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DYNAMIC DEFORMATION CHARACTERISTICS OF THE GROUND IDENTIFIED FROM SEISMIC OBSERVATIONS IN VERTICAL BOREHOLES

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ABSTRACT

Parameter identification analysis based on seismic observations in vertical boreholes is an effective way to understand the dynamic characteristics of ground structures. However, there are some technical issues involved in using this approach, since the inverse problems include instability aspects. A new approach to identifying the dynamic deformation characteristics of layered deposits was proposed. To compensate for the lack of information, the Hardin-Drnevich model was used as the constraint condition in the identification analysis. By using the proposed method, the dynamic deformation characteristics, also as known shear modulus reduction and damping curves, of the surface ground were identified using the seismic records observed in vertical boreholes. The validity of the results was verified by conducting a simulation of strong ground motions recorded during the 2011 Tohoku Earthquake in Japan.

INTRODUCTION

The 2011 Tohoku Earthquake (Mw 9.0, JMA 2011) struck eastern Japan, causing serious damage to lives and property. During the quake, a lot of strong ground motion data was recorded in vertical boreholes installed in the affected area. These data showed nonlinearity in the stress-strain relationships of the subsurface ground. The equivalent linear one-dimensional site response analysis based on the dynamic deformation characteristics of each layer is a convenient way to simulate the nonlinear ground response. The dynamic parameters, such as the S-wave velocities and damping factors, can be estimated from the observation records from vertical boreholes using identification analysis. However, it is difficult to identify the dynamic deformation characteristics of each layer due to a lack of information. This is especially the case for the damping factors. This study introduces a new approach to identifying the dynamic deformation characteristics of each layer. To compensate for the lack of information, the Hardin-Drnevich model (hereinafter, the "HD model") is utilized as the constraint condition in the identification analysis.

MODELING THE DAMPING FACTOR

It is known that the damping effect of seismic waves is frequency-dependent when ground motion is weak (Kurita et al. 1996). However, the damping effect increases as the strain increases (i.e., it is

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strain-dependent) when there are strong motions near the surface. To express both of these features, the following damping model is used in this study:

$$\left.\begin{array}{l} h = h_0(\gamma) + h_1(f) \\ h_1(f) = \alpha \cdot f^{\beta} \end{array}\right\} \tag{1}$$

where, h : damping factor, $h_0(\gamma)$: strain-dependent damping factor, $h_1(f)$ frequency-dependent damping factor, and α and β : coefficients defining the frequency-dependent damping.

IDENTIFICATION METHODLOGY OF DYNAMIC DEFORMATION CHARACTERISTICS

According to the damping curve function of the HD model, the strain-dependent damping factor can be expressed as follows:

$$\frac{h_0(\gamma)}{h_{\max}} = 1 - \frac{G}{G_0} \tag{2}$$

where, G :shear modulus, G_0 : initial shear modulus, and $h_{\max}$: maximum damping factor.

The flow of the proposed method is shown in Figure 1. The process of identifying the dynamic deformation characteristics under the constraint conditions of the HD model is as follows.

(1) Optimum structural model of the ground for weak motion is identified from the average Fourier spectral ratio of observed weak motions. Here, the optimum structure of the ground consists of S-wave velocities, damping factors, densities of soils, and layer thicknesses. Generally, S-wave velocity and damping factors are used as the identification parameters. In this step, the initial shear modulus (G_0) of each layer and the frequency-dependent damping factor ($h_1(f)$) common to all layers are obtained. The Genetic Algorithm (Davis, 1991; hereinafter "GA") is applied for the identification method.

(2) Optimum structural models of the ground for strong motion are identified by GA from the observed strong motions. The shear modulus (G) of each layer and the strain-dependent damping factor (h_0) common to all layers are obtained.

(3) The shear modulus reduction ratio (G/G_0) of each layer is calculated from both optimum models.

(4) By substituting G/G_0 for each layer in Eq. (2), a maximum damping factor ($h_{\max}$) common to all layers can be calculated using the least squares approach.

(5) To assess the strain-dependent damping factor $h_0(\gamma)$ of each layer, the maximum damping factor ($h_{\max}$) for all layers and the shear modulus reduction ratio (G/G_0) of each layer are substituted into Eq. (2).

(6) Fitting Eq. (2) to G/G_0 and $h_0(\gamma)$ using the regression approach, a reference strain (γ_r) and a maximum damping factor ($h_{\max}$) are identified.

Identification of optimum structural model of the ground for weak ground motion from an average Fourier spectral ratio of observed weak ground motion.
"G_0^i, [i : layer number] and $h_1(f)$ common to all layers are obtained."

⇩

Identification of optimum structural model of the ground for strong ground motion from a Fourier spectral ratio of observed strong ground motion.
"G^i, [i : layer number] and h_0 common to all layers are obtained."

⇩

Shear modules reduction ratio G^i / G_0^i of each layer is calculated from the optimum structural model of the ground for weak and strong ground motions.

