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SIMULATIONS OF STRONG GROUND MOTIONS AT KASHIWAZAKI CITY DURING THE 2007 NIIGATA-KEN CHUETSU-OKI EARTHQUAKE

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ABSTRACT

The strong ground motions recorded at K-NET Kashiwazaki during the 2007 Niigata-ken Chuetsu-oki earthquake had spiky acceleration time history, suggesting liquefaction or cyclic mobility of the ground, while those at nearby JR Kashiwazaki did not show such spiky waves. A preliminary attempt was made to examine why such spiky waves were recorded only at the K-NET station during the earthquake and for this purpose, to propose and employ a new method for searching reasonable rock outcrop motion that could simulate the ground motions recorded at the two sites. It has been shown that: (1) Conventional deconvolution and convolution analysis using ground motions recorded at the JR station as reference for estimating those at the K-NET station has been proven effective for this particular pair of stations subjected to a moderate-intensity earthquake, whereas it was ineffective for a strong-intensity shaking which would induce liquefaction of soil deposits under consideration; and (2) The proposed method can reproduce reasonably well the spiky waves observed at the K-NET station and thus could show promise in estimating reasonable rock outcrop motion from ground surface motions recorded at the JR station.

Keywords: Strong Ground Motion, Effective Stress Analysis, Niigata-ken Chuetsu-oki Earthquake

INTRODUCTION

Niigata-ken Chuetsu-oki Earthquake (Mj=6.8) occurred on July 16, 2007, with an epicenter off the Niigata prefecture. The quake affected the coastal areas of the southwestern Niigata prefecture, including Kashiwazaki city and Kariwa village as well as the Kashiwazaki-Kariwa nuclear power plant of Tokyo Electric Power Company (TEPCO), most of which were located on or near the sand dunes that run parallel to the coastline (Tokimatsu, 2008).

The earthquake claimed a death toll of fifteen, with more than 2,340 injuries, as of December 28, 2007. More than forty-one thousand residential houses were either totally collapsed or partially damaged. The strong ground motions recorded at the K-NET (NIG018) station near the Kashiwazaki municipal building had spiky acceleration time history recording with a peak acceleration of 6.7 m/s^2, whereas those at the JR Kashiwazaki station about 1.2 km apart did not show such spiky waves with a peak value of 3.2 m/s^2 (Yoshida et al, 2007; Tokimatsu, 2008).

The objective of this paper is to examine why such spiky waves were induced during the main shock and, for this purpose, to propose and employ a method for searching reasonable rock outcrop motion that could

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simulate the ground surface motions recorded at the two sites during the main shock, based on numerical analyses using dynamic soil properties obtained from field investigation made after the quake.

GEOLOGICAL SETTINGS

Figure 1 shows a geomorphological map of the central part of Kashiwazaki city (Kashiwazaki city, 1983). The city has been developed in the Kashiwazaki plain that faces the Sea of Japan on the northwest. The Kashiwazaki plain consists mainly of the Holocene alluvial deposit formed by the U and Sabaishi rivers and their tributaries. Running in parallel with and between the coastline of the Sea of Japan and the alluvial deposit is the Arahama sand dune that is trisected by the U and Sabaishi rivers where they flow into the Sea of Japan. It extends from the southwest of the city towards the northeast, with its plateau altitude of about 10 m in the central city of Kashiwazaki.

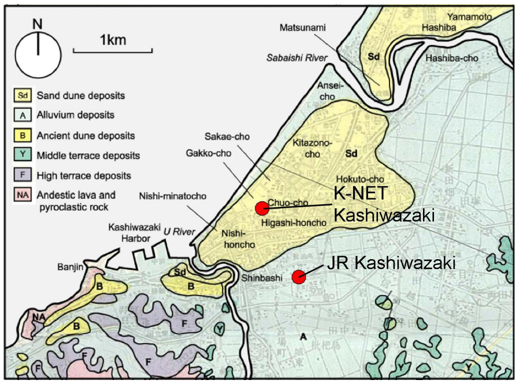

Figure 1. Geomorphological Map of Kashiwazaki City (Kashiwazaki City 1983)

