Evaluation Method of Input Loss Effect in Seismic Design by Means of Static Analysis Method

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More reasonable seismic design can be achieved by considering the input loss effect of the soil-foundation interaction. However, there is no practical evaluation method of the input loss in the seismic design by means of the static analysis method for the foundation widely used in the railway field. A practical method for evaluating input loss using the static analysis method was therefore examined. First, a sensitivity analysis was conducted by varying both ground and pile conditions, and the input loss effect due to the pile foundations was investigated. Practical methods were then proposed for calculating the effective input coefficient by means of a seismic deformation method and for calculating response spectra based on the random vibration theory. Furthermore, the applicability of these methods was verified through comparison between the dynamic analysis results and the evaluated results.

Keywords: input loss, effective input motion, pile foundation, seismic deformation method, random vibration theory, floating pile

1. Introduction

It is generally known that in the structures supported by large-scale foundations, input loss effect occurs due to the soil-pile interaction. Past experiments and analyses [1] etc. on large-scale caisson and other foundations that are highly rigid and very effective in restricting the surrounding ground have shown that such foundations have input loss effects. Practical seismic design consistent with actual phenomena can be achieved by considering input loss. Seismic design standards for railway structures [2] therefore note that structural design may consider input loss.

Seismic response analysis methods used in the seismic design of structures can be roughly divided into dynamic analysis and static analysis methods. In case of dynamic analysis, input loss is automatically considered by using a soil-structure system model. Such methods, while capable of reproducing complex seismic behaviors, require design engineers who have extensive related knowledge and experience. For this reason, dynamic analysis methods are seldom used for design processes except for long bridges, skewed bridges and other structures with special characteristics.

In static analyses, seismic actions are converted to inertia force, ground displacement and other static loads to calculate the responses. In the seismic design standard in Japanese facilities, the demand yield seismic coefficient spectrum is used to calculate the nonlinear responses of structures. The analysis method, which calculates responses based on given design response spectra, is commonly used for design today. Static analysis methods are highly applicable to relatively simple structures dominated by the first mode, like many ordinary railway structures. On the other hand, no techniques are currently available for rationally evaluating input loss in static analysis methods, and so the input loss is not currently considered in seismic design practices. Consequently, there is a need for practical techniques to consider the input loss in static analysis methods for pile foundations widely used in railway structures.

With the above in mind, this study examined techniques for incorporating the input loss generated through pile foundations into static analysis methods. Firstly, analyses were conducted to clarify how changes in the parameters of the ground and pile foundations would impact input loss performance. A practical method was then 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 was subsequently verified by comparing dynamic analysis results and evaluated results.

2. Input loss through pile foundations

Input loss of pile foundations has been discussed and studied [3] and is the focus of Chapter 3 and subsequent discussions in this paper. The characteristics of the effect of the input loss effect specifically on railway structures are outlined in the following sections.

2.1 Outline of the analysis method

Among the different types of pile foundations, grouped-pile foundations are known to be among the most complex to analyze, and methods have been proposed to accurately evaluate such foundations. On the other hand, several methods [4], [5], etc. have been proposed to simplify the formulation by setting up hypotheses.

Many of these simplified methods typically have applicable ranges for the number of piles and pile spacing. Accordingly, this study adopted the single beam equivalent method [4], [5] which is known to provide good approximate solutions for grouped-pile foundations which are
widely used as railway structures. In the method, grouped piles are represented by an equivalent single beam. For details, refer to Reference 5. The equivalent single beam used in this study was calculated based on the hypotheses given below. Figure 1 shows an outline of the beam.

- Grouped piles deform with the soil around them while spacing between them remains the same.
- The moment caused by the frictional force exerted by the soil between the piles onto the piles is ignored.
- The piles are locked from the top by footings, and are thus prevented from rotating.
- The ground and piles consist of horizontally divided elements. The point where the neutral axes of the piles intersect with the top and bottom surfaces of the elements are on the same planes.