⇩

Substituting G^i / G_0^i into the HD model [$h_0^i(\gamma) = h_{\max} \cdot \left(1 - G^i / G_0^i\right)$, i : layer number], we identify $h_{\max}$. Here, the damping factor of each layer is $h^i = h_0^i(\gamma) + h_1(f)$.

⇩

Substituting $h_{\max}$ and G^i / G_0^i into the HD model [$h_0^i(\gamma) = h_{\max} \cdot \left(1 - G^i / G_0^i\right)$, i : layer number], $h_0^i(\gamma)$, [i :layer number] of each layer are calculated.

⇩

Fitting the HD model to G^i / G_0^i and $h_0^i(\gamma)$, [i : layer number] by regression approach, γ_r and $h_{\max}$ are identified.

Figure 1. Identification flow of dynamic deformation characteristics under the constraint conditions of the HD model.

SEISMIC OBSERVATION DATA IN VERTICAL BOREHOLES

Site M was located in a strong motion area during the 2011 Tohoku Earthquake. The seismographs in the vertical borehole at Site M recorded strong motions representing the maximum accelerations, PGA = 439.1 cm/s^2 and 432.1 cm/s^2 in both horizontal components, during the 2011 Tohoku Earthquake. Figure 2 shows a cross-sectional view of the observation system in the vertical borehole and the soil materials. Figure 3 shows the location of the Site M observation station and a PGA distribution map for the 2011 Tohoku Earthquake. The acceleration time histories of the strong motions recorded in this vertical borehole during the 2011 Tohoku Earthquake are shown in Figure 4.

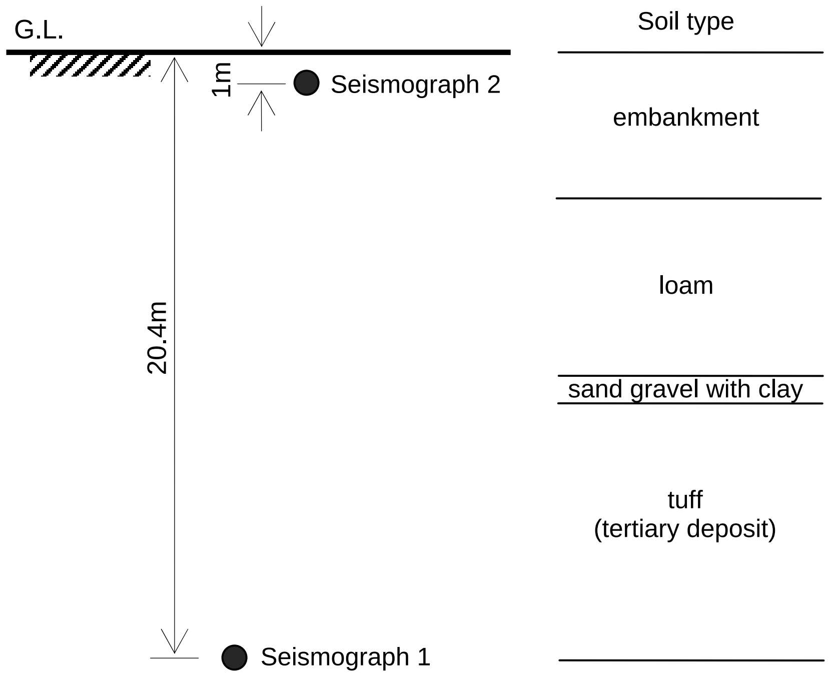


Figure 2. Cross-sectional view of the observation system in the vertical borehole and the soil materials.

