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APPLICATION OF SWAY-ROCKING MODEL TO RETROFIT DESIGN OF BRIDGES

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ABSTRACT :

To evaluate the earthquake resistance of existing bridges, authors have developed the inverse analysis method to obtain elastic constants and damping coefficients of piers with pile foundations. The problem of applying the inverse analysis method to the Sway Rocking model is the examination of the incident seismic wave. As the means, two cases in which the ground is not liquefied and it liquefies are done by dynamic centrifuge tests under the level 2 earthquake motion. As the result, the response of the pier on the not liquefied ground is simulated reasonably when the response acceleration motion on the surface ground is applied as the incident seismic wave. On the other hand, the response on the liquefied ground is simulated when the incident seismic wave is not the surface ground motion but the motion observed at the boundary of liquefiable and not liquefiable layers. The Sway Rocking model is simple but the dynamic analysis of the model give reasonable solutions when the appropriate motion is given as the incident seismic wave.

KEYWORDS: Sway-Rocking model, dynamic centrifuge test, incident seismic wave

1. INTRODUCTION

Soft alluvial layers are widely deposited in the East area of Tokyo. Soil-structure interaction must be considered to evaluate earthquake-resisting capacity of existing bridges in this area. The SR model of 3-degree-of-freedom system composed of a single mass element and a sway-rocking element is a simple dynamic analytical method that considers this interaction (Architectural Institute of Japan, 1996).

Considerations such as an incident seismic wave, elastic constants and damping coefficients should take into account in the SR model. It is generally used the observed earthquake motion of the surface ground as the incident seismic wave of the SR model (Architectural Institute of Japan, 2006). But if the ground liquefies, it is thought that the observed earthquake motion of the surface ground as the incident seismic wave of the SR model is unsuitable. Also the authors proceeded with the analytical method to identify elastic constants and damping coefficients using the observed earthquake motion at the top of the pier and on the closed surface ground (Okada and Ogawa, 2005). To some degree of dozens gal, it was confirmed that this inverse analysis was effective. But the method is not established in elastic constants and damping coefficients of the SR model in level 2 earthquake motion.

In the purpose of this study, we examines the incident seismic wave of the SR model for the applicability by level 2 earthquake motion of the simple dynamic analytical method that we have proceeded with the analytical method to identify elastic constants and damping coefficients for piers with pile foundations. As a means, two types of ground in experiment for the pier with the pile foundation are examined by dynamic centrifuge tests. Also elastic constants and damping coefficients are carried out using the observed oscillatory waves at the top of the pier and on the ground by the inverse analysis.

