EFFECTS OF NONLINEAR SOIL AMPLIFICATION ON STRONG MOTIONS DURING THE NIIGATAKEN CHUETSU-OKI EARTHQUAKE IN 2007

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ABSTRACT :

Strong ground motions were recorded at a downhole array by the service hall in the Kashiwazaki-Kariwa nuclear power station during the Niigataken Chuetsu-oki Earthquake in 2007. The peak period of spectral amplification ratios between the near-surface ground motion and the deepest underground motion recorded during the main shock was similar to those of weak motions during the aftershocks. The spectral amplification ratios in the short period range less than one second of the main shock are less than those of the aftershocks. It seems that the nonlinear amplification due to surface soils might have had a strong effect on the strong motion during the main shock. A field investigation and its spectral analysis based on the surface wave method were conducted to evaluate the near-surface soil profile at the station. In order to simulate the observed strong motions during the main shock, one-dimensional equivalent linear analyses were conducted using the estimated soil profiles. The Fourier spectra of the computed motions agree reasonably well with those of the observed motions. The analysis simulates well the amplification of strong ground motions between the near-surface and the deep underground during different levels of shaking and this suggests that the nonlinear properties of the surface soil might have had strong effects on the strong motion during the main shock.

KEYWORDS: surface soil, strong motion, soil nonlinearity

1. INTRODUCTION

The Niigataken Chuetsu-oki Earthquake of M_w 6.6 that struck the western coastal area of Niigata prefecture, Japan on July 16, 2007 provided a large amount of strong motion records of buildings and on the ground at the Kashiwazaki-Kariwa nuclear power station. The free-field downhole array records of the main shock in the site that can be used as the input motion for the earthquake-resistant design of nuclear power stations, however, were deleted due to over-writing. At the service hall near the power station, the downhole array records of the main shock were obtained. These records are very valuable and are open to the public with the records obtained in the buildings and on the ground in the power station site during the main shock along with the earthquakes before and after the main shock by Tokyo Electric Power Company (TEPCO) immediately after the earthquake.

The peak period of the spectral amplification ratio between the near-surface ground motion and the deepest underground motion recorded at the service hall station, which is situated in a sand dune, during the main shock was similar to those of weak motions during the aftershocks. The spectral amplification ratios in the short period ranges less than one second of the main shock are less than those of the aftershocks. It seems that the nonlinear amplification of the surface soil might have had a strong effect on the strong motion during the main shock.

The objectives of this study are to evaluate the effect of local site conditions on the ground motion characteristics and to estimate the outcrop bedrock motion which can be considered as the input motion to the power station site during the Niigataken Chuetsu-oki Earthquake.

2. GEOLOGICAL AND GEOPHYSICAL CONDITIONS AT STRONG MOTION STATIONS

A large number of seismic records were obtained at the Kashiwazaki-Kariwa nuclear power station during the Niigataken Chuetsu-oki Earthquake in 2007 as well as the earthquakes before and after the main shock. These records are open to the public with the geological logs at the strong motion stations by Tokyo Electric Power Company immediately after the earthquake.

Figure 1 shows a map of the site of the Kashiwazaki-Kariwa nuclear power station along with the strong motion station locations that are under study. The site is on the Sea of Japan and is located in a sand dune. The downhole array at the service hall (KSH) where strong motion records of the main shock were obtained is located on the top of the sand dune. KKZ-1G1 is the strong motion station on the ground in the power station site where strong motion records of the main shock were obtained. KK1 is the downhole array station in the site where strong motion records for the main shock were lost but the other earthquake records were obtained.

Figure 2 shows the geological and geophysical logs with the locations of the downhole seismometers at KK1 and KSH. At the both stations, about 15 m thick Yasuda Formation which mainly consists of clay is piled up above Nishiyama Formation with shear wave velocity of about 600 m/s, which appears at 15 m below the sea level and is considered as the bearing layer of the main buildings of the power station. At KSH, a sand dune consisting of Holocene sands and Banjin Formation is developed on Yasuda Formation with the thickness of about 70 m. At KK1, a sand fill is piled up above Yasuda Formation with the thickness of 6 m.

