EFFECTS OF NONLINEAR PROPERTIES OF SURFACE SOILS ON STRONG GROUND MOTIONS RECORDED IN OJIYA DURING 2004 MID NIIGATA PREFECTURE EARTHQUAKE

KOHJI TOKIMATSUⁱ⁾ and TORU SEKIGUCHIⁱⁱ⁾

ABSTRACT

The peak ground acceleration (PGA) of 13.08 m/s² recorded at K-NET station in Ojiya city during the 2004 Mid Niigata Prefecture earthquake was 1.5–2 times greater than either of the other nearby stations on a similar soft soil (JMA) and on the outcrop rock (SSI). Those at K-NET during earthquakes with less intensity, however, tended to be smaller than those at JMA. The variation in relative magnitude of PGA with earthquake intensity is probably due to the difference in site conditions between K-NET and JMA. Field investigation including boring, PS logging, and spectral analysis of surface wave methods as well as laboratory tests on undisturbed samples obtained from the sites from this and previous studies reveal near-surface soil profiles and their nonlinear dynamic soil properties at both stations. Equivalent linear dynamic analysis is then performed using the detected soil profiles and properties for the two sites with the motions recorded at SSI as input outcrop motions. It is shown that, despite its very low shear wave velocity of about 50 m/s, the near-surface peat at K-NET exhibits weaker nonlinearity with larger damping at small strains but with smaller damping at large strains than does the near-surface silt at JMA. This might have had strong effects on the extremely large peak acceleration at K-NET during the main shock as well as on the variation in relative magnitude of PGA between K-NET and JMA during earthquakes of different intensity.

Key words: damping, (dynamic properties), earthquake, laboratory test, (microtremor measurement), nonlinear, peat, shear modulus, (surface soil) (IGC: D7/E8)

INTRODUCTION

An earthquake ($M_w=6.6$, $M_{JMA}=6.8$) that struck the central part of Niigata Prefecture, Japan, on October 23 of 2004, named the 2004 Mid Niigata Prefecture earthquake, caused severe damage to many wooden frame houses and triggered many landslides, claiming more than 50 fatalities and 4,800 wounded and devastating many roads in the area. As the epicenter of this earthquake was located inland, very large peak ground accelerations and velocities (PGA and PGV) were registered in or near its source region. These include 17.15 m/s² (0.55 m/s PGV) in Tokamachi, 16.76 m/s² (1.50 m/s PGV) in Kawaguchi, and 8.08–13.08 m/s² (0.71–1.27 m/s PGV) in Ojiya. Particularly interesting is the difference between the strong ground motions recorded at three stations in Ojiya immediately west of the epicenter. These include K-NET (Kyoshin NET) and JMA (Japan Meteorological Agency) stations on soft soils, and SSI (Suisen House, Tamari and Tokida, 2004) on outcrop rock. The PGA at K-NET during the main shock was 1.5–2 times greater than either of the other stations located on similar soft soil (JMA) and on the outcrop rock (SSI); however, those

at K-NET during aftershocks with less intensity tended to be smaller than those at JMA. The variation in relative magnitude of PGA between K-NET and JMA with earthquake intensity is probably due to the difference in site conditions between the two stations. There exist, however, few geological and geophysical data available for examining such local site effects.

The objective of this study is to evaluate the effects of local site conditions on the ground motion characteristics during the 2004 Mid Niigata Prefecture earthquakes. Field investigation including boring, PS logging, and spectral analysis of surface wave methods as well as laboratory tests on undisturbed samples obtained from the sites are compiled and/or newly conducted at K-NET and JMA stations to evaluate near-surface soil profiles and their dynamic soil properties. Equivalent linear dynamic analysis is then conducted using the soil profiles and properties determined for the two stations with the strong motions recorded at SSI on rock as outcrop base input motions.

ⁱ⁾ Professor, Tokyo Institute of Technology, Japan (kohji@o.cc.titech.ac.jp).

ⁱⁱ⁾ Graduate Student, ditto.