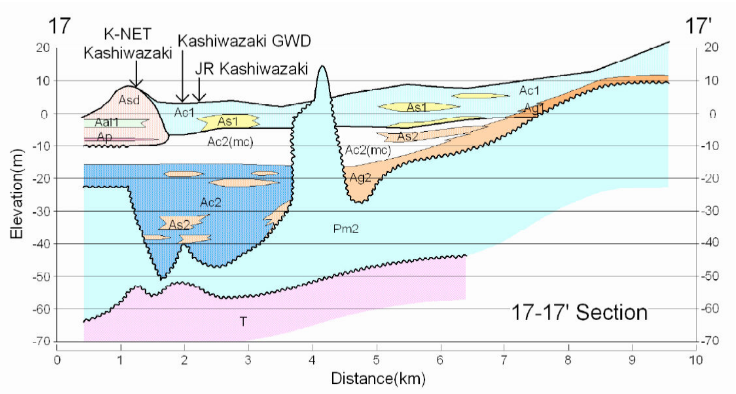

Figure 2. Geological Sections of Kashiwazaki City (Association of Subsurface Exploration in Niigata Prefecture, 2002)

Figure 2 shows a NS geologic section across the city. The Holocene deposit in the lowland consists of the Top, Upper and Lower Kashiwazaki Formations (Ac1/As1, Ac2/As2, and Ac3/As3), with thicknesses varying from 40-70 m along the lower courses of the two rivers, that overlie the Pleistocene and Tertiary Formations (Pm2 and T). The Arahama sand dune about 2 km in width consists of the New Holocene sand dune (Asd) and Pleistocene sand dune called Banjin Formation (Psd) that is underlain by the Kashiwazaki Formations on the south of the Sabaishi River. Typical shear wave velocities of the New Sand Dune, Banjin Formation, Kashiwazaki Formation, Yasuda Formation, and Nishiyama Formation are 100-200, 200-350, 100-200, 350, and 500-600 m/s, respectively.

STRONG GROUND STATIONS AND GROUND CONDITIONS

The Kyoshin strong motion network (K-NET) recorded the main shock at 20 stations within 50 km from the epicenter. Tokyo Electric Power Company (TEPCO) recorded time histories of the main shock at 33 locations within the Kashiwazaki-Kariwa nuclear power plant. In addition, several strong ground motions were recorded in Kashiwazaki city by several organizations including East Japan Railway Company (JR East), East Nippon Expressway Company Limited (E-NEXCO), Kashiwazaki City and Niigata Prefecture. Among the strong motion stations in the central city, only the K-NET station is located on the sand dune while other stations including JR Kashiwazaki, Kashiwazaki Gas and Water, and E-NEXCO Kashiwazaki are on the alluvial plain.

Figure 3 shows acceleration time histories at the K-NET and JR stations during the main shock. The accelerograms at both stations have long period components, probably reflecting the thick alluvial deposit underlying the sites. It is interesting to note that the accelerogram at K-NET Kashiwazaki on the sand dune shows spiky waves, associated with liquefaction or cyclic mobility of sand, and rapidly decreasing its amplitude with time due probably to cyclic degradation of the sand. Similar spiky waves are, however, not observed at JR Kashiwazaki on the alluvial deposit about 1.2 km south.