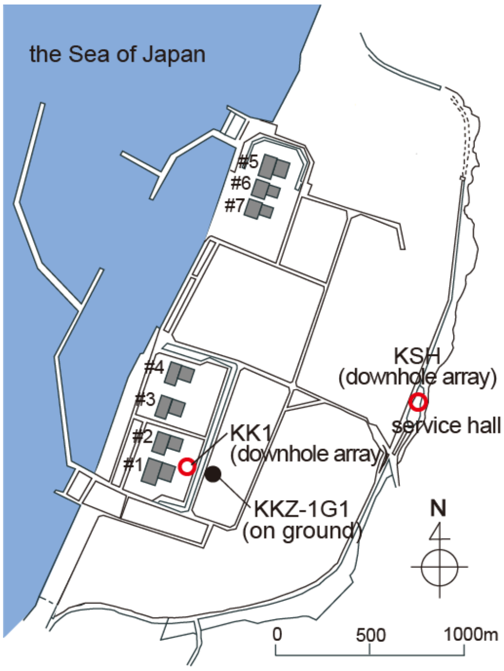

Figure 1 Map showing Kashiwazaki-Kariwa nuclear power station with strong motion stations

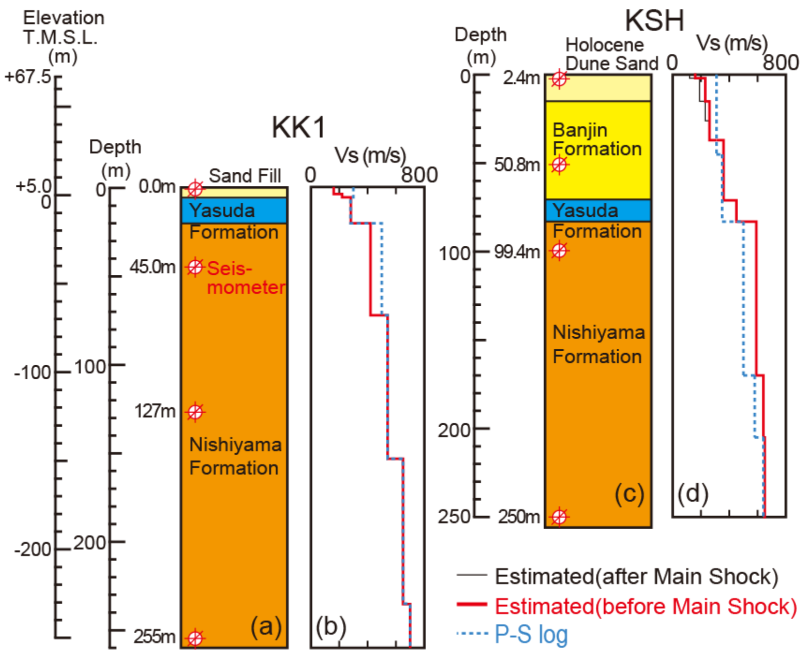

Figure 2 Geological and geophysical logs with the location of the downhole seismometers at KK1 and KSH stations

3. EFFECTS OF NONLINEAR SOIL AMPLIFICATION ON STRONG MOTION RECORDS

Figure 3 compares the spectral amplitude ratios of recorded EW components between 2.4 m and other depths of the service hall station (KSH) during the main shock, with those for earthquakes before and after the main shock. For earthquakes before and after the main shock, the spectral ratios are computed by averaging those of 6 and 17 earthquakes which have large magnitude.

The spectral peak periods of the main shock are elongated from those of other earthquakes except those between 2.4 m and 250 m depths. This suggests that the ground motions at KSH could reflect the effect of nonlinearity of the surface soil that extends to the depth of 99.4 m. When comparing the spectral peak periods of earthquakes before and after the main shock, it is found that those of earthquakes after the main shock are a little elongated from earthquakes before the main shock. It seems that the stiffness of the surface soil which was decreased during the main shock did not recover to the level of that before the main shock.