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Fig. 1. Map showing epicentral region

Fig. 2. Geomorphological land classification map of the central part of Ojiya city

GEOLOGICAL SETTING OF STRONG MOTION STATIONS IN OJIYA

Figure 1 shows a map of the affected area. Ojiya city is located about 7 km west of the epicenter of the main shock. Figure 2 shows a geomorphological land classification map (Niigata Prefecture, 1977) of the central part of Ojiya in which three strong motion stations are located. The central part of Ojiya is situated on the left side of the Shinano River running north towards the Sea of Japan through the Niigata Plain. Gravel terraces dominate in the area, with several lower valley plains formed by the erosion and sedimentation of the tributaries of the Shinano River. On the gravel terraces, either cohesive soil or sandy soil dominates from the ground surface to a depth of 2–5 m, which in turns is underlain by Holocene gravel and Pleistocene rock called Uonuma group. On the valley plains, in contrast, cohesive soil or sandy soil of a similar thickness is directly underlain by the rock of Uonuma Group.

The strong motion accelerometers of K-NET and JMA stations on the gravel terrace were installed on the ground surface of the soft soil, while that of SSI on the valley plain was installed on the basement of a base-isolated building founded directly on the Pleistocene rock of Uonuma Group at 4.45 m below the ground surface. It is conceivable therefore that K-NET and JMA are soft soil sites and SSI is a rock outcrop site.

GROUND MOTION CHARACTERISTICS AT THREE STATIONS IN OJIYA

Strong ground motions during the main shock and 17 aftershocks as well as one before the main shock were successfully recorded at more than two stations including SSI and are available for this study. Table 1 summaries PGA and PGV recorded at those stations during the earthquakes together with major earthquake characteristics. Open circles in Fig. 1 are their epicenters. As most of the epicenters are located about 6–24 km east of Ojiya on a fault striking 30 degrees east of north, dipping down to the northwest at 54 degrees, the fault normal (EW) components are therefore generally dominant in the recorded ground motions at the three stations and are mainly used in this paper.

Figure 3 compares acceleration time histories of EW components of the main shock at the three stations. The acceleration time histories observed at K-NET and JMA are somewhat similar to that at SSI on rock but include different period components with different level of shaking. In particular, the strong motion record at K-NET has the largest peak ground acceleration of 13.08 m/s^2 , showing spiky waves associated with cyclic mobility at 8–11 s.

Figures 4 (a)–(c) compare Fourier spectra (smoothed by Parzen window with 0.3 Hz bandwidth) of EW components of the main shock and several aftershocks recorded at the three stations. The Fourier spectra at SSI in the periods less than 0.1 s are not shown because the accelerometers at this station are insensitive in that period range. A prominent spectral peak appears in most Fourier spectra at K-NET and JMA with its spectral peak period increasing with increasing intensity of ground shaking or spectral amplitude. Such a trend is, however, obscure in the Fourier spectra at SSI. This suggests that the ground motions at K-NET and JMA could reflect nonlinear local site effects but those at SSI are associated with those observed at a rock outcrop site.

Figures 5 (a)–(c) compare the peak ground accelerations of the recorded strong motions between two of the three sites (Tokimatsu and Sekiguchi, 2006). Comparison of Figs. 5 (b) and 5 (c) indicates that the peak ground accelerations at the soft soil sites (K-NET and JMA) are, on the average, about 40 percentage points greater than that at the rock outcrop site (SSI), except for the main shock where the PGA at JMA is almost equal to that at SSI. As a result, the PGA at K-NET tends to be smaller during small intensity earthquakes but equal to or greater than that at JMA during the main shock (Fig. 5(a)). The change in relative magnitude of peak ground acceleration

Table 1. List of 19 earthquakes with PGA and PGV recorded at three stations in Ojiya