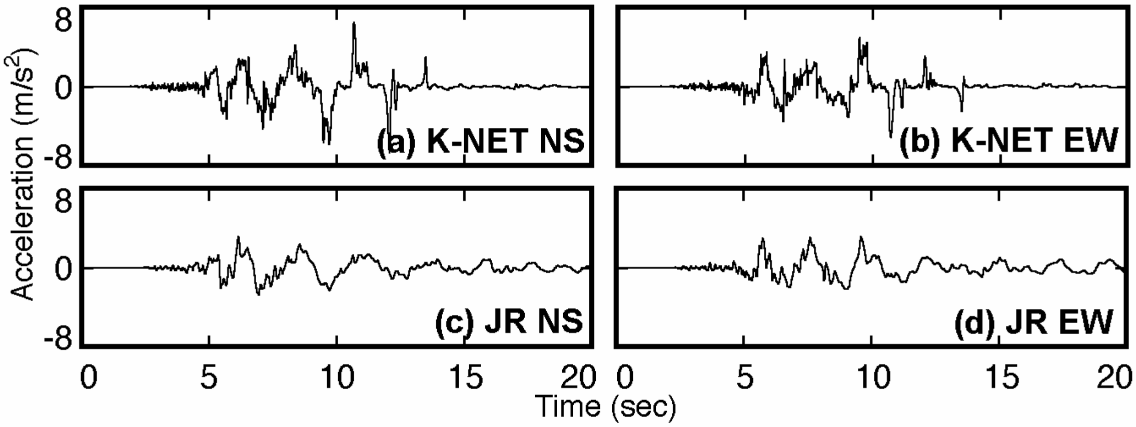

Figure 3. Acceleration Time Histories of K-NET and JR during the main shock

Some of the strong ground motions recorded at both sites during other earthquakes are also available. Figure 4 shows such acceleration time histories during the aftershock of the Niigata-ken Chuetsu Earthquake that occurred at 18:12 on October 23, 2004. Neither spiky waves nor long period component can be seen in any of the records, highlighting the strong nonlinear soil behavior including soil liquefaction at the K-NET station during the main event as shown in Figure 3.

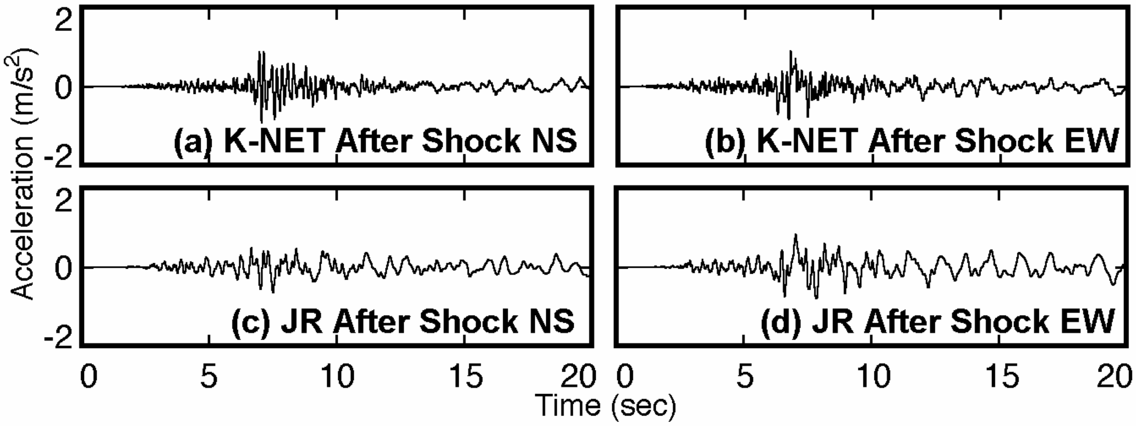

Figure 4. Acceleration Time Histories of K-NET and JR during the after shock (Niigata-ken Chuetsu Earthquake, 18:12, October 23, 2004)

The distance between K-NET to JR is just 1.2km. Geological and geophysical field investigation was made at both stations after the earthquake as well as laboratory tests to determine dynamic soil properties of the sites. Figure 5 shows the geological boring logs and shear wave velocity logs for the two sites. The groundwater table was located at a depth of about 5.0 m and 0.8 m, respectively. The surface soil at K-NET station to a depth of 13 m is dense sand with SPT N-values ranging from 10 to 40 and Vs from 110-250 m/s, which is underlain by a thick clayey soil with Vs 200-290 m/s. Mudstone with Vs over 500 m/s occurs at a depth of about 65 m. The surface soil at JR station to a depth of 18 m, in contrast, consists of soft silty clay and sandy silt with N-Values of 0-1 and VS of 70-100 m/s, which overlays alternate sand and clayey silt with N-values of 3-20 and Vs of 190-450 m/s. Mudstone with Vs over 500 m/s occurs at a depth of about 66 m. It seems that the sandy soils at depths between 5-10 m at K-NET might have undergone cyclic mobility and/or liquefaction, although no evidence of soil liquefaction was identified nearby.