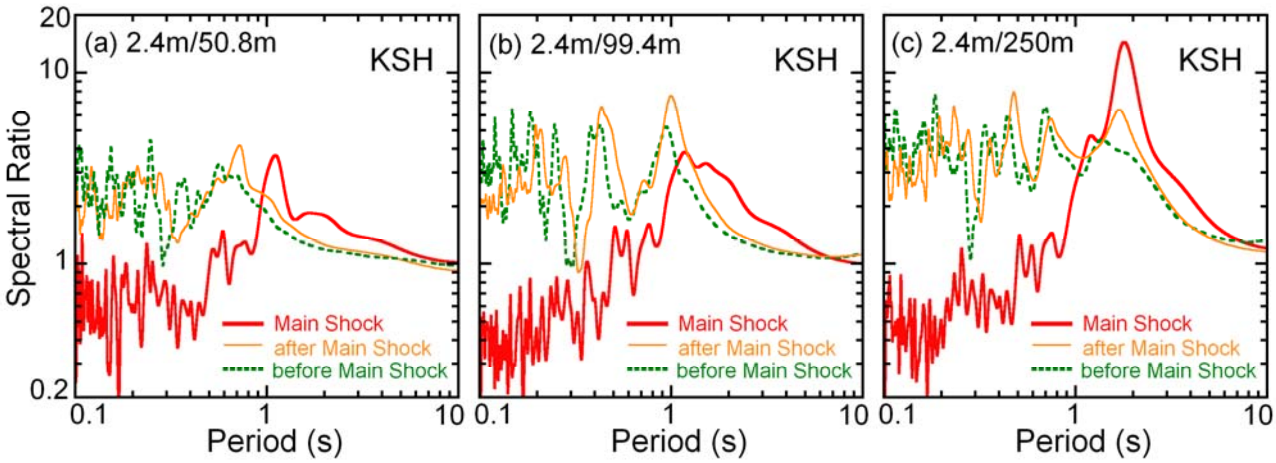

Figure 3 Spectral ratios of recorded EW components between 2.4 m and the other depths at KSH for main shock and earthquakes before and after main shock

4. ESTIMATION OF SHEAR WAVE VELOCITY PROFILES BASED ON SEISMIC RECORDS AND SURFACE WAVE METHOD

The PS loggings that were provided by TEPCO do not have sufficient information about the shallow soil layers because the purpose of the soil investigation was for the deeper soils. Thus the authors have conducted spectral analysis of surface wave method and that based on seismic downhole array records of weak motions to estimate the detailed shear wave velocity profiles of the shallow soil layers at KSH and KK1.

Since the stiffness of the surface soils at KSH after the main shock is considered softer than that before the main shock as mentioned earlier, estimation of the surface soil profile (the shear wave velocity and the thickness) at KSH was conducted based on the spectral analysis of the surface wave method and the seismic records as shown schematically in Figure 4. The estimation of the surface soil profile at KK1 was conducted based on the spectral analysis only of the seismic records before the main shock referring the PS log.

The spectral analysis of the surface wave method was performed at KSH on December, 2007 after the main shock. According to the target wavelength of the surface wave, the active method with an artificial point source using linearly arrayed sensors and the passive method using the circularly arrayed sensors intended for microtremors were used.

Figure 5 shows the dispersion characteristic of the surface wave at KSH in which the computed phase velocities are plotted against periods based on the one-dimensional F-k spectral analysis and spatial autocorrelation method for various sensor distances (Tokimatsu, 1995, Aki, 1957). The solid line in this figure shows the theoretical dispersion curve which is consisting of multiple modes presented by Tokimatsu et al. (1992) for the estimated shear wave velocity profile after the main shock at the station. The computed value is in a fairly good agreement with the observed one, suggesting that the inverted soil structure could be reasonably reliable.

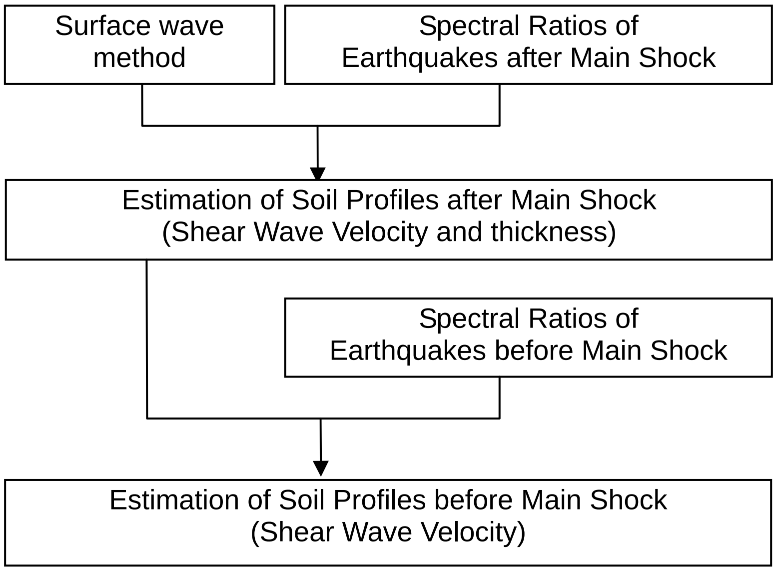

Figure 4 Flowchart of estimation of shear wave velocity profile of surface soil at KSH