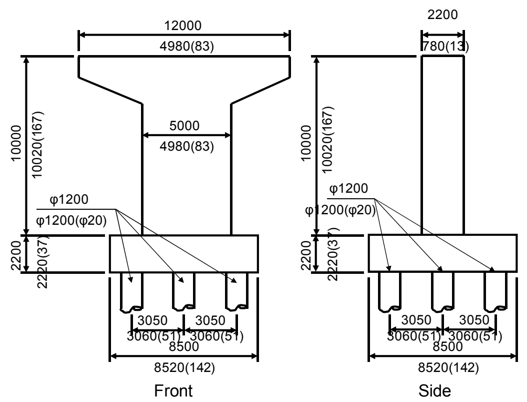

Figure 1 Examination object model

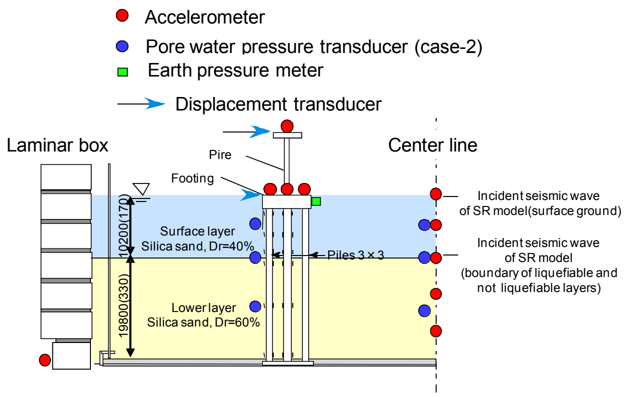

Figure 2 Summary of centrifuge test

Photo 1 Piles-footing-superstructure model

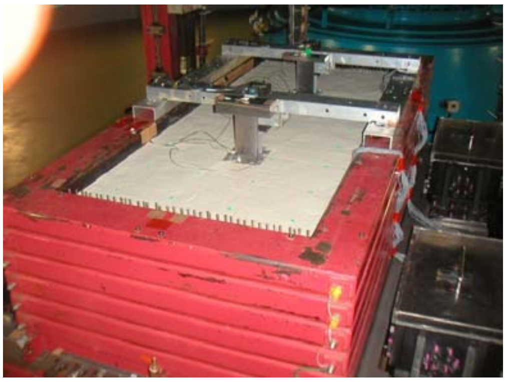

Photo 2 Test setup and location of sensors in model

Table 1 Ground properties(prototype)

Layer	Sand	Depth m	Dr %	γ t/m^3	*Vs* m/sec
Surface	Silica	10.2	60	0.87	123
Lower	Silica	19.8	90	0.93	163

2. EXPERIMENT AND ANALYSIS METHOD

2.1.Dynamic centrifuge test

The experiment was performed by the following procedures: (1) According to literature on reference for highway bridge design (Japan Road Association, 1997), the pier with the pile foundation was modeled so that dimensions and section stiffness accorded as possible. The scale of its prototype and the experiment model were shown by Figure 1. Photo 1 showed that piles were manufactured in aluminum, the pier and the upper were produced in steel. (2) As shown in Figure 2 and Photo 2, the ground assumed it two layers and manufactured relative density 40% on the surface layer, relative density 60% on the lower layer in the laminar box with dimensions of 1950mm (length)×800mm (width)×545mm (height). (3) We performed two cases of experiment. One case saturated the ground with methyl cellulose water solution (case-1), and another case assumed it dry sand (case-2). The properties of the ground were shown by Table 1. (4) The measuring instruments arranged it by the experiment case, as shown in Figure 1. (5) The experiment inputted earthquake vibration from the bottom of the laminar box. The incident seismic waves were shown in Figure 3. The first incident seismic wave inputted the random wave, the second inputted the observed earthquake motion at Kobe Port Island (Kobe-PI wave) during the 1995 Hyogo-Ken Nanbu Earthquake which adjusted the peak

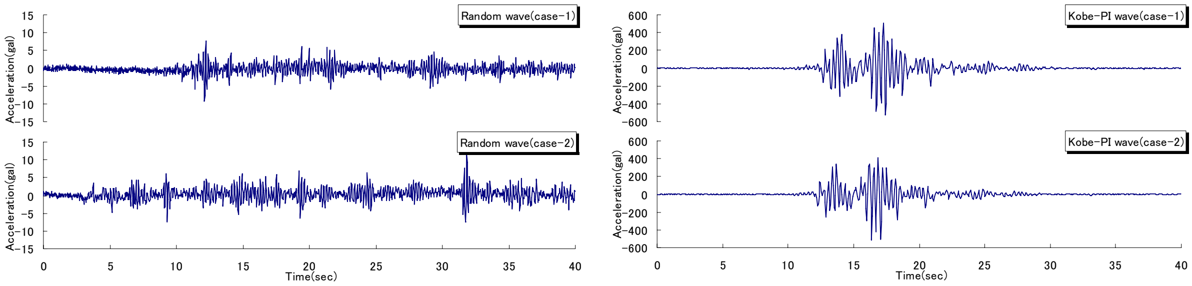

Figure 3 Incident seismic wave

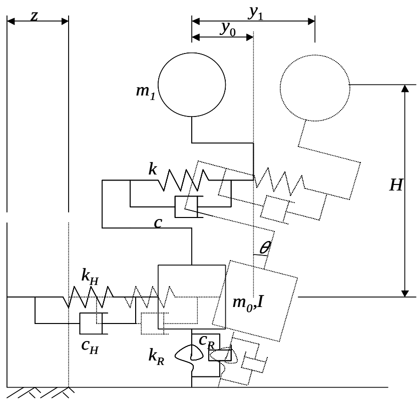

Figure 4 Sway-Rocking model

Table 2 Properties of SR model(prototype)