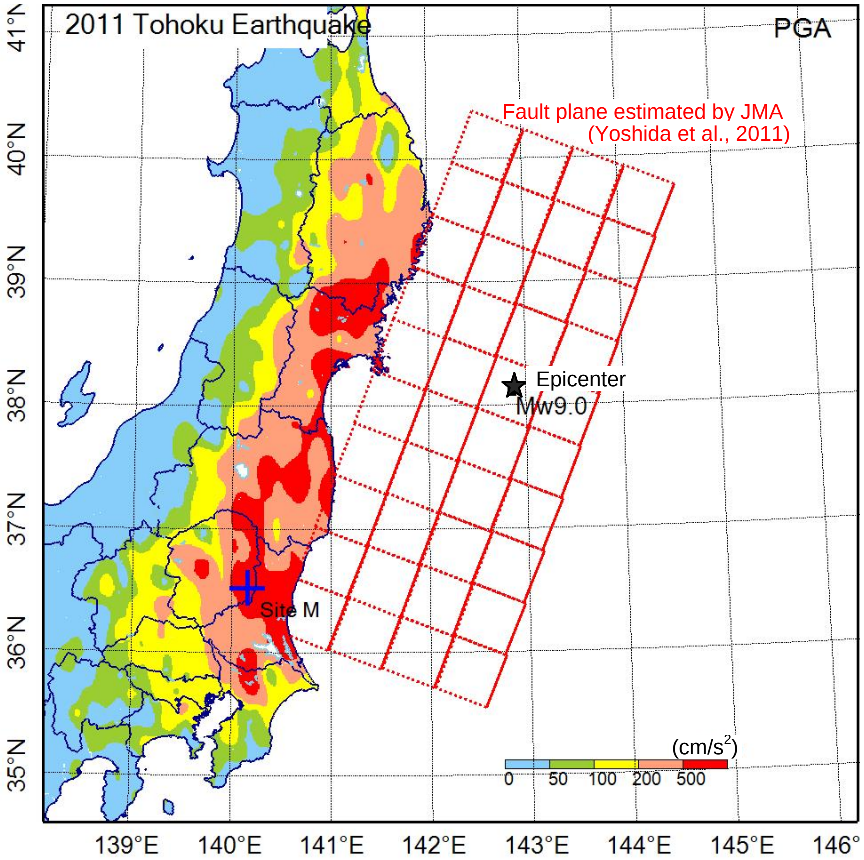


Figure 3. Location of the Site M observation station and a PGA distribution map for the 2011 Tohoku Earthquake.

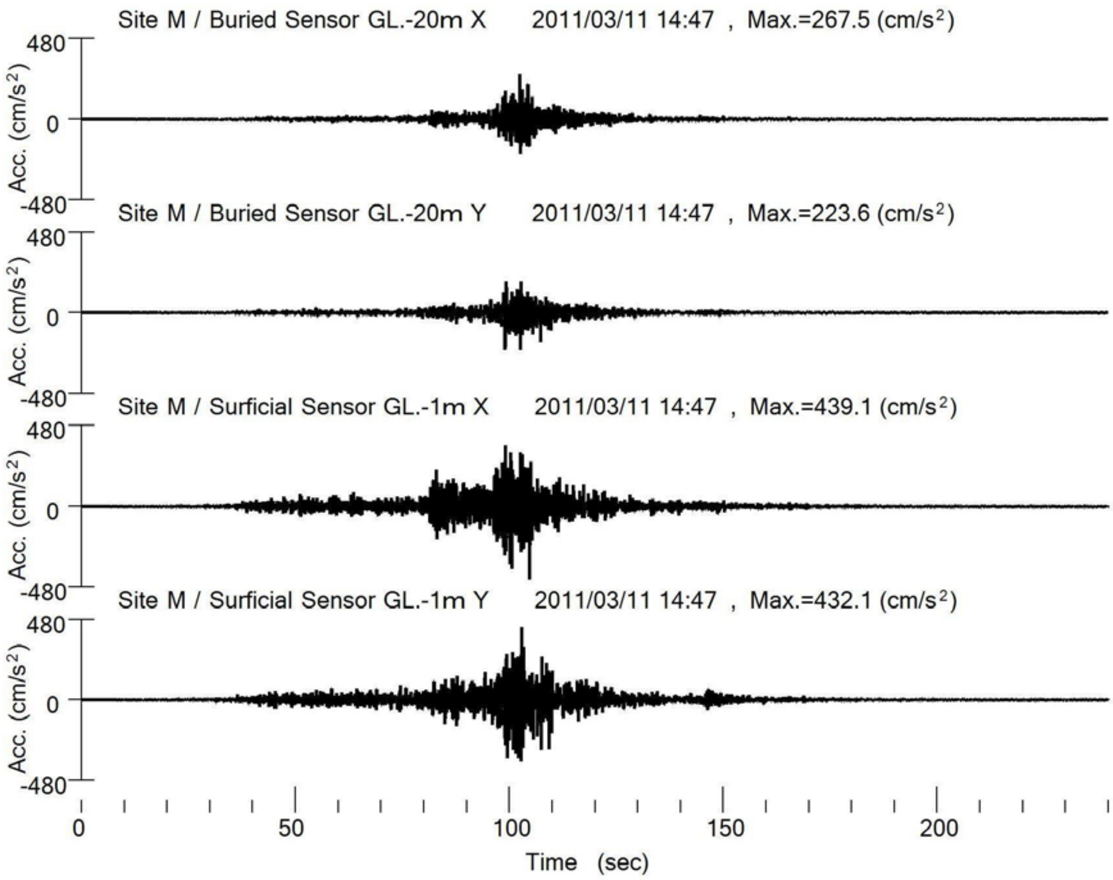


Figure 4. Time histories of strong motions recorded in a vertical borehole during the 2011 Tohoku Earthquake.

IDENTIFIED RESULTS OF DYNAMIC DEFORMATION CHARACTERISTICS CAUSED BY STRONG GROUND MOTION

The frequency-dependent damping factor was identified as $h_1 = 0.0650 f^{-0.0168}$ from the average Fourier spectral ratios of weak motion obtained from past small events. The identified velocity structure for weak motion is shown in Figure 5. There are small differences in S-wave velocities between the identified results and the PS logging data.