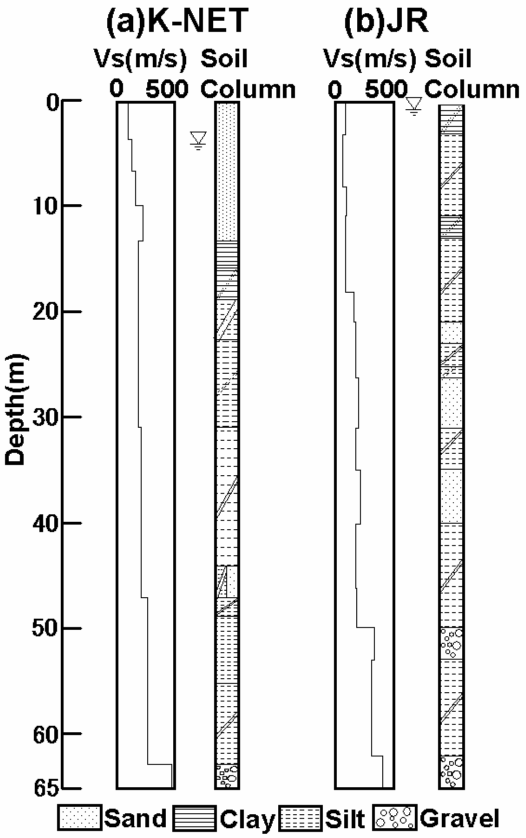

Figure 5. Geological and Geophysical Logs of Sites

ANALYTICAL SIMULATION

Ground Motions during a Moderate-Intensity Earthquake

Figure 6 shows a flowchart to estimate the ground motion recorded at the K-NET from one at the JR station. It was assumed that the rock occurring at a depth of about 65 m is the equivalent rock for the two sites. First, the rock outcrop motion was estimated, based on the deconvolution analysis using the observed ground motions and soil profile at JR Kashiwazaki. The ground surface motion at the K-NET site was then estimated, with the back-calculated rock outcrop motion as input to the soil column of the K-NET station. The programs used for this deconvolution and convolution analyses including the following:

(1) A one-dimensional equivalent-linear response analysis of a deposit subjected to a vertically incident SH waves in which damping ratios of soil depend only on shear strain developed in the soil (hereby call SHAKE 1)

(2) An extended version of the equivalent linear response analysis in which the damping ratios of the deposit are assumed to be dependent on the Fourier amplitude of shear strain in the frequency domain (e.g., Sugito et al, 1993), which has been developed to improve over-damping nature of the original SHAKE (Schnabel et al, 1972) in the short period range during strong shaking (hereby call SHAKE 2)

(3) A nonlinear effective response analysis (Shamoto et al, 1992, hereby call ESA).

The same program was used for both deconvolution and convolution analyses, except for the convolution analysis of ESA for which SHAKE 2 was used for deconvolution analysis.

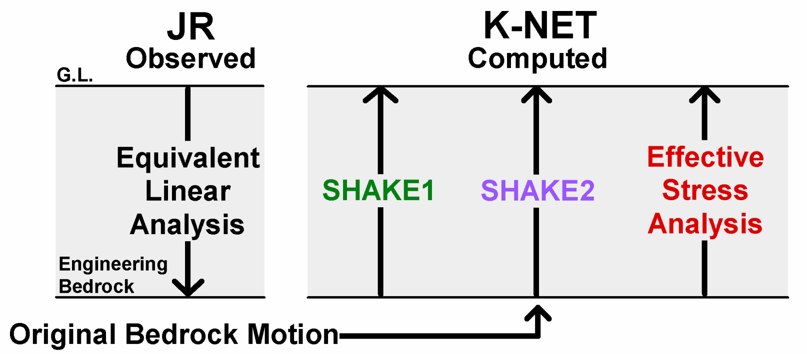

Figure 6. Flowchart to Estimate Ground Motion at K-NET from Recorded Motion at JR

To confirm the applicability of the deconvolution and convolution analyses shown in Figure 6 for this particular pair of stations and for a moderate-intensity earthquake, strong motions recorded at both stations during the aftershock of the Niigata-ken Chuetsu Earthquake that occurred at 18:12 on October 23, 2004 was used.

