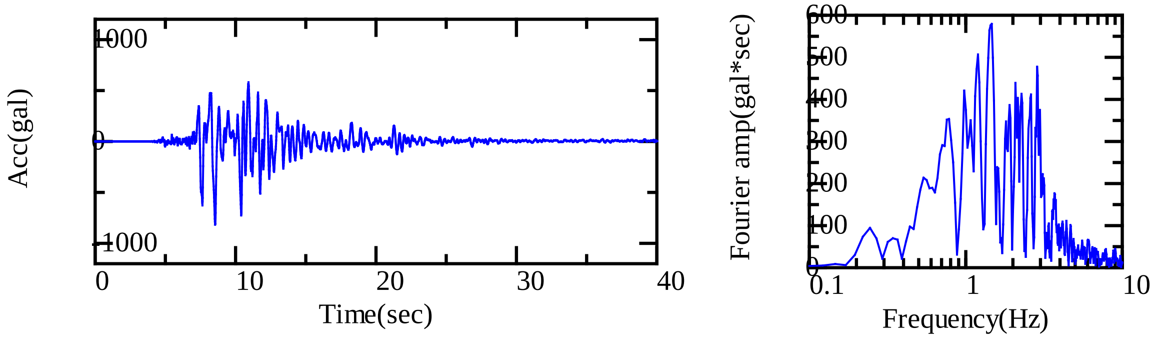
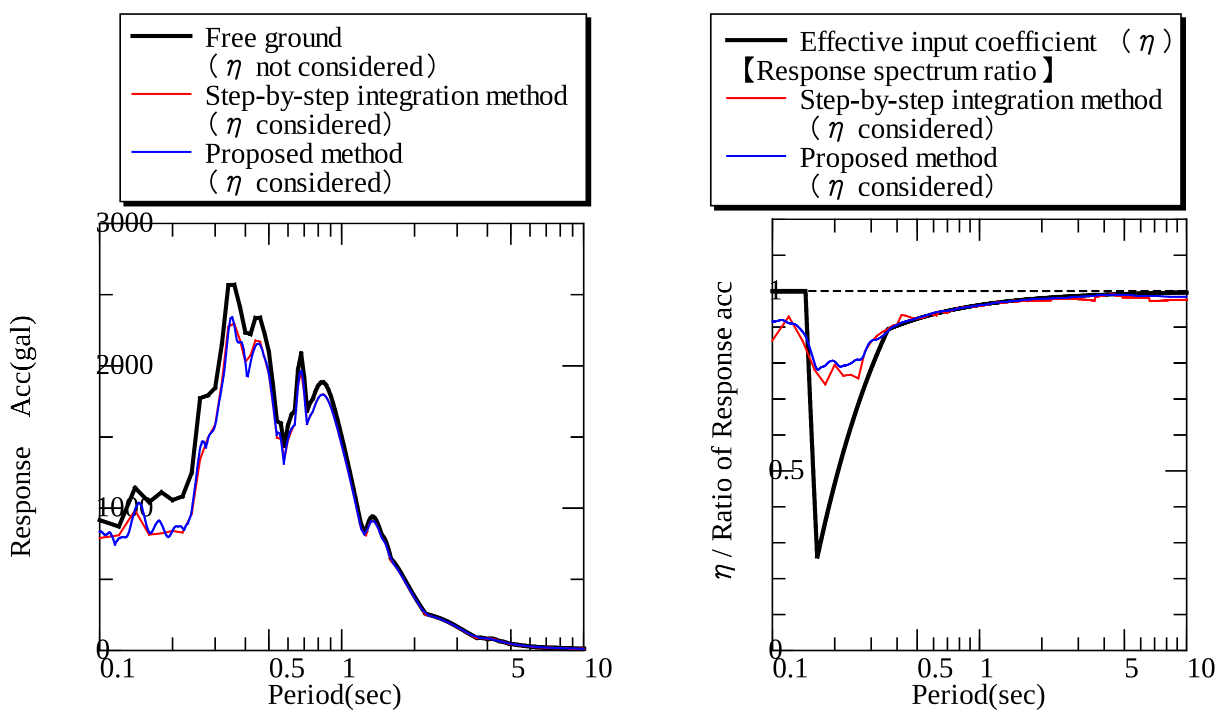


Fig. 7 Time history of seismic wave input and corresponding Fourier amplitude spectrum (KOB waves)