The identification analysis under strong ground motion conditions was carried out based on the proposed method shown in Figure 1. The observation data used were the strong ground motions recorded in a vertical borehole during the 2011 Tohoku Earthquake. Acceleration time histories of the strong ground motion are shown in Figure 4. A comparison between the Fourier spectral ratios of observed strong motion data and the theoretical transfer functions calculated using the identified parameters is shown in Figure 6. The theoretical transfer functions are obtained from the equivalent linear one-dimensional site response analysis. The theoretical transfer functions of the strong motions are consistent with the observed records.

Figure 7 illustrates the identified dynamic deformation characteristics and regression lines to the HD model. As is customary, the effective strain is defined as 65% of the maximum strain. The parameters of the HD model were computed using a regression analysis in which the reference shear strain $\gamma_r = 0.268\%$ and the maximum damping factor $h_{\max} = 0.241$.

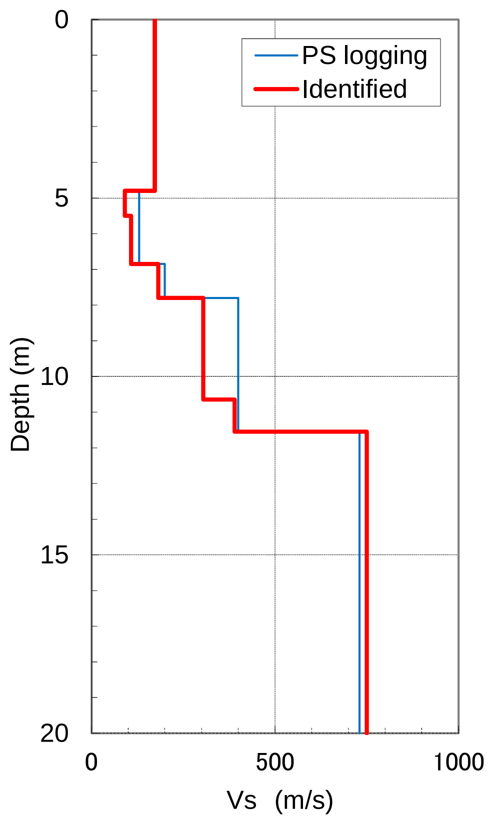
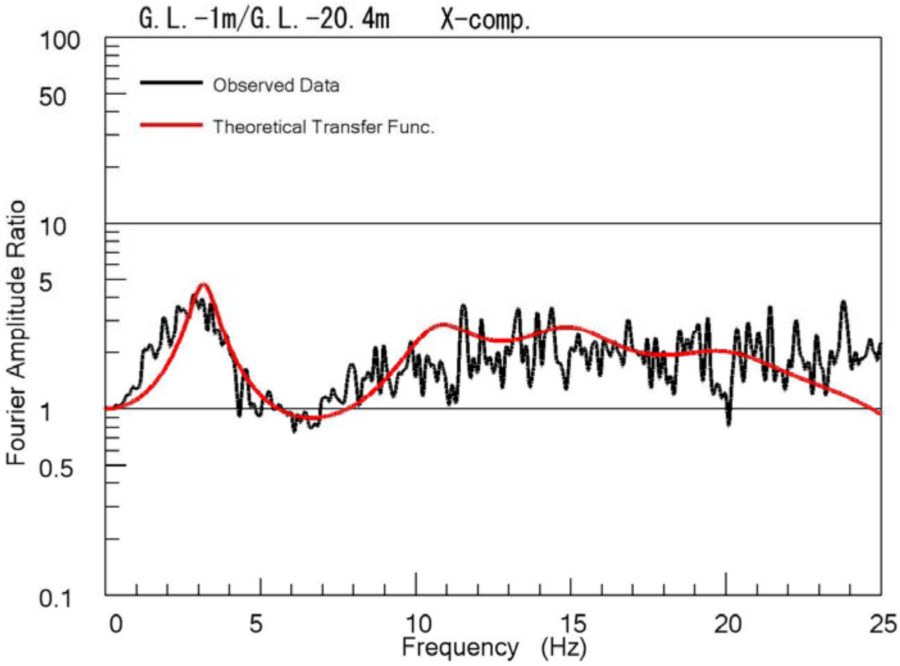
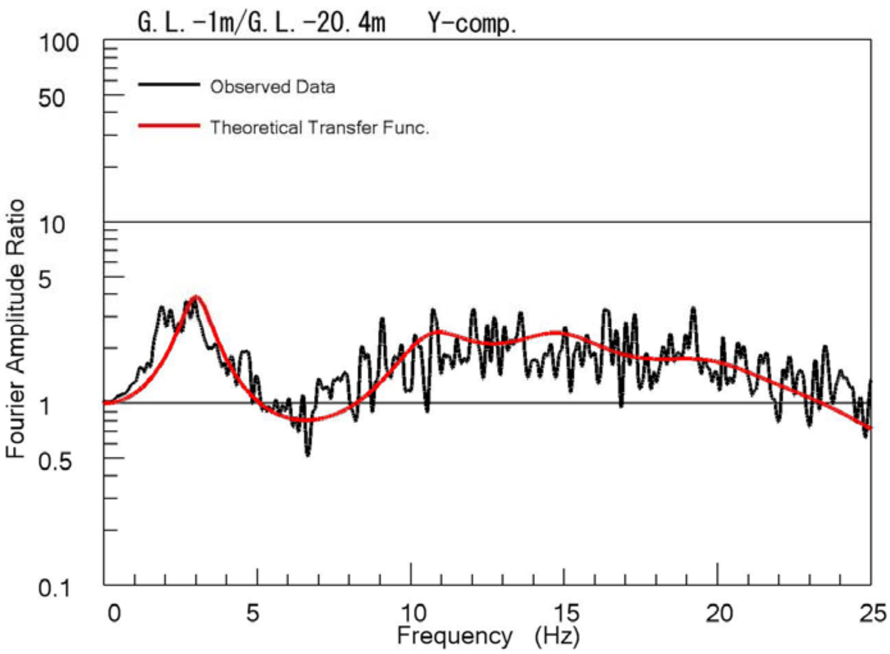