Figure 7 shows the time histories computed by the three methods, compared with the recorded ones. There is a good agreement between the observed and computed values, confirming the applicability of any of the deconvolution and convolution analysis for this particular pair of stations and for a moderate-intensity earthquake.

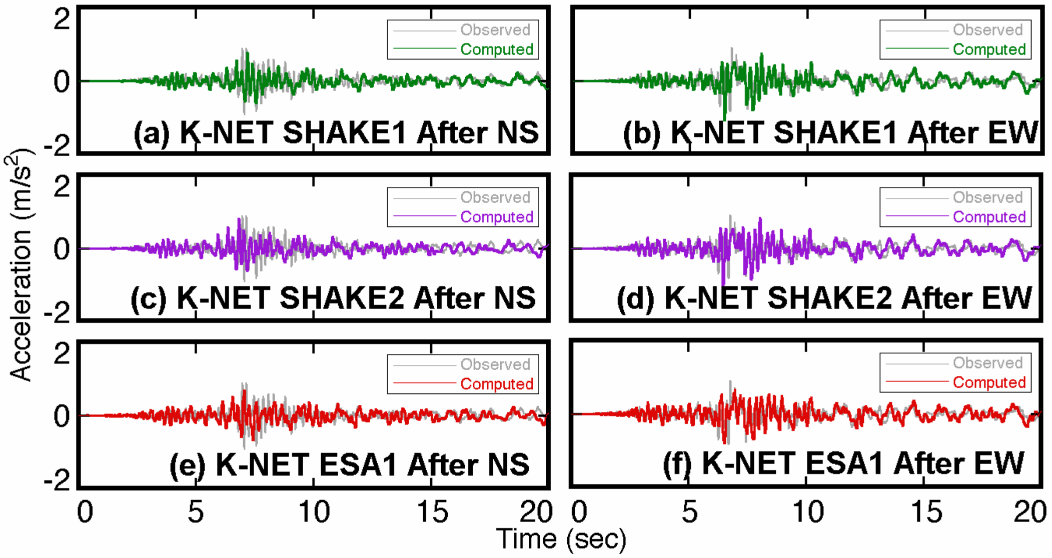

Figure 7. Acceleration Time Histories of Computed Ground Surface Motions, Compared with Those Recorded at K-NET During a Moderate-Intensity Earthquake

Ground Motions during a Strong-Intensity Earthquake

To study further the applicability and limitation of the three deconvolution and convolution methods for estimating site response during strong-intensity shaking and the cause of spiky waves observed in the K-NET Kashiwazaki, similar analysis was made with the strong ground motions recorded during the 2007 Niigata-ken Chuetsu-oki Earthquake.

Figure 8 shows the acceleration time histories of the deconvoluted rock outcrop motions and the ground surface motions computed from the three methods, compared with those of the recorded motions. It seems that the computed results from any of the three methods are inconsistent with the recorded motions and unable to reproduce spiky waves observed in the recorded motions.