To obtain a fairly accurate simulation of seismic wave propagation through the ground, the thin layer element method was used, which is based on hypothesized stratified ground with semi-infinite horizontal expansion. Input loss in the pile foundations was evaluated using an effective input coefficient $\eta$ expressed as the ratio of pile-top displacement to free-field surface displacement, which is calculated by inputting seismic waves into the foundations of the proposed model. It should be noted that the pile foundations were assumed to have no mass in order to eliminate any impact of dynamic interaction other than kinematic interaction, thereby eliminating any inertial interaction effect.

### 2.2 Analytical conditions

The pile foundations and ground used in the analysis are outlined in Fig. 2. The piles were assumed to be end-bearing piles and were rigidly joined to the footings at the pile top. As the analysis was based on the thin-layer method, linear calculations would be the norm. However, stratification of the ground is inevitable with L2 earthquake motion. Thus, based on principles similar to those of the equivalent linearization, the initial shear-wave velocity $V_s0$ was set at a low constant value irrespective of strain level, and the damping constant was set at a rather large value in consideration of hysteresis damping. Specifically, for the analysis, the initial shear-wave velocity $V_s0$ was multiplied by 0.75 by referring to the current seismic design standards [2] while the damping constant was set to 10% by referring to existing indoor soil test results. Other parameters used in the analysis are shown in Table 1 together with the scenarios, or the cases.

KOB waves measured at the Kobe Marine Observatory during the 1995 Hyogo-ken Nambu Earthquake and which are the common reference in many seismic design standards for design earthquake motion, were input for the analysis. Figure 3 shows the time history and Fourier amplitude spectra of the input seismic motions.

### 2.3 Results of the analysis

Figure 4 shows the calculated effective input coefficients $\eta$, which were generally 1.0 in the low-frequency ranges near 0 Hz. At certain frequencies, the effective input coefficient $\eta$ started to decline (i.e. input loss started to increase) and, depending on the parameters of the foundations and ground, dropped to about 0.5 at around 5 Hz. The

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**Fig. 1** Hypotheses for calculating an equivalent single beam

**Fig. 2** Pile foundation parameters

**Fig. 3** Time-history wave and Fourier amplitude spectrum

input loss characteristics identified through comparison of the various cases of the analysis are outlined below.

### 2.3.1 Comparison of impact of ground rigidity

The plotted lines in Fig. 4 representing the different ground rigidities in Cases 1 (a) to 6 (f) were compared to clarify the impact of the ground rigidity. In every case, the lower the ground rigidity (the smaller the $V_s$) is, the greater the input loss effect is.

### 2.3.2 Comparison of impact of pile diameter

The impact of the pile diameter was clarified by comparing Case 1 (a) with a diameter of 1.0 m and Case 2 (b)
with a diameter of 1.5 m (Fig. 4). Case 2 with a greater pile diameter shows greater input loss effects than Case 1 with a smaller pile diameter.

2.3.3 Comparison of impact of pile length

The impact of the pile length was clarified by comparing Case 3 (c) with a pile length of 10 m, Case 1 (a) with a pile length of 15 m and Case 4 (d) with a pile length of 30 m (Fig. 4). Although the impact of the pile length was rather small, the effect of input loss tended to be greater with shorter piles.

2.3.4 Comparison of impact of the number of piles

The impact of the number of piles was clarified by comparing Case 1 (a) with four piles, Case 5 (e) with nine piles and Case 6 (f) with 16 piles (Fig. 4). The effect of input loss was greater with the nine-pile design than the four-pile design although the impact of the number of the pile is less sensitive than the impact of the pile diameter. The 16-pile design had roughly the same impact as the nine-pile design.

2.3.5 Examinations on the analysis results

At higher frequencies, since ground vibration wave-lengths become shorter with pile length, there are phase differences between ground vibrations and pile vibrations following the depth of the pile. As a result, the piles move to restrict deformation of the surrounding ground and act to average it, in effect mitigating the seismic input. The above analytical results suggest that pile foundations are more rigid relative to the ground when 1) the ground is softer, 2) the piles are larger in diameter, 3) the piles are shorter and 4) there are more piles, thereby more aggressively restricting the movement of the ground and mitigating seismic input.