Parameter	Value
m_1 (t)	7.23×10^2
m_0 (t)	7.68×10^2
I (t・m^2)	6.30×10^3
c (kN・sec/m)	3.76×10^2
k (kN/m)	1.22×10^5
H (m)	10.02
k_H (kN/m)	1.98×10^6
k_R (kN・m/rad)	1.78×10^8
c_H (kN・sec/m)	5.56×10^5
c_R (kN・m・sec/rad)	7.12×10^7

ground acceleration.

2.2. Dynamic analysis of SR model

In this study, the SR model is used for the pile-foundation-soil interaction system, as shown in Figure 4. m_1 and m_0 represent mass of upper structure and footing, I is rotational inertia, H is distance between two mass points, k and c are the stiffness and the damping coefficient of the pier, k_H and c_H are the sway stiffness and the sway damping coefficient of pile-foundation-soil, k_R and c_R are the rotational stiffness and the rotational damping coefficient of pile-foundation-soil. The equation of the SR model is

$$\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_0 & 0 \\ 0 & 0 & I \end{bmatrix}\{\ddot{Y}\}+\begin{bmatrix} c & -c & cH \\ -c & c+c_H & -cH \\ cH & -cH & c_R+cH^2 \end{bmatrix}\{\dot{Y}\}+\begin{bmatrix} k & -k & kH \\ -k & k_H+k & -k \\ kH & -k & k_R+kH^2 \end{bmatrix}\{Y\}=-\begin{bmatrix} m_1 & 0 & 0 \\ 0 & m_0 & 0 \\ 0 & 0 & I \end{bmatrix}\begin{bmatrix} 1 \\ 1 \\ 0 \end{bmatrix}\ddot{z} \quad (2.1)$$

Where

$$\{Y\}=[y_1, y_0, \theta]$$

y_1 and y_0 represent relative displacement of the pier and footing from the ground, θ is rotational angle of footing, and $\ddot{z}$ is the incident seismic wave.

As using the response acceleration waves which are measured on the surface ground or the boundary of liquefiable and not liquefiable layers, and the top of the pier, we identified elastic constants and damping coefficients of the SR model. The evaluated equation of the inverse analysis is