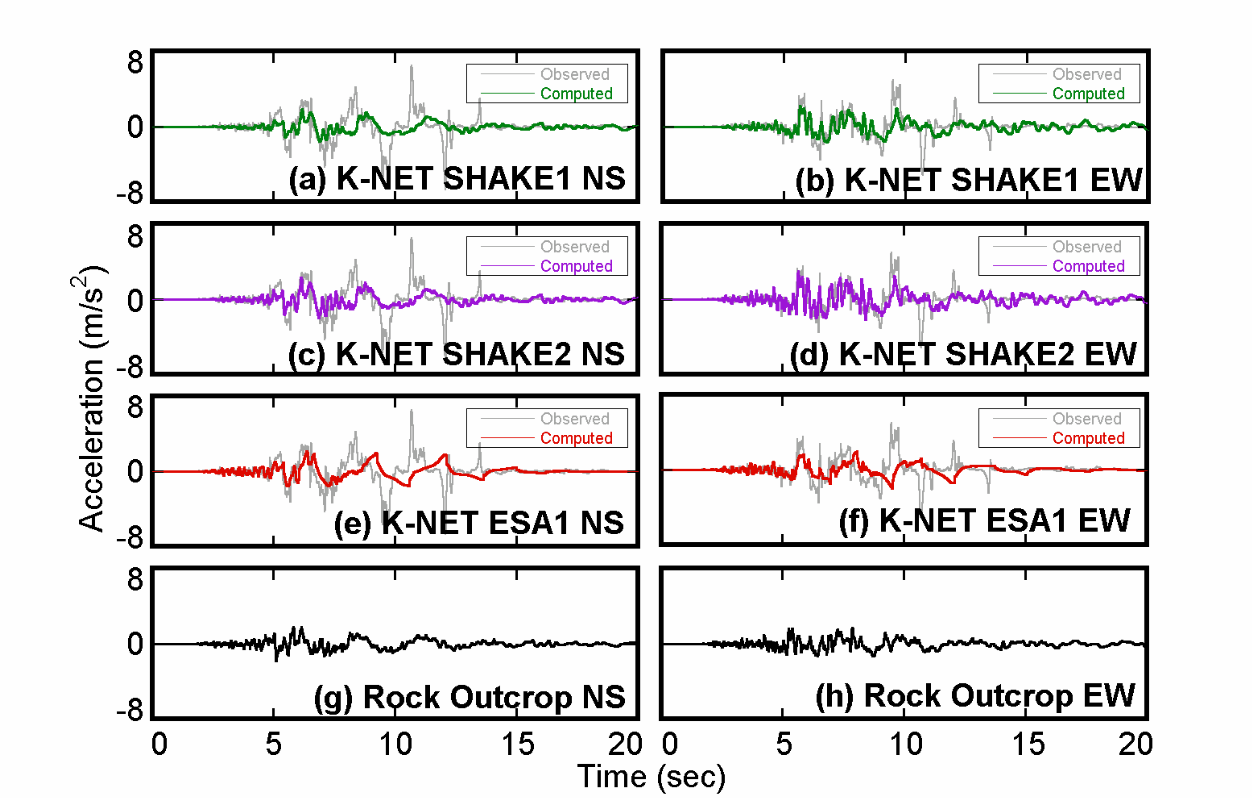

Figure 8. Acceleration time histories of computed rock outcrop and ground surface motions, compared with those recorded at K-NET during the 2007 Niigata-ken Chuetsu-oki earthquakes

A close examination further suggests that the computed ground motion in the later phase is smaller in amplitude and more delayed than the observed one. This suggests that the actual rock outcrop motion in the later phase might have been larger and more behind than the one deconvoluted by the equivalent linear method.

Based on the above discussions, a preliminary attempt was made to search more reasonable rock outcrop motion that could show a better agreement with the ground motions recorded at the two sites during the main shock. This was made by a try-and-error method as shown in the flowchart of Figure 9 in which the rock outcrop motion is updated so that the difference between observed and computed ground surface motions can be minimized.

