Effects of Soil-Structure Interaction at an Earthquake Observation Station Identified by Microtremor Measurement

Toshiro Maeda[a)]

For the 2000 Tottori-ken-seibu earthquake (Mj7.3), strong horizontal motion more than 900gal was recorded at the KiK-net Hino station. We have done micro-tremor observation at and around the station to find significant soil-structure interaction effects around 8Hz for weak motion at the station floor. Then, a soil coupled structure model for the station at a small strain level is constructed to simulate transfer functions of the station floor to the free surface. Finally, we evaluate horizontal motion at the ground surface during main shock by eliminating the interaction effects with equivalent linear soil properties to indicate that the interaction effects were not significant for strong motion during main shock because of large damping due to soil hysteresis.

INTRODUCTION

For the 2000 Tottori-ken-seibu earthquake (Mj7.3), strong horizontal motion more than 900gal was recorded at the KiK-net Hino station. Several studies, e.g. Nagano et al. (2001), Higashi and Abe (2002), and etc., tried to obtain reasonable bedrock motion with horizontally layered models for aftershocks, as well as for the main shock, simulating vertical array transfer functions of the station floor to GL-100m by the genetic algorithm; however, none of them seemed successful to simulate the transfer function from 5 Hz to 10 Hz for aftershocks.

Speculating that the recorded acceleration could be different from the free-surface motion because of soil-structure interaction of a station, we carried out simultaneous observations of micro-tremor at the station terrace and nearby ground surface. We found that the motion at the terrace was amplified around 8 Hz to the ground surface for micro-tremor and weak motion of a small earthquake due to the soil-structure interaction (Hibino et al. 2003). These soil-coupled dynamic characteristics were later identified by free vibration excited by

[a)] Dept. of Architecture, Waseda Univ., 3-4-1, Okubo, Shinjuku-ku, Tokyo, 169-8555, JAPAN.

hammering at the station structure (Yoshimura et al. 2003). We also carried out micro-tremor array observations for Rayleigh wave dispersion curves and found that shear wave velocity just beneath the ground surface must be less than those of PS logging data (Maeda et al. 2003), which is in accordance with aforementioned studies simulating the vertical array transfer functions.

In this paper, we will simulate the transfer functions of the station terrace to the nearby ground surface with a soil-coupled structure model for the station, i.e. a rigid structure model supported by horizontally layered soil model. Then, we compute the horizontal motion at the free surface by eliminating the interaction effects from the record at the station floor during the main shock with equivalent linear soil properties, observing that the interaction effects were not significant for strong motion during main shock because of large damping due to soil hysteresis.

STRUCTURE AND SITE OF HINO STATION

KIK-NET HINO STATION

KiK-net HINO station (NIED) is located at the lakeside in the mountainous area of the western Japan. The station structure is one-story reinforced concrete building of 3.15m high and 2.2m by 3.2m in plan, we designate horizontal axis of X (N53E) parallel to the longer wall and Y (N37W) parallel to the shorter wall as shown in Fig. 1.

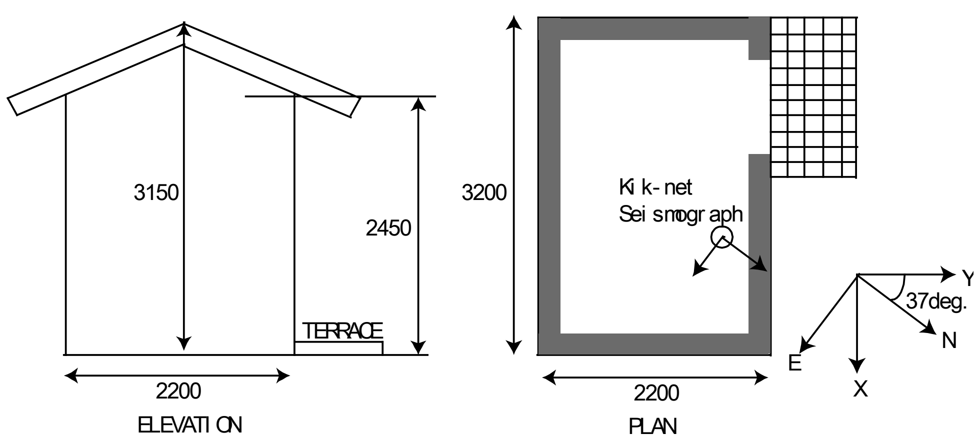

Figure 1. KiK-net Hino station.

The station has two sets of seismographs on the floor and at GL-100m, both of which measure NS, EW, and UD components. Surface geology shows that the station sits on deposit next to rock boundary, and PS logging data reveals stiff soil profile down to GL-100m, with Vs=210m/sec for a top layer of 11 m thick classified as gravel underlain by granite as shown in Fig. 2.

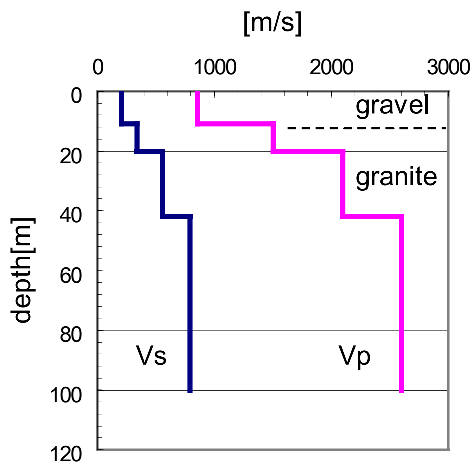

Figure 2. PS logging data at KiK-net Hino station.