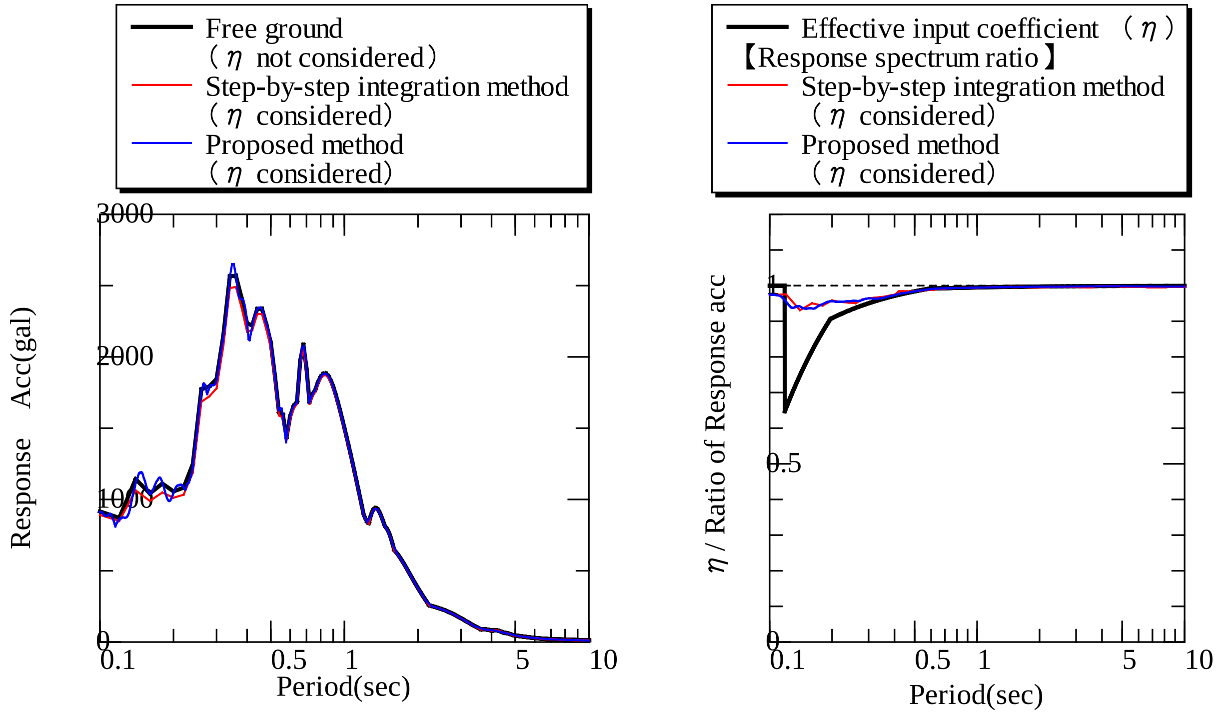
Fig. 8 and 9 show the elastic acceleration response spectra calculated based on the above-mentioned conditions and the ratios of response spectra with consideration of input loss effect to those without consideration of the effect. Fig. 8 (b) and 9 (b) also show the effective input coefficients used in the exercise. Regarding the impact of input loss on structures, it was found that the elastic acceleration response spectra declined significantly in the short-period range, hitting the bottom at the period roughly coinciding with that of the lowest point of the effective input coefficient. It was also found that the response spectra dipped further and in a wider range in Case 1-1 in which the ground had a lower rigidity near the surface than in Case 2-1. This corresponds to the results presented in Section 2 and Section 3. Furthermore, comparison between the results of the proposed method and those of a step-by-step, time-domain integration method revealed that the former results resemble the latter ones fairly well, verifying the applicability of the proposed method.



(a) Elastic acceleration response spectrum

(b) Elastic acceleration responsespectrum ratio

Fig. 8 Comparison of elastic acceleration response spectra – Case 1



(a) Elastic acceleration response spectrum (b) Elastic acceleration responsespectrum ratio

Fig. 9 Comparison of elastic acceleration response spectra – Case 2

5. Conclusion

We examined the kinematic interaction and resultant input loss effect on one-column, one-pile rigid-frame viaducts which are common in Japan, then proposed a simplified method for evaluating the response of structures taking into consideration the input loss effect and examined the applicability of the method. The following findings were obtained.

(1) Rigid-frame viaducts that have widely spaced piles and are therefore not expected to provide the group-pile effect can still produce input loss. Input loss is generated when the seismic response of structures does not follow that of the free field. The input loss effect is larger in high order modes where the wavelength of the seismic wave relative to the pile length becomes shorter in case where the rigidity of the ground is relatively smaller than that of the pile.

(2) Reduction in structural response associated with input loss is significant in short-period ranges.

(3) In an attempt to introduce the input loss effect in static analysis and evaluation of structural response, simplified methods were proposed for calculating effective input coefficients using the seismic deformation method and for calculating response spectra based on the random vibration theory. In addition, the applicability of these proposals was examined, and it was shown that the proposed methods can accurately evaluate the input loss effect.

While this study was executed assuming at linear characteristics of the ground and structures, a broader examination involving nonlinear characteristics of the ground and structures is needed to clarify the kinematic interaction of the ground-foundation system and related impact.

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