On the behavior of near-source strong ground motion from the seismic records in down-hole array at Hyogoken-Nanbu earthquake

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Abstract

Seismic records in down-hole array provide very useful information on actual ground behaviors over a wide range of load conditions, especially for strong seismic motions near seismic fault. These records may be used to identify the characteristics of wave propagation in vertical direction or to verify the numerical procedure employed to the prediction of seismic motion of ground. Although it has been proved effective for even moderate level of motion, this kind of verification is found to be very difficult for strong records near seismic fault. Upon analyses of seismic records in Hyogoken-Nanbu Earthquake, it was recognized that the existence of surface waves in ground motion records raises the problem, and in general, such waves can not be treated properly in a numerical procedure without including seismic source model. This fact should be considered with compensation in seismic resistance design, in which the ground motion is to be predicted by a numerical procedure.

1 Introduction

Seismic motion at ground surface is influenced strongly by surface soil profile. A lot of researches have been carried out and many methods for numerical evaluation have been proposed. Besides field or soil element tests and numerical analyses that proposed previously, seismic observation in down-hole array has been used recently to investigate the behavior during strong earthquake. One-
dimensional numerical analysis is often used in practice for convenience of engineering analysis, in which the surface ground is assumed to consist of horizontal layers over bedrock. In order to verify the accuracy and applicability of numerical model, numerical simulations of seismic observation in down-hole array can be carried out, usually emphasized on material nonlinearity. This approach is reliable when the observation location is relative far from seismic source. However, this simulation is usually very difficult when the observation point is close to a source because of the existence of surface wave, which travels in completely different direction from body wave.

In this paper, the characteristics of surface ground motion near seismic fault have been investigated based on seismic records in down-hole array at Hyogoken-Nanbu Earthquake on January 17, 1995. Numerical simulations are also carried out and compared to the observation, the differences between them are discussed. The numerical procedure here is verified with the results of large-scale laminar box test on shaking table excited in single horizontal direction.

2 Seismic observation

Seismic records observed at SGK and Inagawa\textsuperscript{1}), provided by Kansai Electric Power Company and Public works research institute, Ministry of Construction, respectively, were used in the present analysis. Both sites have a shortest fault distance about 25km. Shown in Figure 1 are S and P wave velocity profiles of these two sites. The former has soft surface soil and the latter is relative stiff. For the NS direction, the maximum accelerations at depth 0m, 25m, and 97m are, respectively, 298.6gal, 181.9gal, and 293.9gal at SGK. Along the same direction, the maximum accelerations at depth 0m and 30m are, respectively, 421.5gal and 200.4gal at Inagawa. Similarly, for the EW direction, these maximum accelerations are 506.6gal, 239.1gal, 319.8gal at SGK and 417.2gal, 185.3gal at
Inagawa, as can be observed from Figure 2 and Figure 3.

![Figure 2 Acceleration histories of SGK record](image)

**Figure 2** Acceleration histories of SGK record

### 3 Analyses of records

The arrangement of down-hole vertical array corresponds to one-dimensional numerical model. Therefore we can calculate the correlation and transfer functions between the pairs of records at different depths, then the shear wave velocity as well as transfer characteristics can be derived.

Originally, transfer function is used as a measurement of linear system. Applying it to nonlinear system gives an equivalent linear characteristics of the system. However equivalent linear characteristics generally vary when exciting level changes. To evaluate the interrelation between the input and output of a system, coherence function presents a very useful index. The transfer function $H_{ij}(\omega)$ and coherence function $\gamma_{ij}^2(\omega)$ are calculated as following,

$$H_{ij}(\omega) = \frac{S_{ij}(\omega)}{S_{ii}(\omega)}$$

(1)
is called cross-power spectra, or auto-power spectra if $i$ is identical to $j$. $a_i(\omega)$ is the Fourier transformation of signal at $i$ and asterisk represents a conjunction. $\omega$ is circle frequency, and $T$ the duration.