TRANSFER FUNCTIONS TO GL-100M

Nagano et al. (2001) tried to evaluate bedrock motion with one-dimensional equivalent linear soil models, which were constructed by simulating vertical array transfer function for a main shock and aftershocks with GA, the genetic algorithm. The Vs structure of their model for aftershocks, shown in Fig. 3, scarcely altered Vs of PS logging, exhibiting lower 1st frequency and less amplitude around 6Hz compared to the averaged transfer function for four aftershocks used in Nagano et al. (2001) as shown in Fig. 4. The lower evaluated 1st frequency was attributed to horizontal layer modeling applied for the complex geology. Higashi and Abe (2002) also constructed one-dimensional model with GA incorporating with reflection survey data to put bedrock at GL-84m of about three times of Vs as PS logging data as shown in Fig. 3, where damping factor was not explicitly described. The 1st frequency for aftershocks was simulated well by Vs structure of Higashi and Abe with damping factor of Nagano et al. assigned; however, the second frequency was higher and amplitude around 6Hz were underestimated as shown in Fig. 4.

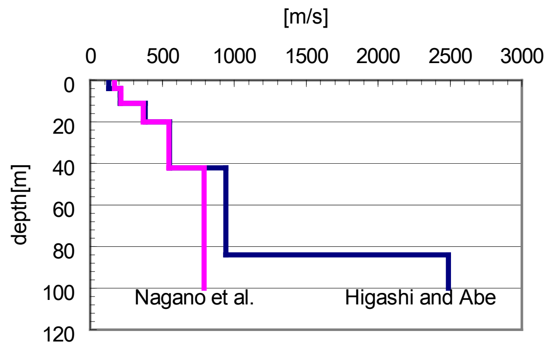

Figure 3. Shear wave velocity structures proposed by Nagano et al. (2001) and Higashi and Abe (2002).

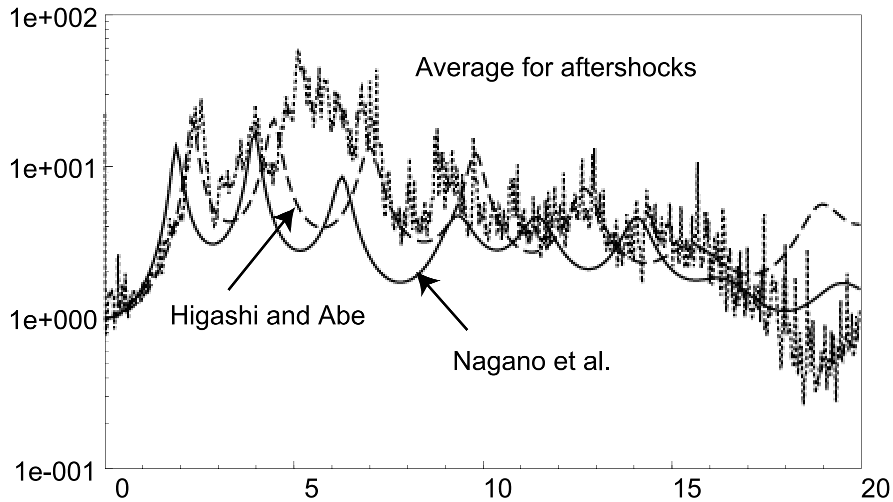

Figure 4. Vertical array transfer functions of Vs structures proposed by Nagano et al. (2001) and Higashi and Abe (2002); aftershocks used for average transfer function are same as those in Nagano et al.; damping factors in Nagano et al. are applied for Vs structures of Higashi and Abe for this transfer function.

MICRO TREMOR OBSERVATION AND SIMULATION

ARRAY OBSERVATION AND DISPERSION CURVES

We carried out micro-tremor array observation near the station for dispersion curves of Rayleigh wave phase velocities. Three circular arrays with different radii of 3m, 10m, and 20m comprise four three-component seismographs, one at the center and other three at the circumference as shown in Fig.5. Those seismographs are over-damped velocity meter with sensitivity of 1V/gal, sampling period of 0.005 sec., and low-pass filtered at 50 Hz. We have applied the SPAC method (Aki 1957) on vertical components to obtain dispersion curves shown in Fig. 6.

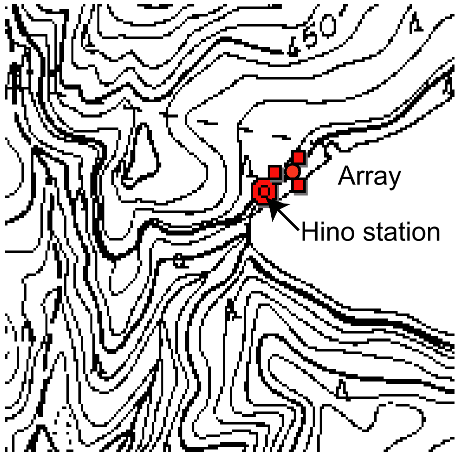

Figure 5. Array configurations (r=20m).

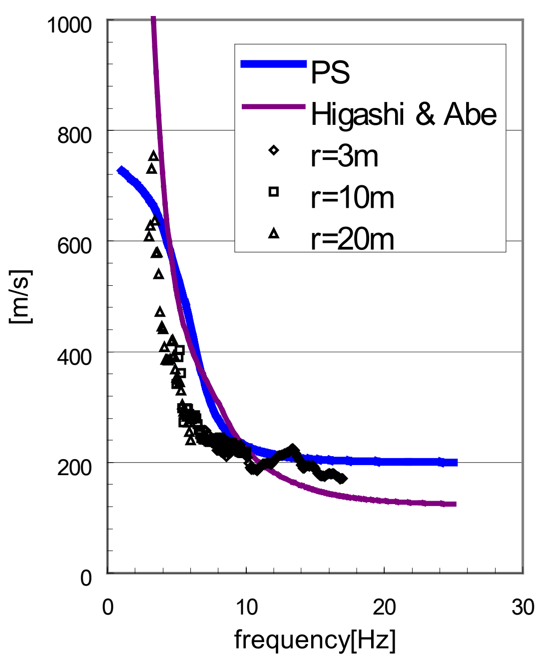

Figure 6. Dispersion curves.