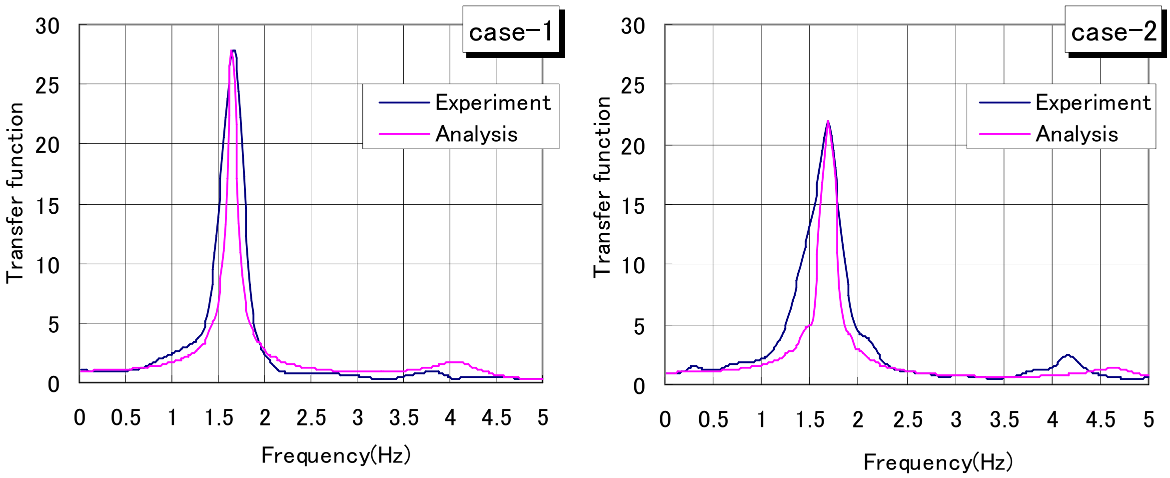

Figure 5 Transfer functions for experiment and inverse analysis(input random wave)

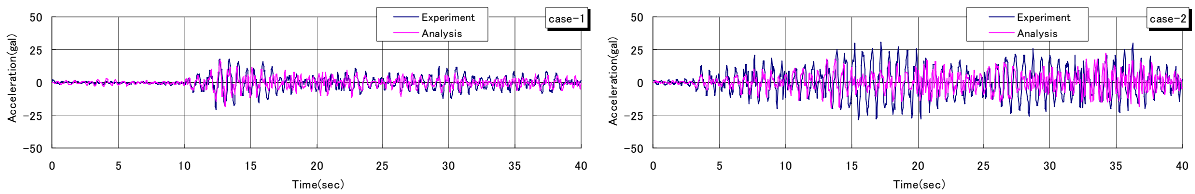

Figure 6 Time histories of pier for experiment and analysis(input random wave)

$$J=\alpha\left(X-\overline{X}\right)^T\left(X-\overline{X}\right)+\left(g_\omega-h_\omega(X)\right)^T\left(g_\omega-h_\omega(X)\right) \tag{2.2}$$

Where α represents the weight coefficient of prior information and posterior information, X is posterior information of 4 parameter(k_H, c_H, k_R, and c_R), $\overline{X}$ is prior information of 4 parameter, g_ω is the transfer function of the experiment, and $h_\omega(X)$ is the transfer function of the inverse analysis, ω is circular frequency.

The inverse analysis is carried out so that the (2.2) equation become the smallest value in frequency domain (Okada and Ogawa, 2005).

The dynamic analysis of the SR model with the identified values carry out in the random wave and level 2 earthquake motion. Also in the comparison with the response acceleration of the pier obtained by the experiment and the analysis, we verify the applicability of the dynamic analytical technique by the SR model in level 2 earthquake motion. The properties of the SR model are shown by Table 2.

3. RESULTS

3.1.Case of inputting random wave

Figure 5 shows the comparison of the transfer function obtained by the experiment and the inverse analysis in case-1 and case-2. The analysis is very similar to the experiment in terms of predominant frequency and the maximum value. Because the tendency of the transfer function derived by the experiment is simple, it is thought that the analysis is in good agreement with the experiment. Figure 6 compares the response wave of the pier obtained by the experiment with those of the dynamic analysis of the SR model using 4 parameter derived by the inverse analysis in case-1 and case-2. Both cases, the response waves of the analysis are almost able to reproduce that of the experiment. But the tendency is showed that maximum acceleration of the analysis is smaller than that of the experiment.