According to the inequality of cross-power spectra

$$\left| \gamma_{ij}^2(\omega) \right|^2 \leq |S_{ij}(\omega)|^2$$

the coherence function varies from 0 to 1, i.e., $0 \leq \gamma_{ij}^2 \leq 1$. The coherence function will be unit if the system is ideally linear and no noise exists at input and output. When any noise mixes with either input or output the coherence between them will be smaller than unit.

During the propagation of seismic wave in a soft soil, nonlinear behavior will become stronger as the seismic motion increases. The shear modulus will decrease and material damping will increase as the shear strain increases in the soil. Consequently, the rate of amplification near resonant frequency becomes small. Compared with that due to a noise, the coherence function will become smaller over a wide range of frequencies if the system behaves nonlinearly.

Shown in Figure 4 and 5 are the transfer and coherence functions between
the surface and underground seismic records at SGK (0m vs. -97m) and Inagawa (0m vs. -30m). It is noted that the nonlinear behavior is stronger at SGK than Inagawa from coherences, which agrees with the soil profiles of two sites.

A sharp amplification appears around 0.7Hz in the transfer function of EW component records at SGK, even though the site shows strong nonlinear response (Figure 4). This implies that around 0.7Hz there exists a motion at ground surface not transferring vertically. Another peak at 9.3Hz, showing an amplification rate over 10, may be attributed to the fact that the seismometer location in ground almost coincides with the node position of vibration mode since the coherence function here is not very small. As to NS component, there is no very sharp peak compared with EW component.

In regarding to the transfer and coherence functions of records at Inagawa, the correlation of the motions between the surface and underground is good to 4Hz. However, the coherence for NS component is lower than 0.4 near 2.6Hz. Since the range of low coherence is narrow, this phenomenon may be due to either resonance or noise like motion travelling in different way. However if the former was true, the resonance should occur in EW too and the peak on transfer function should be found. It is also observed that between 4 to 5Hz, the coherence for the EW component becomes very low but the corresponding transfer function shows a very sharp peak of over 14, implying again that an extra motion in the horizontal direction near the ground surface may exist.

4 Numerical simulation

Numerical simulation has been carried out based on soil profiles given in Figure 1 and observed motion in the ground. The numerical method and comparison are described in following.
4.1 Numerical method

For numerical simulation, the nonlinear relation between the shear strain and shear stress of soil is represented by Ramberg-Osgood's model, with Masing's law defining the hysteretic loop. Direct integration in time domain was implemented. Parameters in Ramberg-Osgood's model are determined by fitting the $G/G_0 \sim \gamma$ curve to that given empirically by Yasuda,

$$G/G_0 = [A_1(\gamma) + A_2(\gamma)\log D_{50}] \times p^{(B_1(\gamma) + B_2(\gamma)\log D_{50})}$$

In Eqn.5, $A_1, A_2, B_1, B_2$ are coefficients determined from experiment data, $p$ the effective confining pressure and $D_{50}$ the mean grain size of the soil.

4.2 Verification of numerical procedure

The accuracy of our numerical procedure described above at large strain level has been verified with the shaking table testing results of a large-scale laminar box, excited in a horizontal direction.

The model ground used in the test was made from natural moisture sands, dropped in a laminar box with 12m in length, 3.5m in width and 6m in height. The sand was then consolidated by pre-shaking. The input motions applied include white noise of different levels and seismic wave named GOC, as shown in Figure 6. Comparison of the measured and calculated maximum accelerations in the lamina box is shown in Figure 8 where a good agreement can be clearly observed.
observed at all levels of vibration. The acceleration histories on the model surface are plotted in Figure 7, which again demonstrates a very good comparison between the numerical simulation and testing. It is further noticed that during the vibration testing, the maximum strain in the sand can reach as high as over 3%. Therefore, the numerical procedure used here can calculate the ground response with a high precision at strain level over several percents, provided that the input motion is in a horizontal direction.