Those dispersion curves are compared for Rayleigh wave fundamental mode computed by the generalized transfer and reflection matrix method proposed by Luco and Apsel (1983). Fig.6 shows that the top layer should have smaller Vs than PS logging data of 210m/s.

SIMULTANEOUS OBSERVATION

We speculated a possibility that acceleration records obtained on the floor were affected by dynamic interaction, and we simultaneously measured micro-tremor at the station terrace and the ground surface at several meters from the station. Transfer functions of the floor to the ground surface are evaluated for X- and Y-components shown in Fig. 7. X-component parallel to the longer wall shows a peak of 9Hz and Y-component to the shorter wall 8Hz. Since Y-component of the transfer function to the ground surface looks simpler and vertical component also shows a peak at 8Hz, we simulate Y-component in the following.

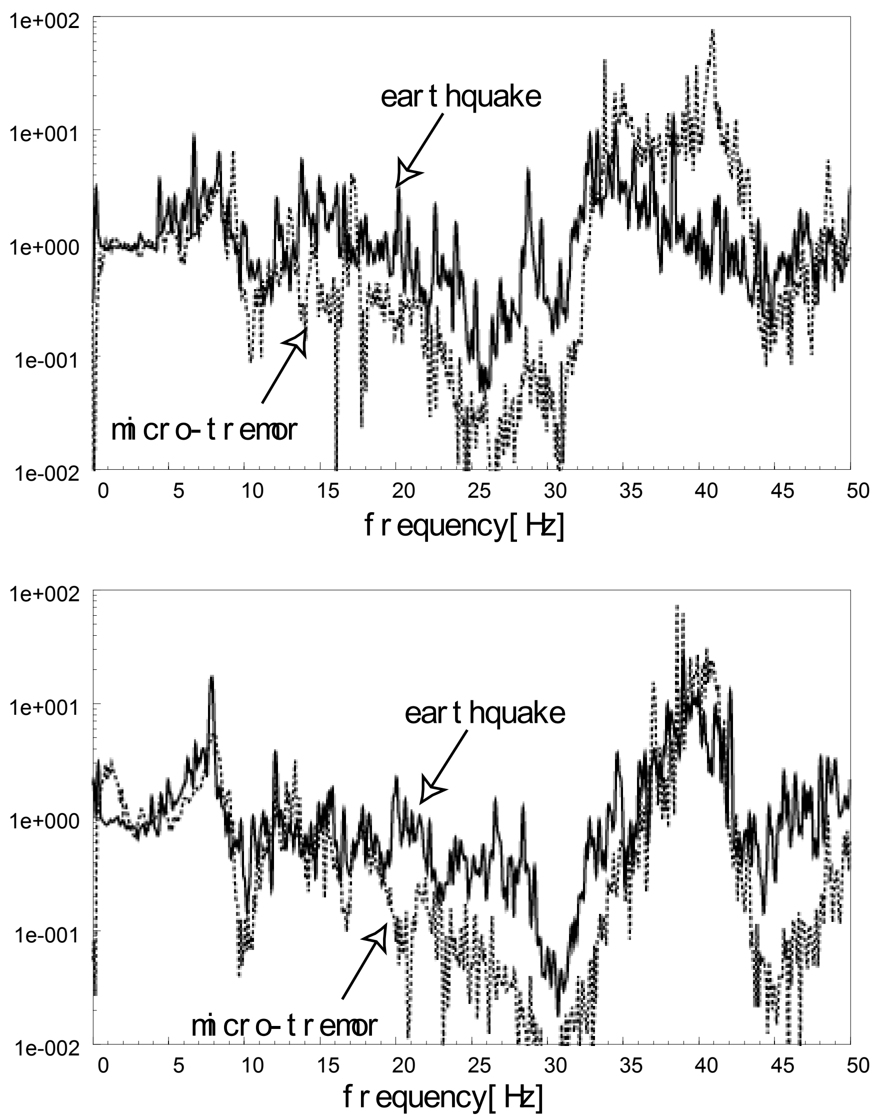

Figure 7. Transfer functions of station terrace to the ground surface, (upper panel) X-component parallel to the longer wall and (lower panel) Y-component parallel to the shorter wall.

Ground motion for a small earthquake of M3.9 in this region was obtained during micro tremor measurement. Acceleration waveform low-pass filtered at 20Hz is shown in Fig.8. Comparison of major part of the acceleration shows remarkable predominance of 8Hz to 9 Hz at the terrace as shown in Fig. 9, and transfer functions have similar properties observed for micro tremor as shown in Fig.7. Thus, transfer functions of the station terrace to the ground surface for micro tremor can be used to study soil-structure interaction for weak motion during earthquakes.