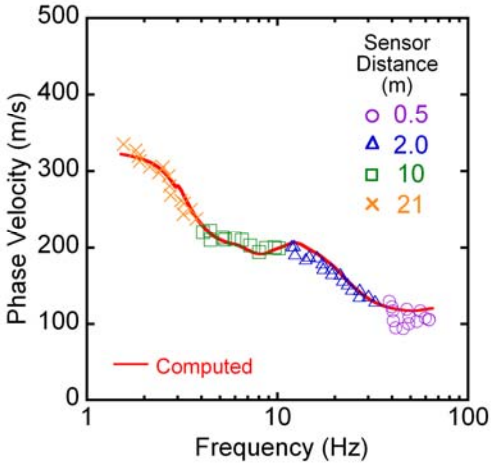

Figure 5 Dispersion characteristic of surface wave at KSH

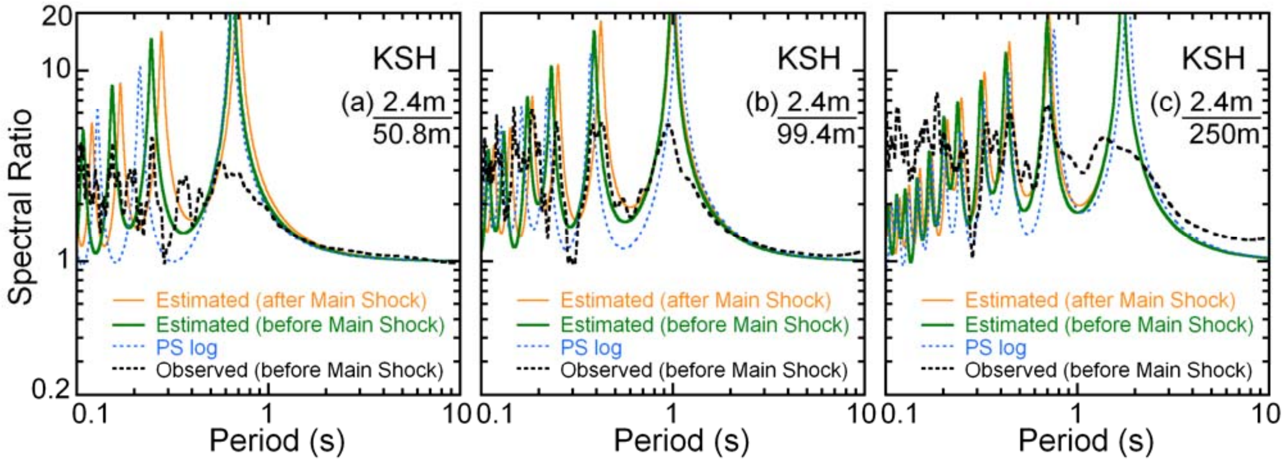

Figure 6 Theoretical transfer functions for the estimated shear wave velocity profile and the PS log at KSH station and spectral amplitude ratios for earthquakes before the main shock