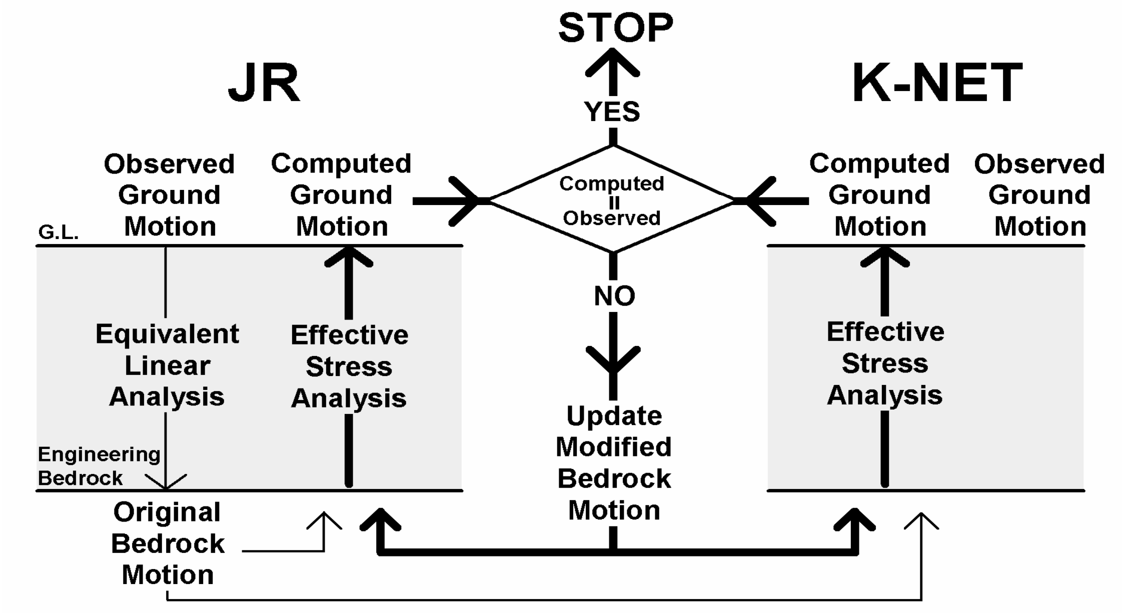

Figure 9. Flowchart to Search Reasonable Rock Outcrop Motion

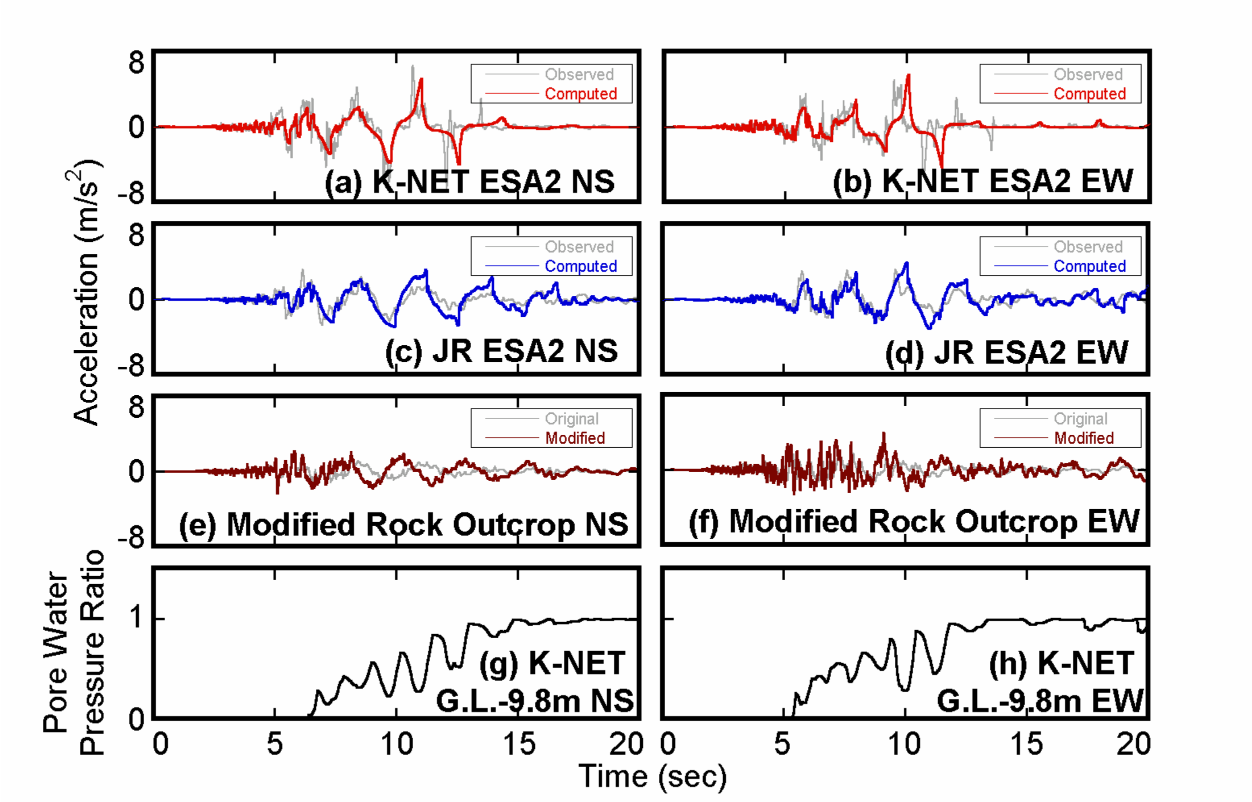

Figure 10. Time histories of computed rock outcrop motion, ground surface motion and pore pressure ratio, compared with those recorded at K-NET and JR Kashiwazaki during the 2007 Niigata-ken Chuetsu-oki earthquake