Date Time	M_{JMA}	Focal depth (km)	Epicentral distance (K-NET) (km)	PGA (m/s ²)			PGV (m/s)		
				K-NET	NS EW	JMA	NS EW	SSI	NS EW
2001/01/04 13:18	5.1	14	38	1.14		0.74		0.44	
				1.11		0.63		0.61	
2004/10/23 17:56	6.8	13	7	11.47		7.79		7.40	
				13.08		8.98		8.08	
2004/10/23 17:59	5.3	16	6	3.67		4.76		1.18	
				2.62		3.65		1.03	
2004/10/27 00:56	4.3	13	8	0.41		1.01		0.59	
				0.61		0.83		0.35	
2004/10/27 02:05	3.8	11	12	0.39		0.61		0.38	
				0.49		0.36		0.26	
2004/10/27 10:26	4.3	14	12	0.62		0.97		0.48	
				0.85		0.53		0.21	
2004/10/27 10:40	6.1	12	9	1.78		1.97		1.35	
				4.96		3.91		1.99	
2004/11/01 04:35	5.0	8	14	0.83		1.10		0.53	
				1.16		1.16		0.57	
2004/11/02 00:40	4.1	9	14	0.15		0.31		0.13	
				0.15		0.39		0.11	
2004/11/03 05:28	3.0	8	10	0.15		—		0.24	
				0.12		—		0.19	
2004/11/03 18:02	3.2	9	9	0.22		0.27		0.16	
				0.21		0.47		0.16	
2004/11/04 08:57	5.2	18	18	3.26		2.71		2.07	
				1.86		2.55		0.92	
2004/11/05 14:56	4.2	7	15	0.44		0.70		0.22	
				0.43		0.66		0.20	
2004/11/06 22:05	4.4	13	10	0.27		0.48		0.36	
				0.55		0.47		0.24	
2004/11/08 11:15	5.9	0	24	0.67		0.90		0.54	
				0.73		1.23		0.38	
2004/11/09 04:15	5.0	0	19	0.38		0.38		0.27	
				0.27		0.62		0.27	
2004/11/10 03:43	5.3	5	20	0.47		0.47		0.24	
				0.34		0.46		0.20	
2004/11/11 18:04	3.9	7	12	0.43		0.41		0.21	
				0.26		0.69		0.12	
2004/11/12 02:24	4.3	10	15	0.41		0.32		0.15	
				0.48		0.46		0.19

Fig. 3. Acceleration time histories at three stations for the main shock

with intensity of shaking at the two sites suggests that the difference in nonlinear soil properties exists between the sites.

Figure 6 shows the relation between spectral peak period, T_p , of the Fourier spectrum and peak ground acceleration for the recorded strong motions at K-NET and JMA. Although some data are widely scattered, there is a definite trend in which spectral peak period increases with increasing intensity of shaking at both sites. The increase in spectral peak period at JMA is, however, more significant than that at K-NET. Namely, it increases from 0.15 to 0.8 s at JMA whereas it increases from 0.25 to 0.7 s at K-NET. The larger elongation of spectral peak period at JMA suggests that the soil at JMA might have shown stronger nonlinearity than that at K-NET during the main shock.

Fig. 4. Fourier spectra of EW components at three stations during several earthquakes

Fig. 5. Comparison of observed peak ground accelerations between two of three stations (Tokimatsu and Sekiguchi, 2006)

Fig. 6. Relations between spectral peak period and peak ground acceleration at K-NET and JMA

Fig. 7. Geological and geophysical logs and installation sections of accelerometers at three stations

FIELD INVESTIGATION

Geological and Geophysical Logs from Current and Previous Studies

Geological and PS logs are available for K-NET and SSI stations but PS log is unavailable for JMA station. In addition, nonlinear soil properties of soft surface soils at K-NET and JMA, which might have had significant effects on the ground motions, were unknown. Field investigation including boring, sampling, and PS logging was, therefore, recently conducted to determine the characteristics of the soft soils and the Holocene gravel down to a depth of about 7 m at K-NET and JMA (Tokimatsu et al., 2006).