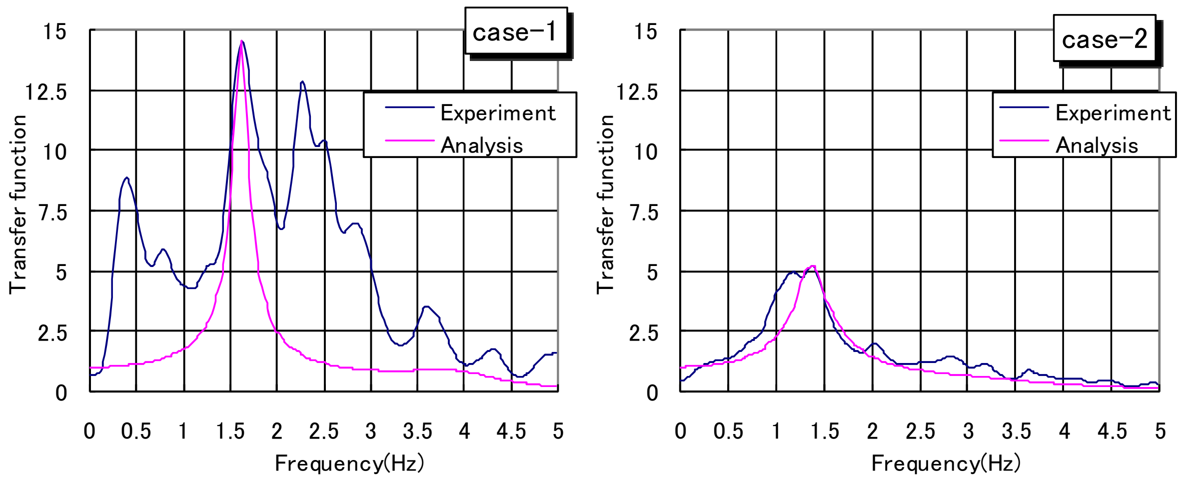

Figure 7 Transfer functions for experiment and inverse analysis(input Kobe-PI wave)

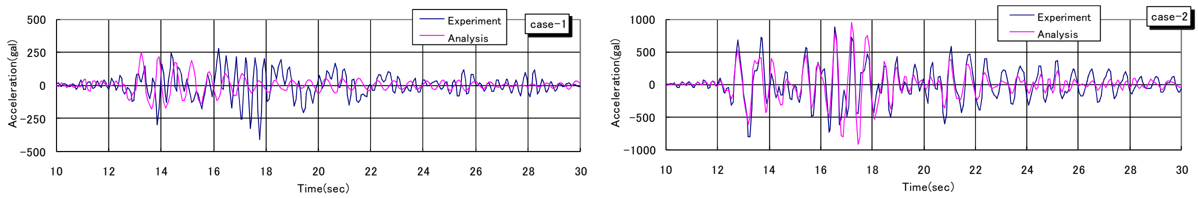

Figure 8 Time histories of pier for experiment and analysis(input Kobe-PI wave)

In a previous paper (Okada and Ogawa, 2005), the tendency of these results is similar to that which we analyzed for existing bridges.

3.2. Level 2 earthquake motion as incident seismic wave of SR model

3.2.1Case of surface ground motion

Figure 7 shows the comparison of the transfer function obtained by the experiment and the inverse analysis in case-1 and case-2. The analysis almost accords with the experiment in terms of case-2. However, about case-1, the transfer function of the analysis is inconsistent with that of the experiment. Because the transfer function obtained by the experiment is complex, it is thought that the analysis is different from the experiment. Figure 8 compares the response wave of the pier obtained by the experiment with that of the dynamic analysis of the SR model using 4 parameter derived by the inverse analysis in case-1 and case-2. The response wave of the analysis is almost able to reproduce that of the experiment in terms of case-2. But, about case-1, because of the differences in the transfer function of the analysis and the experiment, the response wave of the analysis is inconsistent with that of the experiment.

3.2.2Case of ground motion at boundary of liquefiable and not liquefiable layers

Figure 9 shows the comparison of the transfer function obtained by the experiment and the inverse analysis in case-1 of the measured earthquake motion at the boundary of liquefiable and not liquefiable layers as the incident seismic wave of the SR model. Both the transfer functions of the analysis and the experiment are in good agreement. These mean that the transfer function obtained by the experiment is simple. Figure 10 compares the response wave of the pier obtained by the experiment with that of the dynamic analysis of the SR model using 4 parameter derived by the inverse analysis in case-1. The response wave of the analysis is almost able to reproduce that of the experiment.

As a result, when it regards the observed earthquake motion of the surface ground as the incident seismic wave of the SR model under the non-liquefaction ground, the dynamic analysis of the SR model is able to reproduce the measured earthquake motion of the pier.