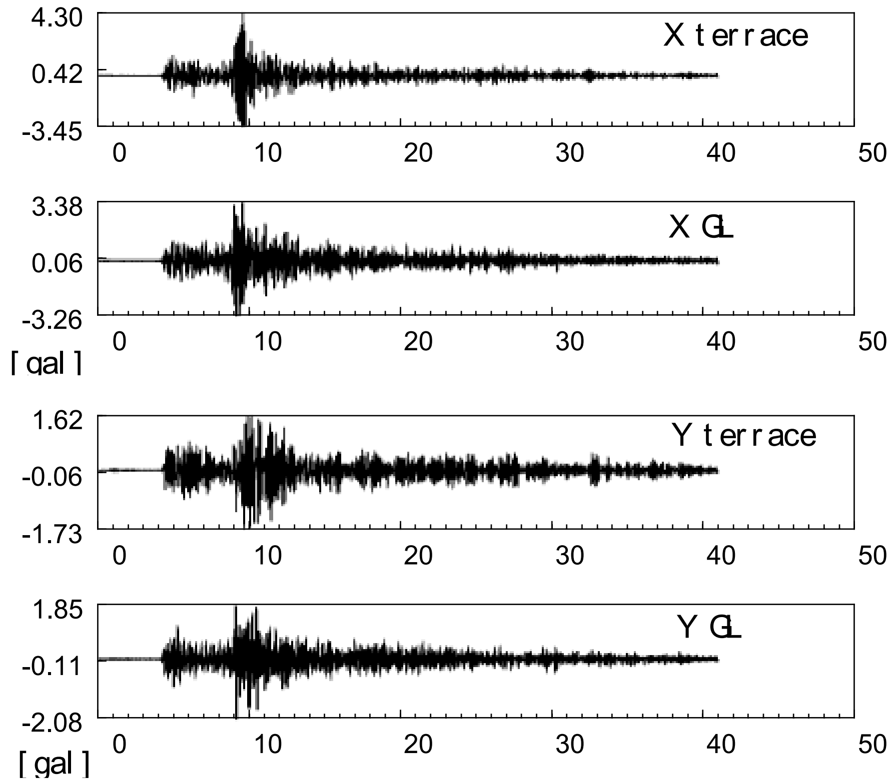

Figure 8. Weak motion of small earthquake observed during micro-tremor measurement (upper two panels) X-component parallel to the longer wall and (lower two panels) Y-component parallel to the shorter wall.

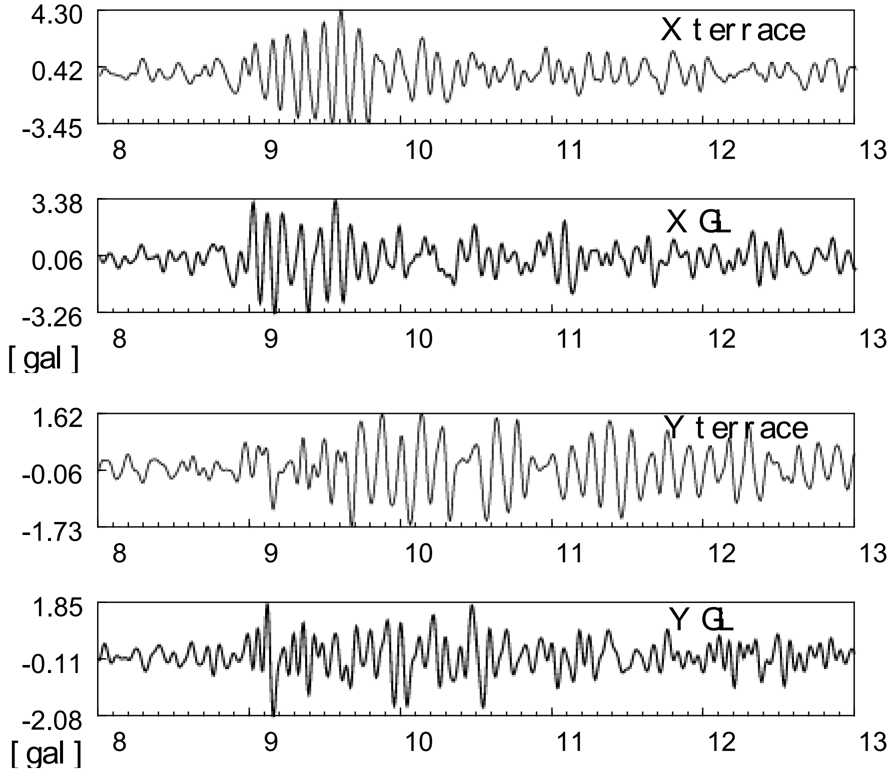

Figure 9. Major part of weak motion of small earthquake, (upper two panels) X-component parallel to the longer wall and (lower two panels) Y-component parallel to the shorter wall.

MODELING OF THE STATION

The station is made of reinforced concrete, yet detailed specifications are not known. We assume density of 2.4t/m^3, projected roof thickness 0.3m for horizontal area, wall thickness of 0.2m, and foundation thickness of 0.5m, 0.7m, and 1.0m. The superstructure is modeled by two lumped mass of 7.6t at GL+2.8m and 11.0t, 14.4t, and 19.5t according to foundation thickness at GL-0m. Preceding to the FEM analysis, we evaluated equivalent semi-infinite soil model by specifying natural frequency of soil-coupled rigid structure of 8 Hz to $\omega_1/(2\pi)$ shown in Eq. (1) from Tajimi (1976) with static stiffness of Eq. (2) for a square foundation evaluated by average displacement from AIJ (1996).

$$\begin{Bmatrix} \omega_1^2/\omega_H^2 \\ \omega_2^2/\omega_H^2 \end{Bmatrix} = \frac{1}{2}\left[1+\frac{e_0^2}{i_0^2}+\frac{s^2}{i_0^2} \mp \sqrt{\left(1+\frac{e_0^2}{i_0^2}+\frac{s^2}{i_0^2}\right)^2 - 4\frac{e_0^2}{i_0^2}}\right] \quad , \tag{1}$$

$\omega_{1,2}$: 1st and 2nd soil-coupled natural frequencies,

$$\omega_H^2 = K_H / m, e_0^2 = K_R / K_H, \; i_0^2 = I_G / m,$$

where m stands for total mass, I_G for inertia moment with regard to the gravity center, K_H for horizontal foundation stiffness, K_R for rocking foundation stiffness, s for height of the gravity center.

$$K_H = 1.345 \frac{2\pi GB}{2-\nu}, \qquad (2a)$$

$$K_R = 2.264 \frac{\pi GB^3}{2(1-\nu)}, \qquad (2a)$$

where $G = \rho V_s^2$ stands for rigidity with $\rho = 1.7t/m^3$, ν for horizontal foundation stiffness set equal to 0.4, B for half width of equivalent square foundation set equal to 1.3m. Fig. 10 shows that equivalent stiffness should correspond to the shear wave velocity of about 100m/sec for 8Hz peak, disregarding frequency dependence of soil impedances.