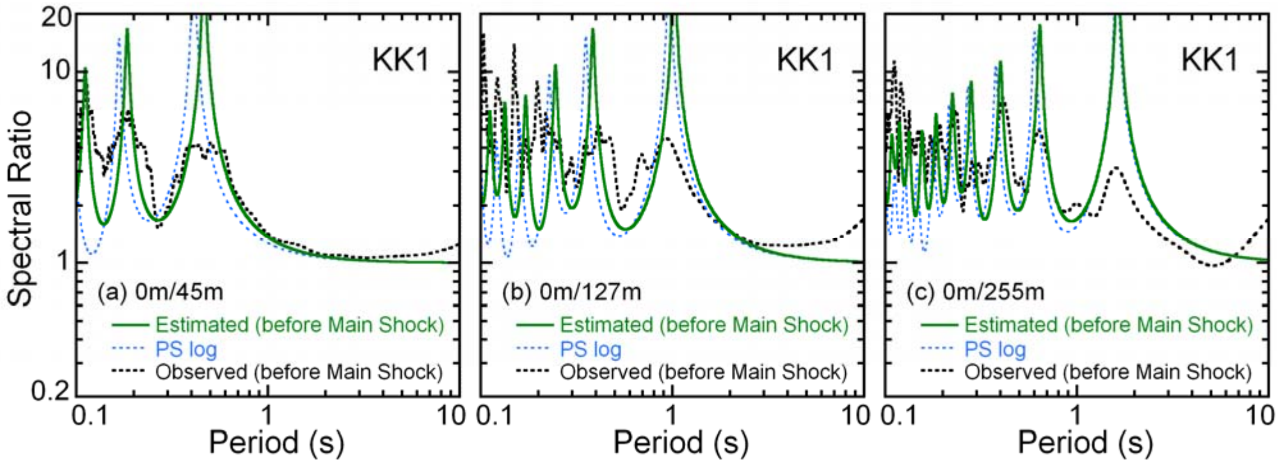

Figure 7 Theoretical transfer functions for estimated shear wave velocity profile and PS log at KK1 and spectral amplitude ratios for earthquakes before the main shock

Figures 6 and 7 show the theoretical transfer functions, defined as the spectral ratio between the ground surface and other layers, for the estimated shear wave velocity profile after and before the main shock and the PS log at KSH and KK1 as well as the spectral amplitude ratios of the earthquakes before the main shock. The theoretical transfer functions for the estimated profile before the main shock are in better agreement with the observed ones when compared to those from the PS log.

The bold and solid lines in Figure 2 (b), (d) show the estimated shear wave velocity profiles at the stations. The estimated shear wave velocities near the ground surface are smaller than those of PS logs.

5. DYNAMIC RESPONSE ANALYSIS

To evaluate the effect of local site conditions on the ground motion characteristics and to estimate the outcrop bedrock motion as the input motion to the power station site during the Niigataken Chuetsu-oki Earthquake, a one-dimensional equivalent linear dynamic response analysis with frequency dependent damping (Schnabel at al., 1972, Sugito et al., 1993) was conducted using the soil profiles shown in Figure 2. The acceleration record of the EW component at a depth of 250 m at KSH during the main shock was used as the input within motion to compute the outcrop bedrock motion at the same depth. The computed bedrock motion was used as the input outcrop motion at a depth of 255 m for KK1. Figure 8 shows the nonlinear dynamic soil properties used for the analysis, which are based on the study by Imazu and Fukutake (1986). It is assumed that Nishiyama Formation is linear elastic and its damping ratio is assumed as 2 %.

Figure 9 shows the distribution of the computed effective shear strain, the shear modulus ratio and the damping ratio at KK1 and KSH. The sand layers piled on Yasuda Formation at the both stations showing a nonlinear behavior, with the shear modulus ratio of about 0.1 at the shear strain of about 1 % down to the depth of 6 m at KK1 and the shear modulus ratio of about 0.3 at the shear strain of about 0.3 % down to the depth of about 35 m at KSH.

Figure 10 shows the computed transfer functions between 2.4 m and other depths at KSH together with the observed spectral ratios for the main shock. The computed transfer functions agree reasonably well with the observed spectral ratios especially from the view point of the elongated first peak periods in Figure 10 (a), (b), suggesting that the simulation of the strong ground motions with nonlinear behavior could be reasonably reliable.

Figure 11 compares the Fourier spectra of the computed and observed motions of the near surface and the deepest layer at KSH for the main shock as well as that of the computed ground motion at KK1 with that of the observed motion at KKZ-1G1 near KK1 as shown in Figure 1. The Fourier spectrum of the computed ground motion at KK1 agrees fairly well with that of the observed motion at KKZ-1G1 in spite of the fact that these are different points in the site, suggesting that the computed outcrop bedrock motion could be reasonably reliable.

Figure 12 compares the acceleration and the velocity time histories of the computed and observed ground motions at KSH and KK1, and shows the computed outcrop bedrock motion at KSH as well. The time histories of the computed ground motions at those stations are roughly consistent with those observed at the same or near stations. The differences in the acceleration time histories can be due to the difference between the computed transfer function and the spectral ratio of the observed motions in the short period range less than one second as shown in Figure 10.