Figure 5. Identified velocity structure for weak motion.

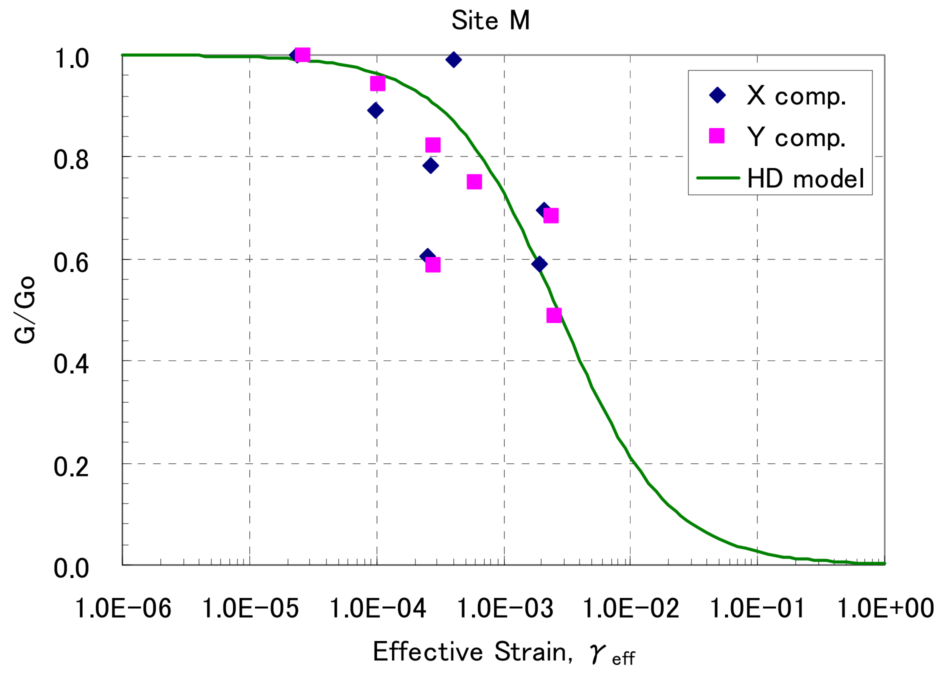


(1) X component

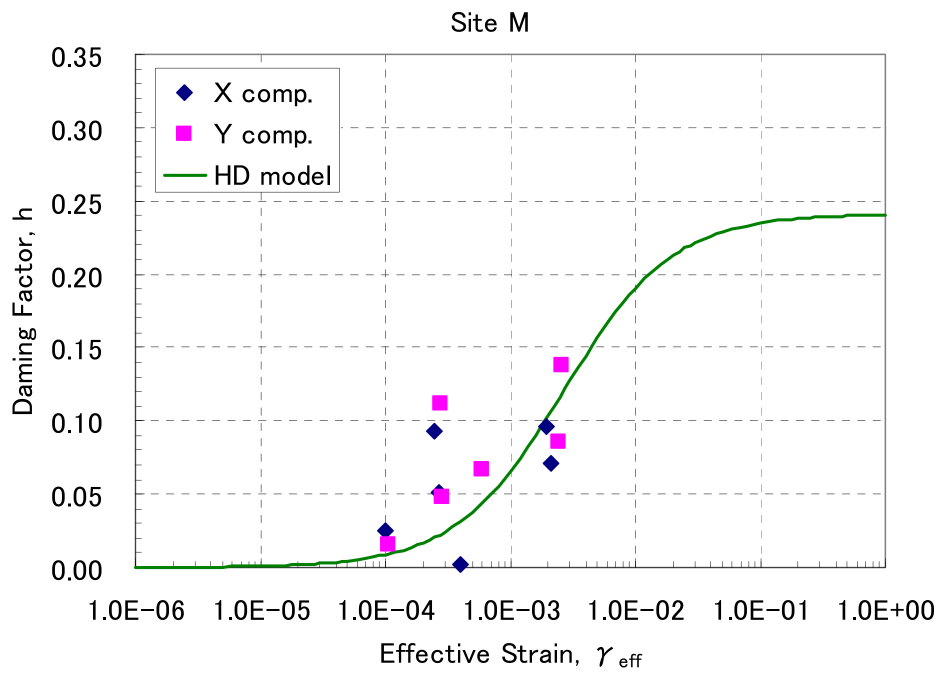


(2) Y component

Figure 6. Comparison between the Fourier spectral ratios of observed data and the theoretical transfer functions. Observed data was smoothed using a Parzen window with a bandwidth of 0.2 Hz.



(1) G/G_0 - γ_{eff} relations



(2) h - γ_{eff} relations

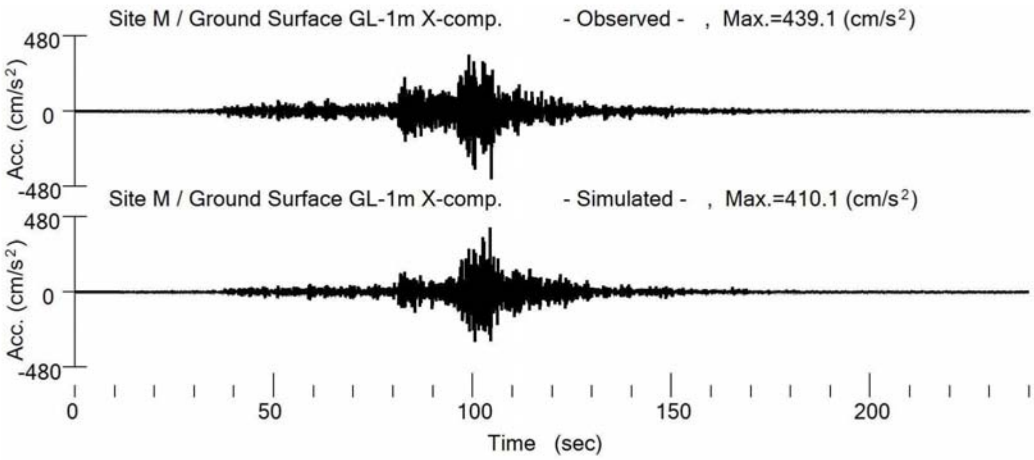
Figure 7. Identified dynamic deformation characteristics and regression lines to the HD model.

SIMULATION ANALYSES OF STRONG GROUND MOTION

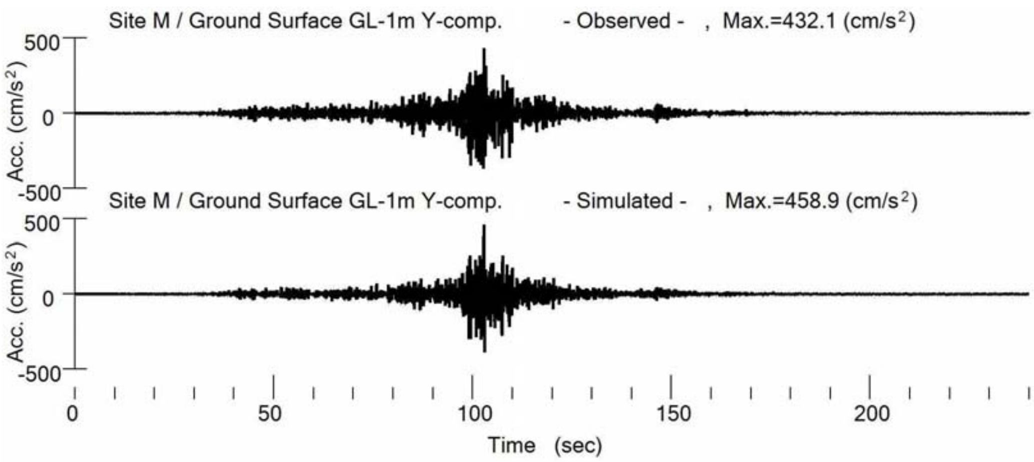
To verify the proposed method, numerical simulations of strong ground motions at Site M during the 2011 Tohoku Earthquake were carried out using the identified dynamic deformation characteristics. An equivalent linear one-dimensional site response analysis was used as the simulation method. The observation data recorded at GL.-20.4m was used as the input ground motion.

Figure 8 shows the time history comparison between the observed data and the simulation results. A comparison of the Fourier spectra obtained from the observed data and the simulation results is shown in Figure 9. In this figure, the Fourier spectra were smoothed using a Parzen window with a bandwidth of 0.2 Hz. The results indicate consistency between the observed data and the simulation results.