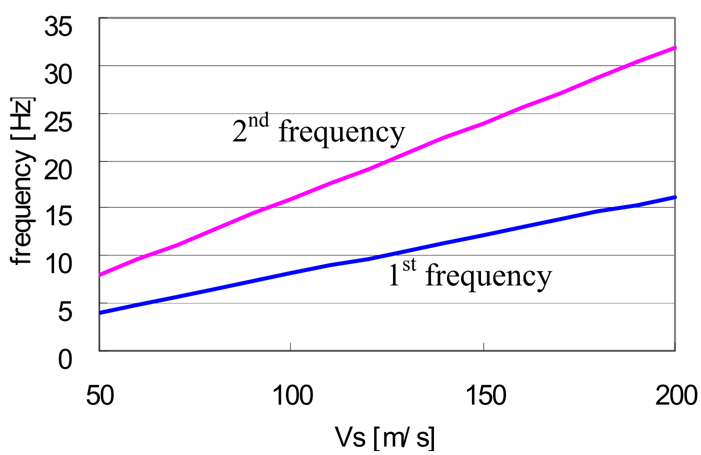

Figure 10. Axisymmetric FE model for simulation.

Soil is modeled by axisymmetric FEM valid up to 20 Hz with an energy transmitting boundary at the circumference and viscous boundary at the bottom, as shown in Fig. 11. Since the top layer of the soil should have less shear wave velocity than that of PS logging data, 210m/s, implied also from the preliminary study with static foundation stiffness, we consult the shear wave velocity structure proposed by Higashi and Abe (2002) for soil-structure interaction simulation, of which the top layer has Vs of 127m/s as shown in Table 1.

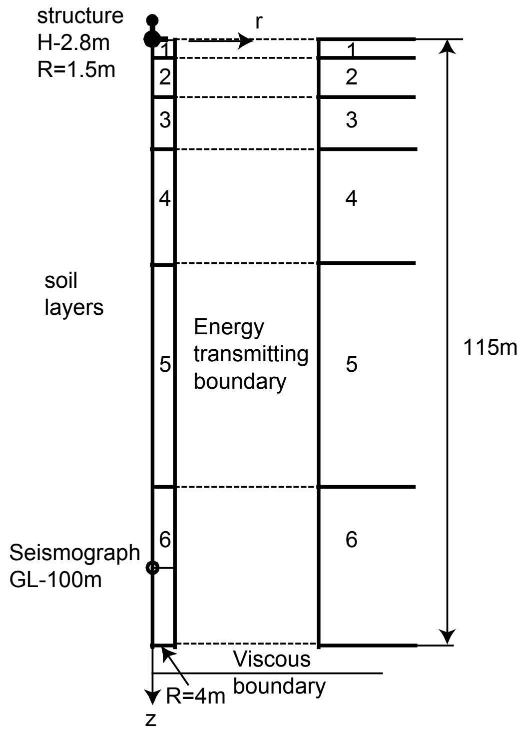

Figure 11. Axisymmetric FE model for simulation.

Table 1. Soil model parameters for soil-structure interaction

No.	Depth [m]	Thickness [m]	Density [t/m^3]	Poisson ratio	Vs_init [m/s]	h_init	Vs_eq [m/s]	h_eq
1	4	4	1.7	0.4	127	0.01	64	0.20
2	11	7	1.7	0.4	211	0.01	105	0.21
3	21	10	1.9	0.4	382	0.01	266	0.15
4	43	22	1.9	0.4	551	0.01	418	0.12
5	85	42	2.2	0.4	943	0.01	822	0.07
6	115	30	2.2	0.4	2487	0.01	2466	0.02

SIMULATION OF TRANSFER FUNCTION TO THE GROUND SURFACE

Fig. 12 compares amplitudes of the transfer functions evaluated by micro-tremor and computed by FEM with different foundation thicknesses. With Vs structure proposed by Higashi and Abe, Y-component of the transfer function of the terrace to the ground surface is simulated well by the structure model with foundation of 0.7m thick, exhibiting a peak at 8Hz with amplification of around 2 and a trough at 9.5Hz with de-amplification of around 1/5.

Although the structure model is roughly assumed and we do not adhere to the foundation thickness of 0.7m, we will use this in the following for a case strudy.

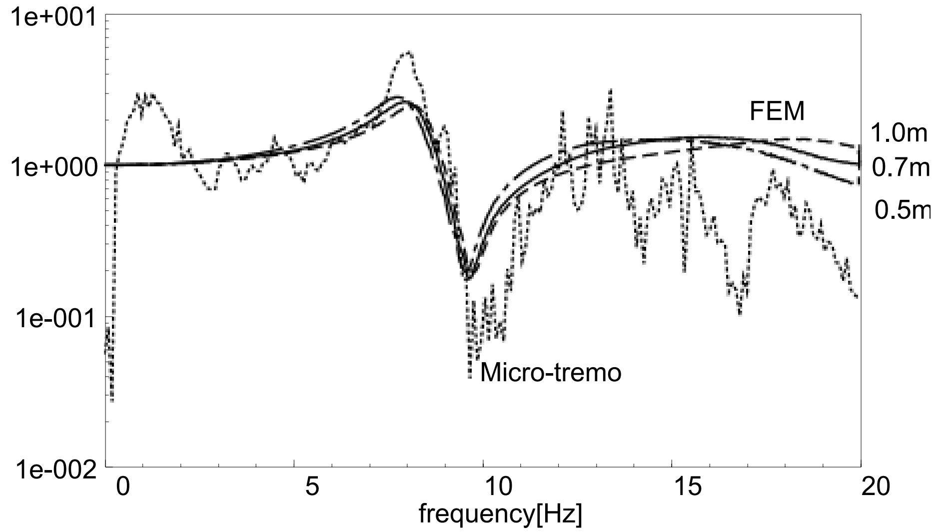

Figure 12. Comparison of transfer functions of the floor to the ground surface for weak motion.