The rock outcrop motion initially assumed is one determined as deconvolution analysis of the modified SHAKE using the observed ground surface motion at the JR station. The effective stress analysis was then employed to determine the ground surface motions at the two sites using the rock outcrop motion. The rock outcrop motion was modified in terms of amplitude and phase so that the difference between the computed and observed ground surface motions at the two sites becomes small. This convolution analysis and modification of rock outcrop motion was repeated until the observed and computed ground surface motions become compatible with each other.

Figure 10 shows the acceleration time histories of the ground surface motions computed with the most updated rock outcrop motion, compared with the recorded ones. Also shown in the figure are those of pore pressure ratio in a critical layer. There is a good agreement between the observed and computed values. A comparison of the back-caluculated rock outcrop motions shown in Figs. 8 and 10 confirms that the actual rock outcrop motion in the later phase might have been larger and more behind than the one deconvoluted by the equivalent linear method. The computed pore pressure ratio in the dense near-surface layer at a depth of about 10 m reaches to unity, suggesting that soil liquefaction might have occurred in this layer and contributed to the spiky acceleration waves observed in the strong motion recording observed at K-NET Kashiwazaki. The above discussions suggest that the rock outcrop motion may be estimated based on the method presented in this study, although more refinement is definitely needed.

CONCLUSION

The strong ground motions recorded at K-NET Kashiwazaki had spiky acceleration time history recording with a peak acceleration of 6.7 m/s^2, suggesting liquefaction or cyclic mobility of the ground, while those at nearby JR Kashiwazaki did not show such spiky waves with a peak value of 3.2 m/s^2. A preliminary attempt has been made to examine why such spiky waves were induced during the main shock and, for this purpose, to propose and employ the method for searching reasonable rock outcrop motion that could simulate the ground surface motions recorded at the two sites during the main shock. On the basis of the analysis and discussions, the following conclusions have been made:

(1) Conventional deconvolution and convolution analysis using strong motions recording at one site as reference for estimating those at nearby other station has been proven effective for this particular pair of stations subjected to a moderate-intensity earthquake, whereas it was ineffective for a strong-intensity shaking which would induce liquefaction of soil deposits under consideration.

(2) The proposed method can reproduce reasonably well the spiky waves observed in the recorded motions at K-NET Kashiwazaki and thus could show promise in estimating reasonable rock outcrop motion from strong ground motions recorded during strong-intensity shaking which would induce liquefaction of soil deposits under consideration.

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REFERENCES

ASENP (2002): Geotechnical Engineering Map of Niigata prefecture, Editorial Committee for geological map of Niigata prefecture, Association of Subsurface Exploration in Niigata Prefecture (ASENP), (in Japanese).

Kashiwazaki city (1983): Historical records of Kashiwazaki city (in Japanese).

Schnabel, P.B., J. Lysmer, and H.B. Seed (1972): SHAKE – A computer program for earthquake response analysis of horizontally layered sites, EERC Report, No. 72-12.

Sugito, M., Goda, H., Masuda, T. and Etsunada, K. (1993): Equi-linearlized method with frequency-dependent shear modulus and damping, Proc., 28th Japan National Conference on SMFE, pp. 1129-1132 (in Japanese).

Shamoto, Y., Tokimatsu, K., and Ariizumi, K. (1992): Applicability of A One-Dimensional Effective Stress analysis to An Existing Soil Deposit, J. Struct. Constr. Eng., AIJ, 433, 113-119. (in Japanese)

Tokimatsu, K. (2008): Geotechnical Problems in the 2007 Niigata-ken Chuetsu-oki Earthquake, Geotechnical Earthquake Engineering and Soil Dynamics (GSP 181), ASCE, Proceedings of the Geotechnical Earthquake Engineering and Soil Dynamics IV Congress 2008, 30pp.

Yoshida, N. et al. (2007): Investigation on Record at K-NET Kashiwazaki during the 2007 Niigatakeb-chuetsu-oki earthquake.