Next, a comparative study of the dynamic deformation characteristics in the site response analysis was conducted. Figure 10 shows a quantitative comparison of the time histories between the identified results and the laboratory test results with respect to the dynamic deformation characteristics in the site response analysis. In this figure, “Identified” shows the results of a site response analysis with identified dynamic deformation characteristics obtained using the proposed method. “Labo. Test” refers to the dynamic deformation characteristics indicated by laboratory tests in a previous study. The correlation coefficients and residual sums of squares were calculated by comparing the observation data and the simulation results. Figure 11 shows the same results for the Fourier spectra.

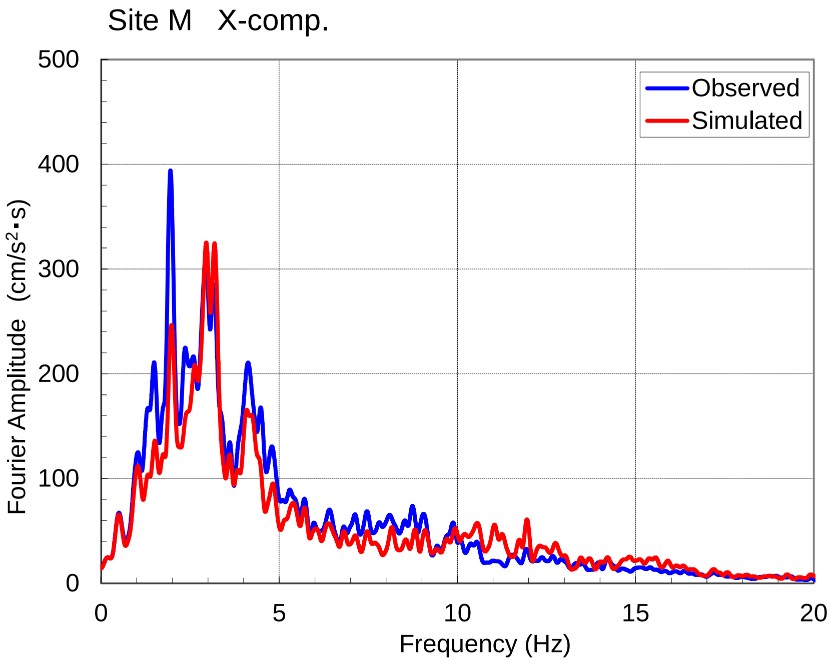


(1) X component

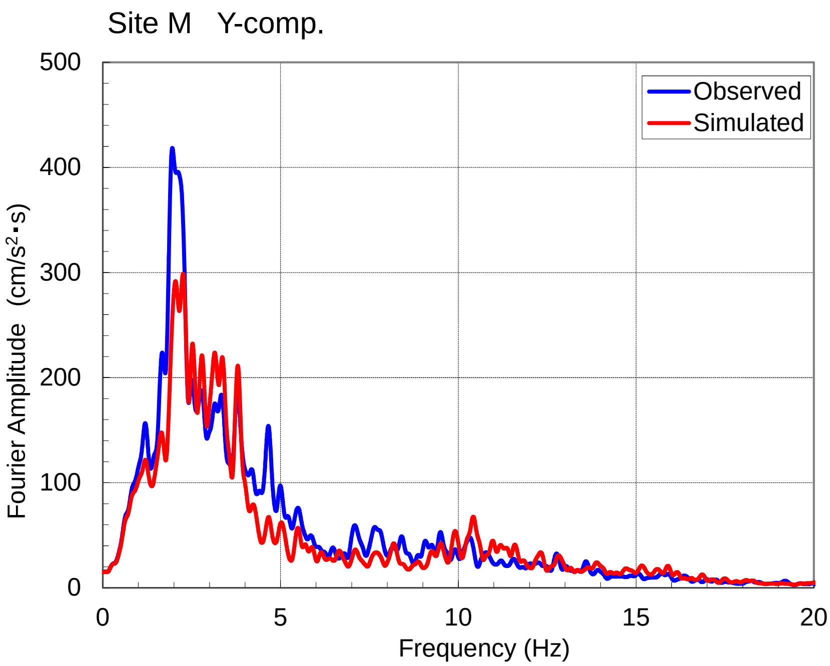


(2) Y component

Figure 8. Comparison of time histories between the observed data and the simulated results.