![Input seismic wave](image)

**Figure 6 Acceleration history of input seismic wave**

![Comparison of acceleration on surface of laminar box](image)

**Figure 7 Comparison of acceleration on surface of laminar box**

### 4.3 Simulation of observations

After verifying successfully our numerical procedure, we now apply it to the simulation of observations at SGK and Inagawa. Shown in Figure 9 and Figure 10 are the results from the numerical simulation. For the site at SGK, the surface responses were calculated by using the observed record at GL-97m as input. It is observed from Figure 9 that for NS component, the simulation agrees well with the observation until 13.0s. Thereafter, the difference becomes evident and time lag arises between calculated and measured peaks. Regarding EW component, the calculated and measured amplitudes show differences but arriving times are almost the same until 14.3s. Although the maximum peak is about 500gal, the first and second peaks are on the same level as those of NS component.

For the seismic observation at Inagawa, deconvolution results were calculated using the surface records. It is noted from Figure 10 that in the whole duration, a good agreement was achieved except for the differences at the 2nd to 4th peaks for the NS-component and the 4th to 6th peaks for the EW-component.
Figure 8 Comparison of distribution of maximum acceleration at different exiting level

Figure 9 Simulation of surface responses at SGK

Figure 10 Simulation of bedrock responses at Inagawa
For the NS-component, a time lag can also be detected in company with the difference in the amplitude.

5 The surface wave and its influence

Based on the analyses of down-hole array records and numerical simulation foregoing, it can be found that, besides the vertically propagating seismic motion, there exist motions propagating in totally different way. The influence of such motions on the time of dominant vibration is not negligible since the records were picked up near seismic fault. From theory of elastodynamic, these can be attributed to horizontally travelling surface wave, which contribute as noises to the calculation of the coherence for down-hole records. In consequence, the coherence becomes small and one-dimensional model fails to simulate the seismic observation. If the site is far enough from seismic fault that the arrivals of body wave and surface wave are separated in time due to difference in travelling speed, the above influence can be ignored.

The down-hole array records provide us with very useful information on the ground responses, especially on the very strong seismic motion near a fault area, since either indoor or in-situ experiments can only be carried out at very limited conditions. It should be noted that however, if the transfer properties or ground profiles are calculated based on the one-dimensional model, the correlation between the surface and underground records shall be verified in advance in order to obtain a reliable assessment because the influence of surface waves.

The surface waves can be roughly divided into a Rayleigh and Love wave. In general, not only the down-hole array but also the horizontal array observation is demanded in order to distinguish the types of surface waves. But this kind of record is still rare. If we concentrate on fundamental mode of Rayleigh wave, the trace of particle in a vertical plane is useful since the horizontal component changes phase at certain depth from surface, but never for vertical component.

The displacements at certain interested range of frequency are computed from acceleration history with a band-filter. For records at Inagawa, the change of rotating direction of the trace in NS-UD plane indicates the existence of a Rayleigh wave around 2~3Hz, as shown in Figure 11. However in EW-UD plane the contribution of Rayleigh wave is small. Similarly, between 0.7~0.9Hz a Rayleigh wave was detected in NS direction from SGK records (not shown here due to limited space). For EW component, the presence of a Love wave is a reasonable explanation for sharp peaks and low coherence in Figure 4 around 0.7Hz since a Rayleigh wave of higher mode is seldom to exist at such a low frequency.

6 Conclusion

For seismic motion of surface near a seismic fault, the influence of surface wave becomes evident even during the dominant time of vibration. Therefore it is difficult to predict the near fault response of ground based on the one-dimensional model. Unfortunately there is no practical replacement now in
Figure 11 the displacement trace of motion from observation of Inagawa engineering. Besides, the effort in analysis as well as cost in ground survey make most engineers give up three dimensional numerical model although actual soil profile may vary in space. To distinguish surface waves and make out their affects on structure responses not only vertical but also horizontal array of observation are required. If only the strength of ground motion is interested, some kind of compensation for input motion can be used in aseismic design. However if a structure is sensitive to different motion in space, the propagation characteristic of surface wave becomes very important.

References

1. Strong-motion acceleration records from public works in Japan(No.21), Technical note of public works research institute, Vol.64, June 1995