GROUND MOTION EVALUATED FROM THE RECORDS

SIMULATION OF WEAK MOTION

We evaluate the ground motion from the records obtained at the terrace and compare that with the records obtained at the ground surface for weak motion of a small earthquake. Fourier amplitudes smoothed by the Parzen window of 0.2Hz are compared in Fig. 13, which shows that dominated components around 8Hz at the terrace is removed, but higher frequency components are not recovered to the observed level. In Fig. 14, acceleration wave form shows less dominated components of 8Hz as compared with Fig. 8 and Fig. 9.

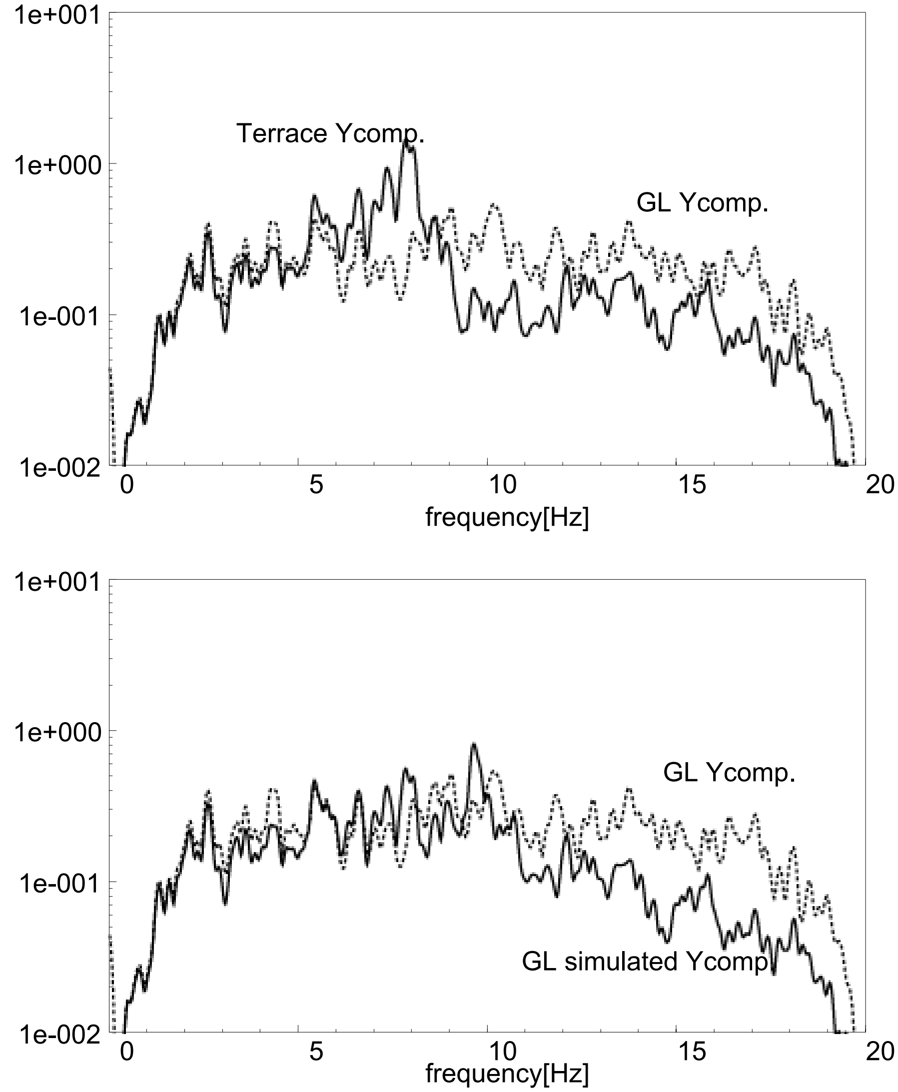

Figure 13. Fourier amplitudes of weak motion of a small earthquake (Y-component), (upper panel) Records on the terrace and the ground surface and (lower panel) Record and simulation on the ground.

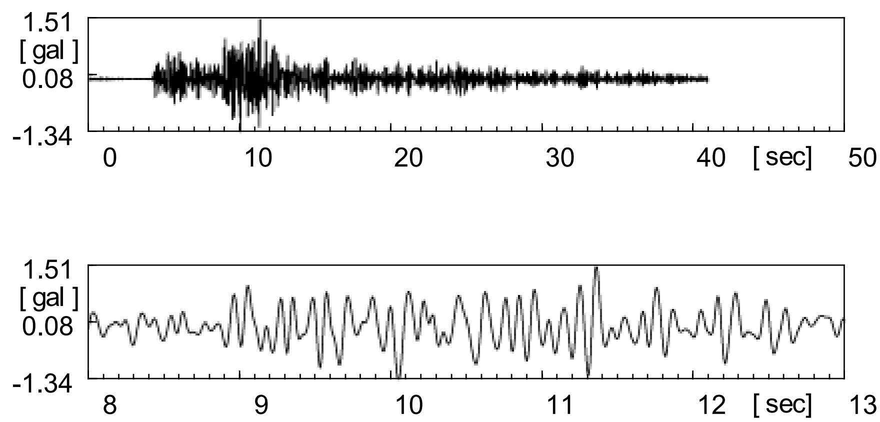

Figure 14. Simulated acceleration of weak motion at the ground surface (Y-component), (upper panel) Whole waveform and (lower panel) Major part of waveform.