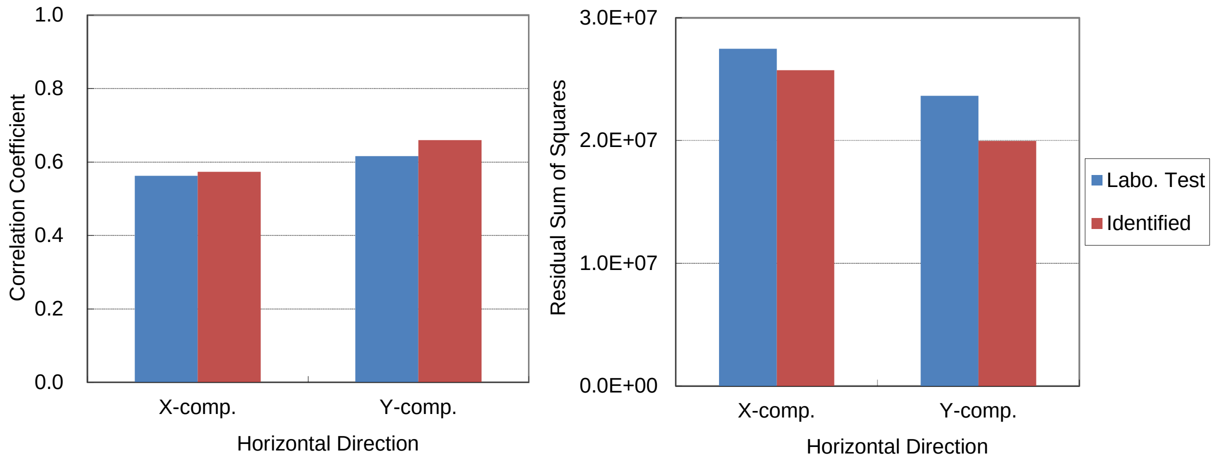


(1) X component



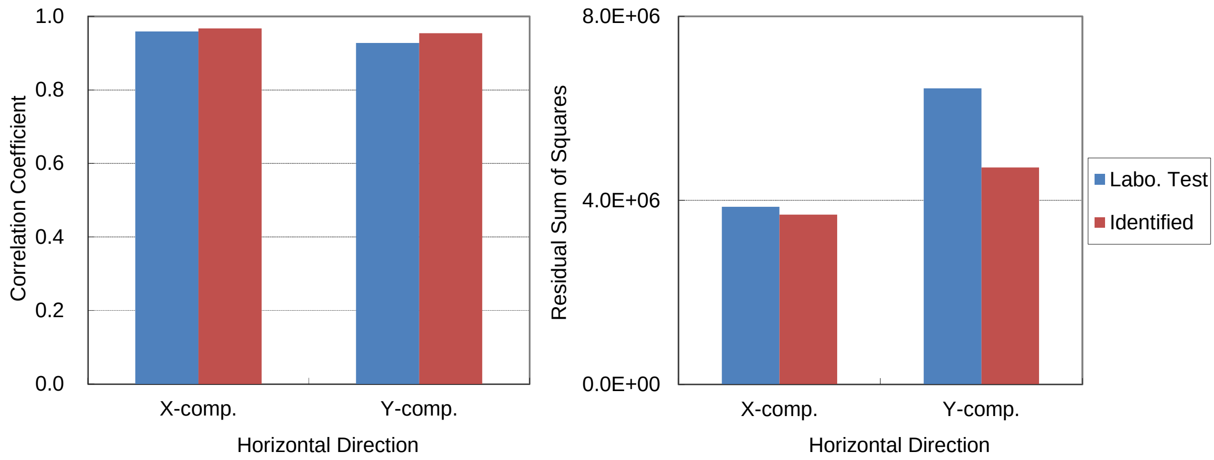
(2) Y component

Figure 9. Comparison of Fourier spectra between the observed data and simulation results. Spectra were smoothed using a Parzen window with a bandwidth of 0.2Hz.



(1) Correlation coefficient (2) Residual sum of squares

Figure 10. Quantitative comparison of time histories between the identified results and laboratory test results with respect to dynamic deformation characteristics in the site response analysis.



(1) Correlation coefficient (2) Residual sum of squares

Figure 11. Quantitative comparison of Fourier spectra between the identified results and the laboratory test results with respect to dynamic deformation characteristics in the site response analysis.

Both results show that the simulated responses with the identified dynamic deformation characteristics are more compatible with the observed data than the laboratory test results, since the correlation coefficients are larger and the residual sums of squares are smaller. These results indicate the validity of the proposed identification method.

CONCLUSIONS

Seismic ground motion records from vertical boreholes are useful for analyzing the dynamic behaviors of subsurface ground. Generally, it is difficult to identify the dynamic deformation characteristics of the ground from observations in vertical boreholes due to a lack of information. This study introduced a new approach to identifying the dynamic deformation characteristics of layered soil deposits. To compensate for the lack of information, the HD model was used as the constraint condition in the identification analysis. By using the proposed method, the dynamic deformation characteristics, also known as shear modulus reduction and damping curves, of the surface ground were derived from the seismic records observed in vertical boreholes. Numerical simulations of the strong ground motion that occurred during the 2011 Tohoku Earthquake were carried out using the equivalent linear one-dimensional site response analysis with identified dynamic deformation characteristics. The simulation results showed that the calculated responses at ground level provide a good explanation of the strong ground motion observed. The validity of the results was verified by the simulation of strong ground motion recorded during the 2011 Tohoku Earthquake in Japan.

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