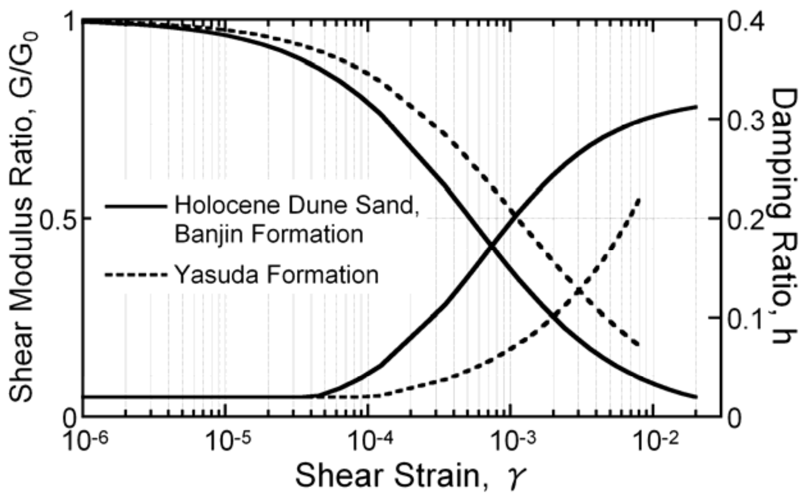

Figure 8 Relations of shear modulus ratio and damping ratio with shear strain used for dynamic analysis

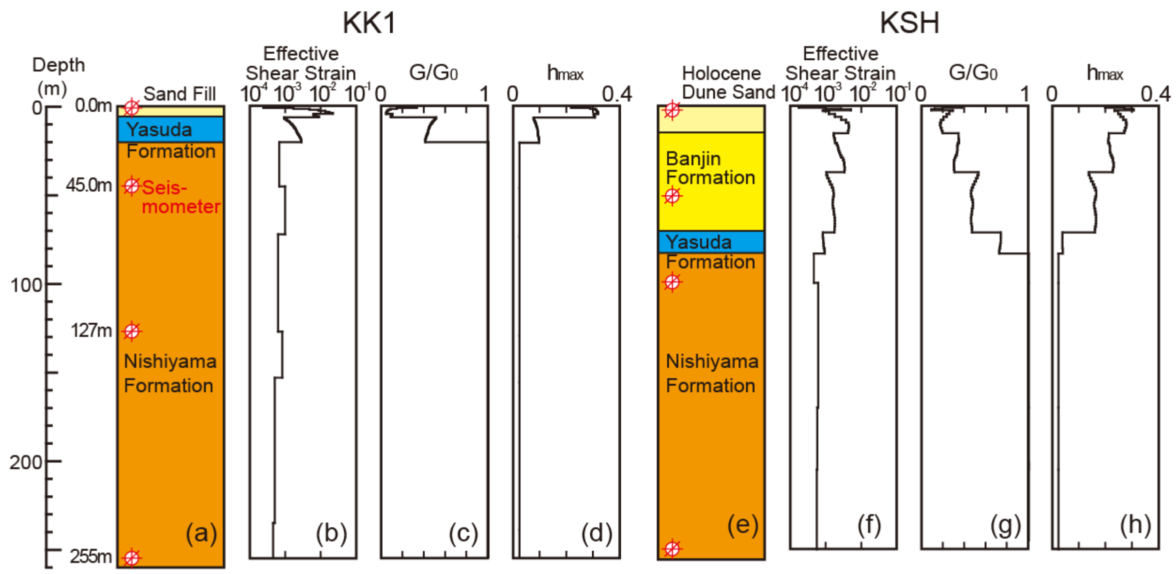

Figure 9 Distribution of computed effective shear strain, shear modulus ratio and damping ratio