SIMULATION OF STRONG MOTION

We evaluate Vs and damping factors in equivalent linear analysis by specifying acceleration records at GL-100m of the model shown in Table 1. G-γ and h-γ curves shown in Fig. 15, which are proposed for sand in Japanese national codes for buildings, are used for layers other than bedrock. We take average of converged Vs and damping factors over sub layers in each layer to define layer parameters as shown in Table 1. With these soil parameters, transfer function of the floor to the ground surface during the main shock is evaluated by axisymmetric FEM up to 20Hz.

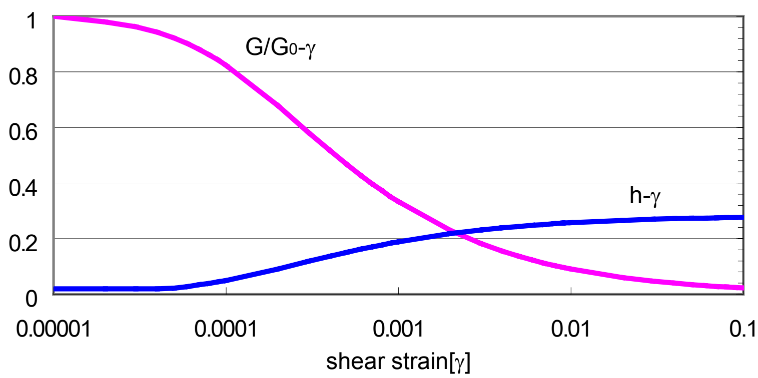

Figure 15. G/G0-γ and h-γ curves for equivalent linear model.

Comparison of impedance functions for strong motion with those for weak motion shown in Fig. 16 exhibits remarkable decrease in real part and comparable imaginary part implying dominated damping effect. The evaluated transfer function exhibits a wide and smooth peak around 3Hz with amplitude a little larger than unity as shown in Fig. 17.

The acceleration record obtained at the floor is divided by this transfer function to give acceleration time history shown in Fig.18 via inverse FFT. Comparison of the computed motion at the ground surface and the records on the floor low-pass filtered at 20 Hz shows little difference due to soil-structure interaction. This insignificant effect is attributable to large damping factor around 0.2 evaluated by equivalent linear analysis. Vibration caused by inertial soil-structure interaction should be died out quickly by large hysteretic energy loss in the soil.

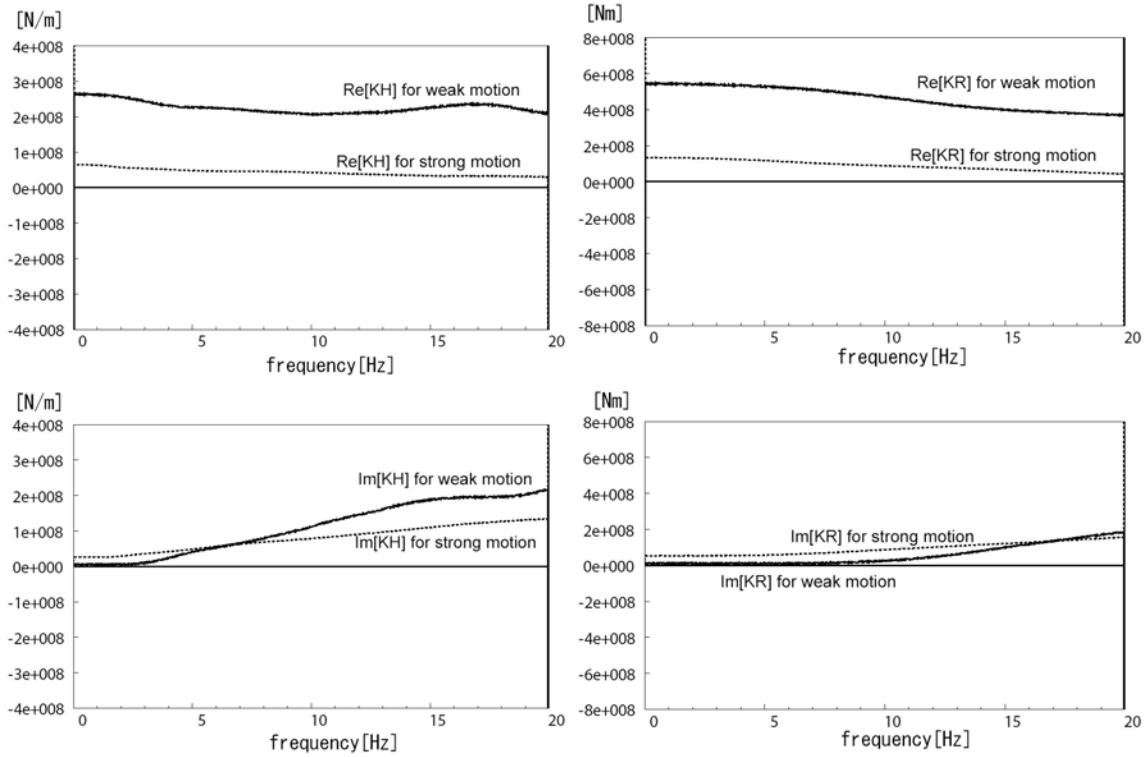

Figure 16. Comparison of impedance functions for weak and strong motion, (upper left) real part of horizontal impedance, (lower left) imaginary part of horizontal impedance, (upper right) real part of rocking impedance, (lower right) imaginary part of rocking impedance.