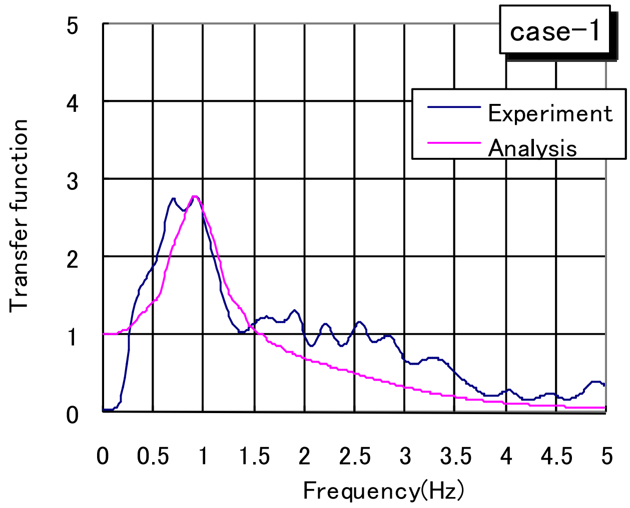

Figure 9 Transfer functions for experiment and inverse analysis
(input observed wave at boundary of liquefiable and not liquefiable layers)

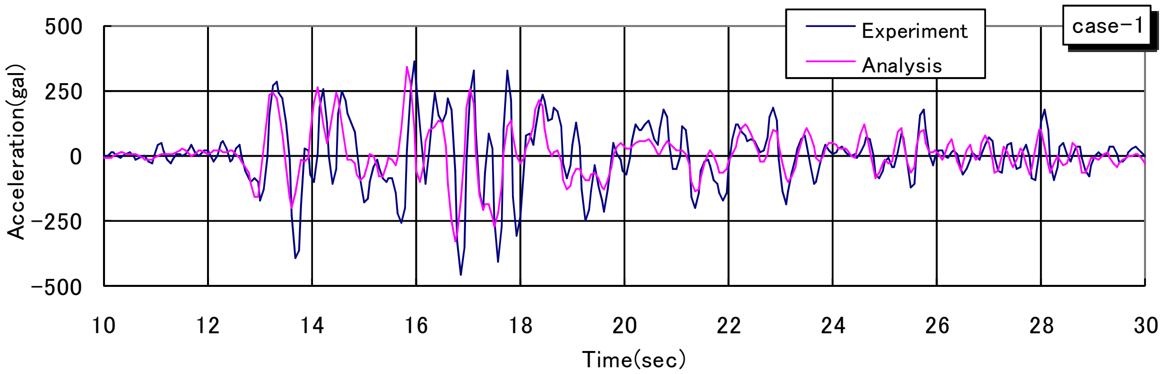

Figure 10 Time histories of pier for experiment and analysis
(input observed wave at boundary of liquefiable and not liquefiable layers)

In addition, when it regards the observed earthquake motion at the boundary of liquefiable and not liquefiable layers as the incident seismic wave of the SR model under the liquefaction ground, the dynamic analysis of the SR model is able to reproduce the measured earthquake motion of the pier.

4. DISCUSSION

About the applicability of the inverse analysis method to the SR model, it is examined in level 2 earthquake motion.

As a result, both of the non-liquefaction ground and the liquefaction ground, the dynamic analysis of the SR model is able to reproduce the measured earthquake motion of the pier. But about the incident seismic wave of the SR model under the liquefaction ground, it is thought that a detailed examination is necessary.