Figure 7 and Tables 2 to 4 show the geological logs and the shear wave velocity logs from the recent and/or previous investigations at K-NET, JMA and SSI,

together with the installation sections of the accelerometers. The surface soil to a depth of 3 m at K-NET station is extremely soft, consisting of silty clay and peat with V_s as low as 50 m/s and mass density as low as 1.2 Mg/m^3 . The surface soil to a depth of 3 m at JMA station, in contrast, consists of silty clay and sandy silt with V_s about 100 m/s. Underlying the 3-m thick surface layer at each station is a gravel layer with V_s of about 400 m/s, which is underlain by Pleistocene rock (Uonuma Group) occurring at a depth of about 13 m. Thus, the impedance contrasts between the 3-m thick surface soil and the gravel layer at both stations are quite high. Figure 8 shows the grain size distribution curves of the silty clay (C-1) at K-NET and the silty clay (C-2) and the sandy silt (S-1) at JMA. Those of the peat at K-NET are unavailable because of its organic contents. The ignition loss of the peat is 62%. The surface soil to a depth of 2 m at SSI

Table 2. Soil profile from PS logging at K-NET

Thickness (m)	ρ (Mg/m ³)	V_p (m/s)	V_s (m/s)	ν
1.65	1.65	250	70	0.457
1.45	1.20	660	50	0.497
1.10	2.00	820	210	0.465
2.80	2.00	820	360	0.381

Table 3. Soil profile from PS logging at JMA

Thickness (m)	ρ (Mg/m ³)	V_p (m/s)	V_s (m/s)	ν
1.40	1.70	310	80	0.464
1.55	1.80	550	130	0.470
3.15	2.00	680	360	0.305
0.90	1.95	610	310	0.326

Table 4. Soil profile from PS logging at SSI

Thickness (m)	ρ (Mg/m ³)	V_p (m/s)	V_s (m/s)	ν
2.0	1.90	530	140	0.461
8.0	1.90	1300	430	0.438
4.0	1.90	910	430	0.356
6.0	1.90	1390	430	0.447

Fig. 8. Grain size distribution curves of silty clay at K-NET and silty clay and sandy silt at JMA

consists of sandy silt, which is underlain by Pleistocene rock of Uonuma Group with V_s of 430 m/s. The accelerometer at this site was placed on the basement of the base-isolated building founded directly on the rock at 4.45 m below the ground surface. The shear wave velocity of the rock at SSI is almost the same with those of the stiff gravel layer occurring at 3 m and the Pleistocene rock occurring at 13 m depth at K-NET and JMA.

Deeper Shear Wave Velocity Profiles from Spectral Analysis of Surface Wave Methods

Active and passive techniques of spectral analysis of

Fig. 9. Microtremor dispersion curves and H/V spectra at K-NET and JMA

surface wave methods were also performed to estimate the shear wave velocity profiles to a depth of about 200 m at K-NET and JMA. In the active method of exploring shallow soil profiles, an artificial point source was observed with different linear arrays of several vertical sensors distributed at an equal spacing on a line with the source. The natural period of the sensors was 0.1 s and the sensor spacing varied from 0.5 to 2 m. In the passive method of exploring deep soil profile, microtremors were measured with different circular arrays of three-component sensors. The natural period of the sensors was either 1.0 or 5 s and the array radius varied from 10 to 200 m. The largest arrays used at the two stations are shown in Fig. 2. Further details of the test procedures have been described elsewhere (Tokimatsu, 1997).

Based on the F-k spectral analysis of the observed vertical motions, dispersion characteristics at the two stations were computed. Figures 9 (a) and (b) show the computed phase velocities plotted against periods with symbols corresponding to the sensor distances used. The phase velocities at K-NET in periods less than 0.1 s are about 70 m/s and increase to more than 400 m/s at periods greater than 0.3 s. The phase velocities at JMA in periods less than 0.05 s are about 100 m/s and increase to more than 400 m/s at periods greater than 0.1 s.

The H/V spectra were calculated from the three component motions of microtremors at the two stations and are shown with open circles in Figs. 9 (c) and (d). A sharp prominent H/V spectral peak occurs at a period of 0.30 s for K-NET and a period of 0.12 s for JMA, each period of which roughly corresponds to that of the Fourier spectrum of the aftershock with the smallest intensity as shown in Fig. 4.