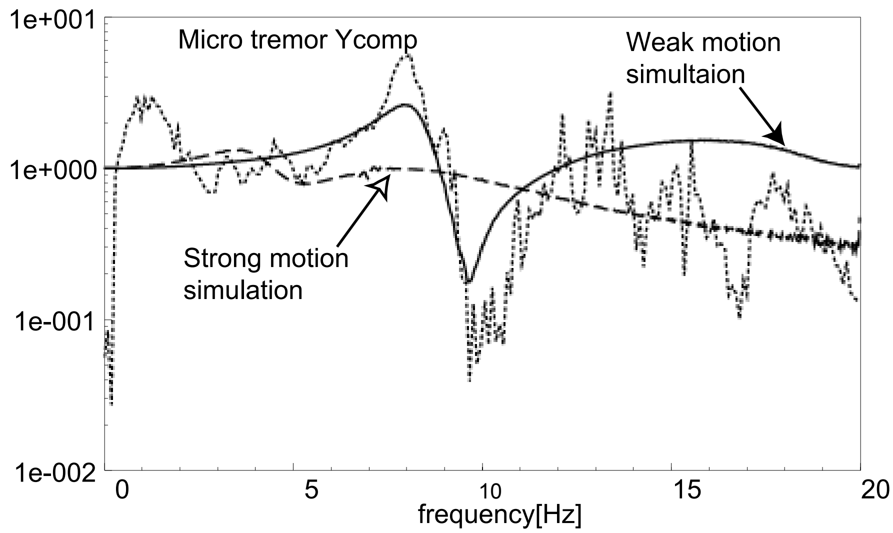

Figure 17. Comparison of transfer functions to the ground surface for the main shock.

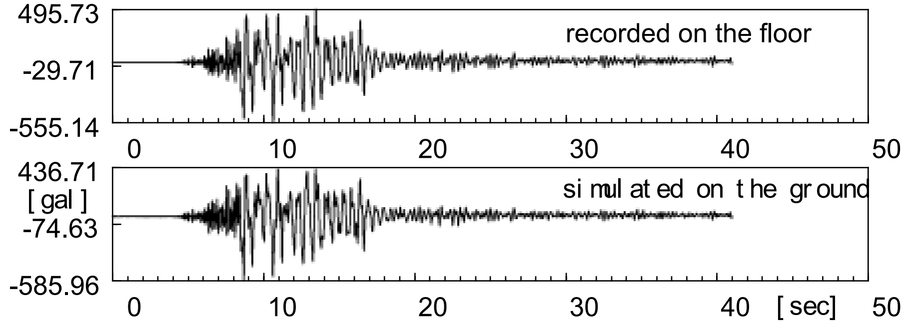

Figure 18. Strong motion records and evaluated ground motion during the main shock, (upper panel) Record in the station and (lower panel) Simulation on the ground surface.

CONCLUSIONS

Micro-tremor measurement was carried out to find soil-structure interaction effects on the record of KiK-net Hino station during the 2000 Tottori-ken-seibu earthquake. Simultaneous observation at the station terrace and nearby ground surface shows significant amplification at the terrace around 8Hz revealing the interaction effects for micro-tremor and weak motion of a small earthquake. We have simulated transfer function of the terrace to the ground surface by axisymmetric FEM with a rigid structure model supported by horizontally layered soil model to show a good agreement consulting soil parameters proposed for vertical array simulation. Then we have evaluated acceleration waveform of the main shock on the ground surface from the record obtained inside the station by adapting equivalent linear soil parameters to the FE model to depict that soil-structure interaction effects on the record of the main shock was insignificant due to large damping representing large plastic deformation.

We wish to express our gratitude to National Research Institute for Earth Science and Disaster Prevention for allowing us to use KiK-net data.

REFERENCES

Architectural Institute of Japan (AIJ), 1996. “An Introduction to Dynamic Soil-Structural Interaction”, Architectural Institute of Japan, 342 pp. (in Japanese).

Aki K., 1957. *Space and Time Spectra of Stationary Stochastic Waves, with Special Reference to Microtremors*, *Bulletin of the Earthquake Research Institute*, Vol. 35, pp.415–457.

Hibino H., Maeda T., Yoshimura C., Kurauchi N., and Uchiyama Y., 2003. *Estimation of bedrock ground motion during 2000 Tottori-ken-seibu earthquake at KiK-net Hino considering effect of observation house. Part 1 Effect of observation house obtained from microtremor and earthquake* *observation*, *Summaries of Technical Papers of Annual Meeting Architectural Institute of JAPAN*, B-2, pp.165-166 (in Japanese).

Higashi S. and Abe S., 2002. *Estimation of bedrock motions at KiK-net Hino site during the 2000 Tottori-ken Seibu Earthquake based on the results of seismic reflection survey*, *Proceedings of the 11th Japan Earthquake Engineering Symposium*, pp. 461-464 (in Japanese).

Luco J. E. and Apsel R., 1983. *On the Green's Functions for a Layered Half-space Part 1*, *Bulletin of the Seismological Society of America*, Vol. 73(4), pp.909–929.

Maeda T., Kurauchi N., Hibino H., Yoshimura C., and Uchiyama Y., 2003. *Phase velocity dispersion curves around the Tottori-Hino KiK-net station by micro-tremor array observation*, *Programme and abstracts*, *The seismological society of Japan 2003, Fall meeting*, B043(in Japanese).

Nagano M., Kato K., and Takemura M., 2001. *Estimation of bedrock motions near seismic fault during the 2000 Tottori-ken Seibu Earthquake*, *J. Struct. Constr. Eng., AIJ*, 2001, No.550, pp. 39-46 (in Japanese).

National Research Institute for Earth Science and Disaster Prevention (NIED), http://www.kik.bosai.go.jp/kik/index_en.shtml.

Tajimi, H., 1976. "Introduction to Structural Dynamics", Corona Publishing Co., Ltd., 81 pp. (in Japanese).

Yoshimura C., Hibino H., Uchiyama Y., Maeda T., Kurauchi N., and Aoi S., 2003. *Vibration characteristics of the observation house at KiK-net Hino*, *Abstracts 2003 Japan Earth and Planetary Science Joint Meeting*, (in Japanese).