Figure 11 and 12 shows the comparison of the time history and Fourier spectrum observed at footing, the surface ground and the boundary of liquefiable and not liquefiable layers. In comparing time domain and frequency one, the observed earthquake motion at the boundary of liquefiable and not liquefiable layers is better suited than that of the surface ground as the incident seismic wave of the SR model in the case of the liquefaction ground. The acceleration response of the ground decreases with

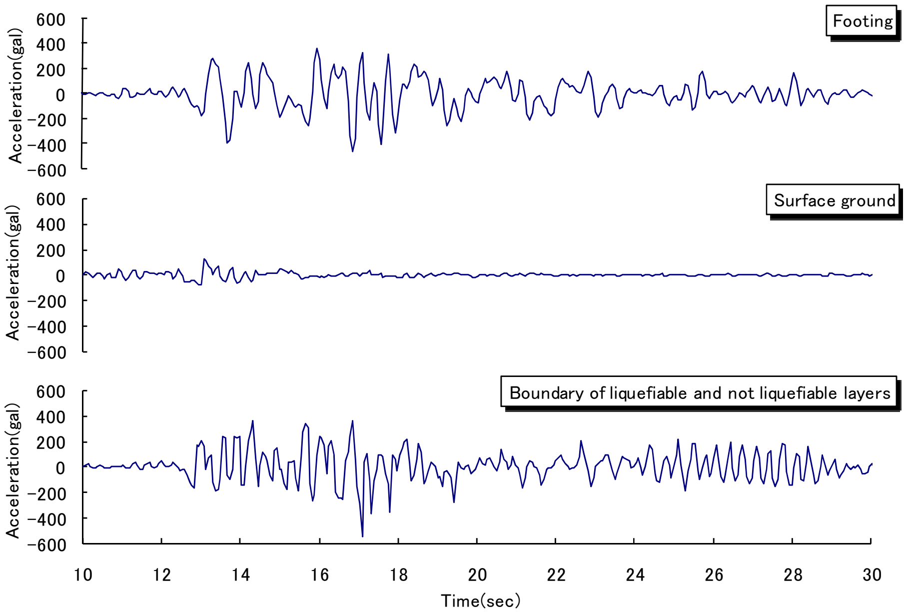

Figure 11 Time histories for footing, surface ground and ground motion at boundary of liquefiable and not liquefiable layers

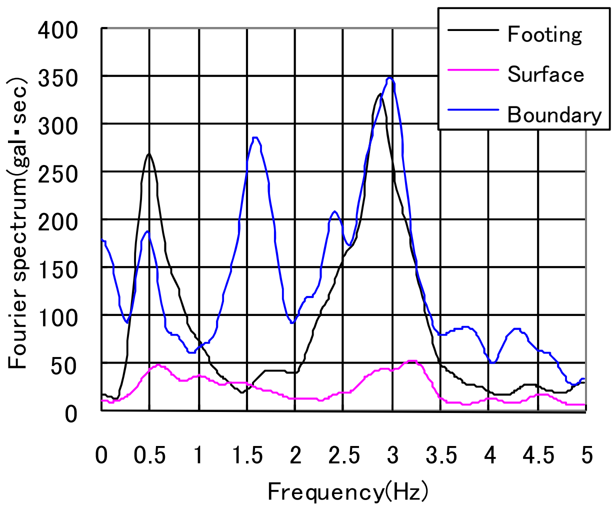

Figure 12 Fourier spectrums for footing, surface ground and ground motion at boundary of liquefiable and not liquefiable layers

liquefaction, whereas it is thought that the earthquake motion is inputted into footing through piles.

In conclusion, we are able to confirm the applicability of the dynamic analytical technique by the SR model in level 2 earthquake motion by the experiment and the analysis.

5. CONCLUSIONS

In study, the applicability of the SR model using the inverse analysis in level 2 earthquake motion have been examined for the incident seismic wave. In conclusions, we have obtained the following from the experiment and the analysis:

(1) When the ground is not liquefied, the response acceleration motion on the surface ground is

appropriate for the incident seismic wave of the SR model.

(2) When the ground is liquefied, the response acceleration motion at the boundary of liquefiable and not liquefiable layers is suited for the incident seismic wave of the SR model.

(3) The simple dynamic analysis of the SR model gives reasonable solution when the appropriate motion is given as the incident seismic wave.

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