3. Challenges in achieving seismic design that consider the input loss effect

As discussed in Chapter 1, dynamic analysis is used only when designing long bridges and specially shaped structures. Rigid-frame viaducts and piers of railway structures are mostly simple in shape with much of the weight concentrated on the upper portion of the structure. Consequently, it has been confirmed that these structures can be simulated using a single-degree-of-freedom system that consider the first mode of vibration. For this reason, seismic responses are calculated using the demand yield seismic coefficient spectrum and the results are fed back for pushover analysis to evaluate the damage level to each member.

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**Table 1 Analytical parameters**

| Pile specifications | Ground specifications |
|---------------------|-----------------------|
| D (m)   | Number of piles | h (m) | Elongation coefficient | Initial shear-wave velocity | Equivalent shear-wave velocity | Poisson's ratio | Layer height |
| 1.0     | 2 x 2 | 15 | 2.5 x 10^7 | 270 | 200 | 0.45 | 15 |
| 1.5     | 3 x 3 | 15 | 2.5 x 10^7 | 200 | 150 | 0.45 | 10 |
| 1.0     | 4 x 4 | 15 | 2.5 x 10^7 | 130 | 100 | 0.45 | 15 |

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**Fig. 4 Evaluation of effective input coefficient η (input loss effect) by the thin-layer method**
Some method is needed to enable design processes based on static analysis as described above to consider the effect of input loss effect discussed in this paper. Specifically, the following two requirements must be met:

1) Effective input coefficient $\eta$ can be calculated in static analysis arrangements, not by using multi-mass dynamic analysis.

2) The effective input coefficient $\eta$ calculated in 1) can be duly taken into consideration in the demand yield seismic coefficient spectrum.

Methods to meet requirements 1) and 2) are proposed in Chapter 4 and Chapter 5, respectively.

4. Simplified method for evaluating the effective input coefficient

4.1 Outline of the evaluation method

Kinematic interactions in the ground-foundation system during an earthquake can be regarded as interactions between the ground and pile foundations caused by natural ground vibrations. Based on this, the following was assumed: Eigenmodes derived from eigenvalues of each mode of natural ground can be regarded as ground displacement, and then the input loss can be evaluated based on the ratio of the response displacement of the foundations to ground displacement. During this process, the seismic deformation method can be used. The seismic deformation method is one of the static analysis methods, where ground displacement is statically applied to the foundations to determine displacement and sectional force of foundations. The method has been used as a basic method in the seismic design of pile, caisson and other deep foundations of railway structures.

Besides the railway field, the method is often used in design processes in the fields of civil engineering and architecture as well. The proposed simplified evaluation method is applied in the following steps, which are outlined in Fig. 5.

Step 1: The free field is modeled and an eigenvalue analysis is applied in the following steps, which are outlined in Fig. 5. Step 1: The free field is modeled and an eigenvalue analysis is conducted whereby the natural frequency and mode shape are calculated for each mode.

Step 2: The mode shapes calculated in the eigenvalue analysis are applied as ground displacement to the foundations by means of the deformation method to calculate the foundations’ displacement responses. In the process, the maximum amplitude of each mode applied is set to 1.0.

Step 3: The displacement of the foundations at the top of the pile, calculated using the deformation method, is divided by the free field displacement to calculate the effective input coefficient $\eta$ for the natural frequency of each mode.

Step 4: The effective input coefficients $\eta$ in the frequency domain is estimated by linear interpolation between $\eta$ calculated for the natural frequencies.

The eigenvalue analysis in Step 1 needs to be conducted up to the third mode, which corresponds to the frequency band of structures covered by seismic design.

4.2 Verification of applicability of the evaluation method

The proposed method was applied to grouped-pile foundations shown in Fig. 6 to verify its applicability. Three types of grouped-pile foundations were used, all with four piles ($2 \times 2$), and each with differing pile length, and two with end-bearing piles and one with floating piles. The piles were rigidly joined to the footings at the top. The ground was a single-layer ground with an equivalent shear-wave velocity $V_s$ of 100 m/s.

For the dynamic analysis that was conducted for comparison, the free field and foundations were modeled as lumped mass models. To eliminate any impact of dynamic interaction other than kinematic interaction, the foundations were assumed to have no mass. Table 2 shows the conditions for the verification analysis.