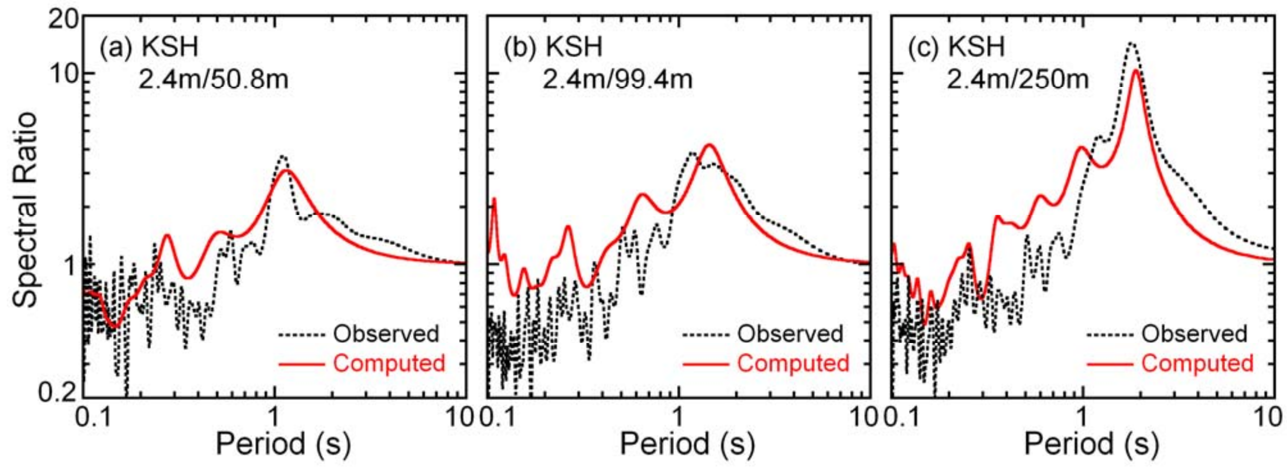

Figure 10 Comparison of transfer functions and observed spectral amplitude ratio for main shock at KSH

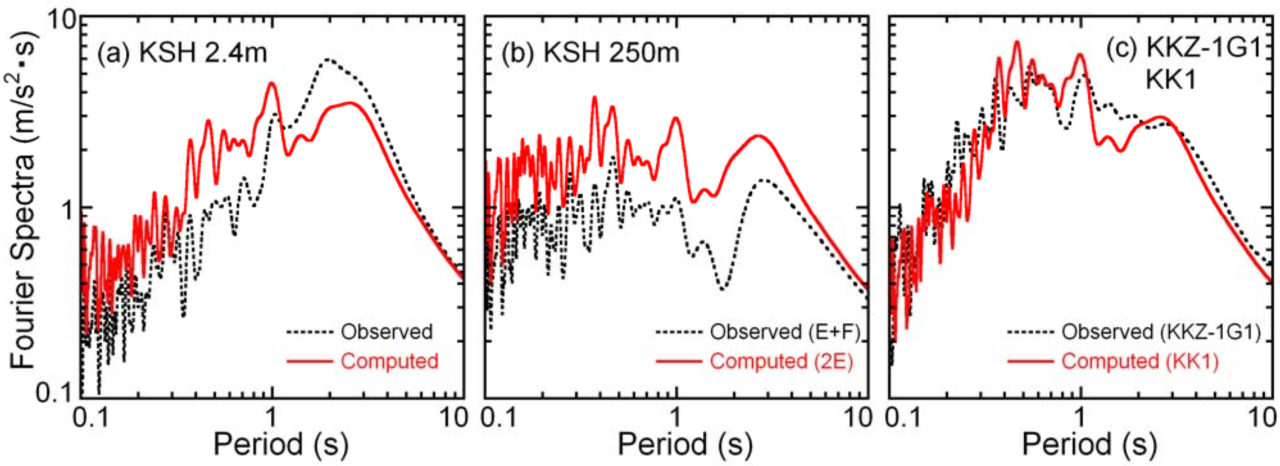

Figure 11 Comparison of observed and computed Fourier spectra for main shock at three stations