Figure 7 shows the displacements of the free field and foundations (at the top of the pile) for the first to third modes in Case 1 and Case 3 calculated according to Step 1 and Step 2 described in the Section 4.1 above. The figure indicates that input loss occurs because displacement of the foundations becomes unable to follow that of the free field. This tendency becomes more pronounced in higher modes. This is because in higher modes where deformation wavelengths of piles are shorter, it is more difficult for pile foundations to deform in response to the displacement of the ground, and are thus less displaced, relative to the ground. Consequently, the input loss effect is greater in higher modes with higher frequencies. Figure 8 shows the effective input coefficients $\eta$ calculated by means of the proposed method and those by dynamic analysis. The figure indicates that the effective input coefficients $\eta$ calculated

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**Table 2** Analytical conditions

| Case | Pile length (m) | Layer height (m) | Pile center-to-center distance (m) | Diameter of pile (cm) | Number of piles | Supporting type |
|------|----------------|-----------------|----------------------------------|----------------------|----------------|----------------|
| Case1| 15.0           | 14.0            | 3.0                              | 1.0                  | 2 × 2          | End-bearing pile |
| Case2| 10.0           | 9.0             | 3.0                              | 1.0                  | 2 × 2          | Floating pile   |
| Case3| 10.0           | 14.0            | 3.0                              | 1.0                  | 2 × 2          | Floating pile   |
by the proposed method approximated fairly well with those from the dynamic analysis, meaning that the method can be used to evaluate input loss with a high degree of accuracy. In the bottom right comparative graph in Fig. 8, the overall indication is that the effective input coefficient $\eta$ in Case 1 (with end-bearing piles) decreases more than in Case 3 (with floating piles), demonstrating the greater input loss effect. This is because, as indicated in Fig. 7, the end-bearing capacity (fixation) of the piles in Case 3 at a depth of around 10 m is smaller, leading to greater rocking movement of the piles, allowing them to follow ground displacement more easily, resulting in less input loss effect in the piles than in the end-bearing piles.

5. Simple method for lowering the demand yield seismic coefficient spectra by means of input loss

The challenge was to correct the demand yield seismic coefficient spectrum using the effective input coefficient $\eta$ (input loss) calculated by the method proposed in Chapter 4. Generally, this can be achieved through the following steps: Fourier spectra of ground motions are multiplied by the effective input coefficient $\eta$. Then, a single-degree-of-freedom nonlinear dynamic analysis is conducted to calculate the demand yield seismic coefficient spectrum. This set of steps, however, requires the dual process of applying a Fourier transform and inverse Fourier transform in addition to redefining the design demand yield seismic coefficient, which is not an easy process to use in normal design practices.

Accordingly, this chapter proposes a method for directly lowering the demand yield seismic coefficient spectrum by means of the random vibration theory for evaluation of structural response while considering the input loss. In addition, the applicability of the proposed method is evaluated by comparing the results from the method and those from a step-by-step integration method.

5.1 Calculation of spectral ratio based on random vibration theory

In the random vibration theory, vibrations are handled using power spectra and root mean square (RMS) values while the maximum responses of structures are evaluated by determining the peak factor $p$ based on stochastic response evaluation. The root mean square (RMS) value is an indicator of the average magnitude and can be expressed by (1) for the square root of the product of the squared transfer function of a single-degree-of-freedom absolute acceleration and the acceleration power spectral density of earthquake motion.

$$\sigma_x(\omega_0, h) = \sqrt{\int |H_x(\omega_0, h, \omega)| \cdot G_x(\omega)d\omega} \quad (1)$$

where $G_x(\omega)d\omega$ is the acceleration power spectral density of earthquake motion; $H_x(\omega_0, h, \omega)$, the transfer function of a single-degree-of-freedom absolute acceleration; $\omega_0$, the fundamental circular frequency of a structure; and $h$, the damping constant of a structure. The maximum acceleration response $S_x(\omega_0, h)$ of a single-degree-of-freedom structure can be determined by multiplying the root mean square value of (1) by the peak factor $p$. When the original response spectra where the input loss is not considered is $S_x^{\text{org}}(\omega_0, h)$ and the response spectra where the input loss effect is considered is $S_x^{\text{loss}}(\omega_0, h)$, and the ratio of these response spectra of this structure is $R$, peak factor $p$ is eliminated and, based on (1), the following equation applies:

$$R = \frac{S_x^{\text{org}}(\omega_0, h)}{S_x^{\text{loss}}(\omega_0, h)} = \frac{\int |H_x(\omega_0, h, \omega)| \cdot |\eta(\omega)|^2 \cdot G_x(\omega)d\omega}{\int |H_x(\omega_0, h, \omega)| \cdot G_x(\omega)d\omega} \quad (2)$$

where $\eta(\omega)$ is the effective input coefficient.

While (2) represents a linear response spectral ratio, in seismic design today, it is necessary to consider the nonlinearity of structures. Therefore, to lower the demand yield seismic coefficient spectrum, (2) needs to take into account the nonlinearity of structures. To do this, the equivalent linearization is employed whereby the fundamental circular frequency of a structure $\omega_0$ and the damping constant of a structure $\hat{h}$ in (2) are replaced with the equivalent circular frequency of a structure $\omega_{eq}$ and the equivalent damping constant of a structure $\hat{h}_{eq}$ to be obtained by (3):

$$\omega_{eq} = \frac{\omega_0}{\sqrt{\mu}}, \quad \hat{h}_{eq} = \hat{h} + \frac{1}{\pi} \left[ 1 - \frac{1}{\sqrt{\mu}} \right] \quad (3)$$

where $\mu$ is the response ductility rate and $\hat{h}$ is the initial damping, which in this case is set to 5%. With the above,
when the nonlinearity of structures is to be considered, (4) applies in place of (2):

$$R = \sqrt{\int_{-\infty}^{\infty} |H_1(\omega, h_0, \omega)|^2 \cdot \{\eta(\omega)\}^2 \cdot G_0(\omega) d\omega}$$

(4)

The proposed method uses (4) to evaluate the reduction in the demand yield seismic coefficient spectrum where the input loss is considered.

5.2 Applicability of the proposed method

Comparison was made between the demand yield seismic coefficient spectrum determined using the proposed method and that determined using a step-by-step integration method based on the effective input motions. The grouped-pile foundations mentioned in Chapter 4 were used for the comparison. Earthquake motion dominated by short-period components, as shown in Fig. 9, which had been recorded in Tsukudate during the 2011 off the Pacific coast of Tohoku Earthquake, were used for the comparison. The demand yield seismic coefficient spectrum were calculated in accordance with the current seismic design standards [2] using a step-by-step integration method. An initial damping constant $\mu_0$ of 5% was used for the proposed method.

The effective input coefficient $\eta$ of Case 1 in Fig. 8, calculated using the response deformation method, was used for the comparison.

Figure 10 shows the demand yield seismic coefficient spectrum at a response ductility rate $\mu$ of 2 and 4, both calculated as above. The figure also shows the demand yield seismic coefficient spectrum in the case where the input loss was not considered. As indicated in the figure, the proposed method reproduces fairly well the characteristics of the results obtained using a step-by-step integration method, confirming the validity of (4) of the proposed method. In addition, the reduction in the demand yield seismic coefficient spectra is more significant for shorter periods.

6. Conclusions

In this study, a method was proposed to consider the input loss effect of pile foundations widely used in railway structures in static analysis. Firstly, analyses were conducted to clarify how changes in the parameters of ground and pile foundations would impact input loss performance. As a result, the following conclusions were obtained:

1) Eigenmodes of the ground can be regarded as ground displacement, and the input loss effect can be approximated fairly well by calculating the effective input coefficient $\eta$, based on the ratio of the pile-top displacement determined by the deformation method to the ground displacement.

2) It was clarified that the effective input coefficient $\eta$ calculated above could be taken into consideration in the response spectra used in the design process by using random vibration theory.

3) The input loss effect causes a greater reduction in the demand yield seismic coefficient spectrum at shorter periods.

4) It was clarified that the input loss effect could be duly taken into account in the current railway design system.

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