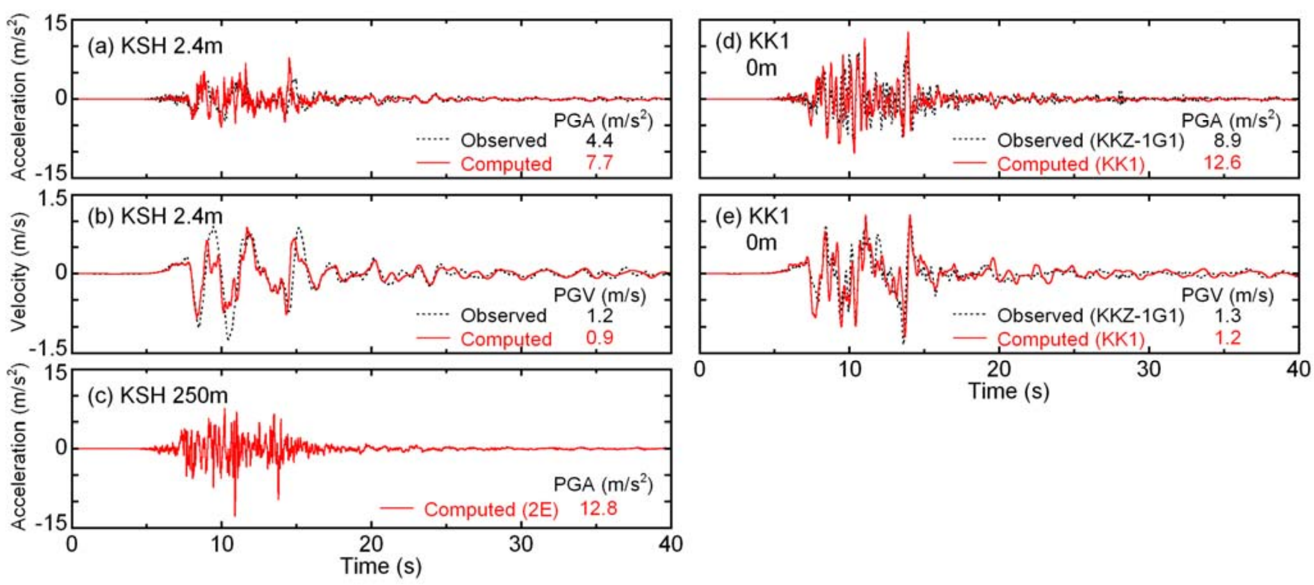

Figure 12 Comparison of computed acceleration and velocity time histories for main shock with observed ones

CONCLUSIONS

The effect of local site conditions on the recorded ground motions during the Niigataken Chuetsu-oki Earthquake in 2007 was examined and the outcrop bedrock motion of the Kashiwazaki-Kariwa nuclear power station site was estimated, based on the field investigations and subsequent analyses. The following conclusions can be made through this study:

1. The dune sand layers piled above Yasuda Formation at KSH may have exhibited a nonlinear behavior, with the shear modulus ratio of about 0.3 at the shear strain of about 0.3 % down to the depth of about 35 m at KSH.

2. The equivalent linear analysis can simulate reasonably well the strong motions observed at KSH and KKZ-1G1 near or in the Kashiwazaki-Kariwa nuclear power station site during the Niigataken Chuetsu-oki Earthquake in 2007.

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REFERENCES

Aki, K. (1957). Space and time spectra of stationary stochastic waves, with special reference to microtremors, *Bulletin, Earthquake Research Institute*, **35**, 415-456.

Imazu, M. and Fukutake, K. (1986). Dynamic shear modulus and damping of gravel materials, *Proceedings of the 21th Japan National Conference on Soil Mechanics and Foundation Engineering*, 509-512 (in Japanese).

Schnabel, P.B., Lysmer, J. and Seed, H.B. (1972). SHAKE-A Computer Program for Earthquake Response Analysis of Horizontally Layered Sites, *EERC Report*, **72-12**

Sugito, M., Goda, H., Masuda, T. and Etsunada, K. (1993). Equi-linearlized method with frequency-dependent shear modulus and damping, *Proceedings of the 28th Japan National Conference on Soil Mechanics and Foundation Engineering*, 1129-1132 (in Japanese).

Tokimatsu, K. (1995). Geotechnical site characterization using surface waves, *Proceedings of the first international conference on earthquake geotechnical engineering*, 1333-1368.

Tokimatsu, K., Tamura, S. and Kojima, H. (1992). Effects of multiple modes on Rayleigh wave dispersion, *Journal of geotechnical engineering*, ASCE, **118**, **10**, 1529-1543.

Tokyo Electric Power Company (2007). Acceleration time histories at Kashiwazaki-Kariwa nuclear power station during the Niigataken Chuetsu-oki Earthquake in 2007 etc., DVD-ROM.