Shear wave velocity profiles down to a depth of 200 m for the two stations were back-calculated based on an inverse analysis using both dispersion curves and H/V spectra (Arai and Tokimatsu, 2005). The solid lines in Fig. 9 show the theoretical dispersion curves and H/V spectra for the inverted shear wave velocity profiles. The

Fig. 10. V_s profiles from spectral analysis of surface waves method compared with those from PS logging at K-NET and JMA

computed values are in fairly good agreement with the observed ones, suggesting that the inverted V_s profiles are reasonably reliable.

Figure 10 shows the estimated shear wave velocity profiles to a depth of 20 m together with those to a depth of 200 m. The broken lines in the figure are those from the PS logging. The V_s profiles determined by the spectral analysis of surface waves are generally consistent with those determined by the PS logging, suggesting that the surface layer at K-NET does have a very low shear wave velocity. In addition, the impedance contrasts between the top 3 m thick layer and the underlying gravel layer at both stations are significantly higher than any other, which might have induced the large amplification near the spectral peak observed in Fig. 4 as well as the increase in spectral peak period with increasing earthquake intensity.

NONLINEAR DYNAMIC PROPERTIES OF SURFACE SOILS FROM LABORATORY TEST

To examine nonlinear dynamic soil properties of the surface soils, undisturbed sampling was recently made at K-NET and JMA using a thin-wall tube sampler (C-1) and a triple tube sampler (P-1, P-2, C-2, S-1). Cyclic torsion shear tests were then conducted on hollow specimens, 100 mm high having 70 mm outer and 30 mm inner diameters that were trimmed from the samples obtained at the sites (Tokimatsu and Sekiguchi, 2006). The specimens tested include silty clay (C-1) and peat (P-1, P-2) at K-NET and silty clay (C-2) and sandy silt (S-1) at JMA, sampling depths of which are shown in Fig. 7. Each specimen was isotropically consolidated under a confining pressure (C-1, C-2, P-1: 29 kPa, P-2, S-1: 39 kPa) as close as possible to the vertical effective stress of the specimen in-situ but not less than 29 kPa below which the test results may be inaccurate. Being saturated with the aid of percolation of carbon dioxide and de-aired water and then a back-pressure of 200 kPa, each specimen was subjected to a sequence of undrained multi-stage cyclic loading in which the resulting shear strain increases stepwise from about 10^{-5} to 3×10^{-2} .

Figure 11 shows the relations of shear modulus, shear modulus ratio, and damping factor with shear strain for the specimens tested. The elastic shear moduli at a shear strain of 10^{-5} of the specimen are generally consistent with those computed from the shear wave velocity in the field, as indicated in Figs. 11 (a) and (d) in solid lines.

Despite its very low shear wave velocity of about 50 m/s, the peat at K-NET (P-1, P-2) shows weaker nonlinearity than does any other soil. Namely, the shear modulus ratio and damping factor of the peat at K-NET at a shear strain of 1% are about 0.5 and 10%. These values are equivalent to those of the other soils at a shear strain of 0.1%, which is about one order of magnitude smaller than 1%. The shear modulus ratio and damping factor of the soils other than the peat are as low as 0.1 and as high as 15–20% at a shear strain of 1%. The damping factor at small strains (e.g., 3×10^{-5}) of the peat at K-NET is, on the contrary, 3–4%, which is unexpectedly higher than that of the soils at JMA. Such peculiar shear modulus and damping characteristics of peat have been presented elsewhere (Boulanger et al., 1998; Wehling et al., 2003).

DYNAMIC RESPONSE ANALYSIS

One-dimensional dynamic response analysis similar to one originally presented by Schnabel et al. (1972) and later modified by Sugito et al. (1993) for frequency dependent shear modulus and damping was performed for K-NET and JMA. The objective of this analysis is to examine not only whether it can simulate the observed strong motions at K-NET and JMA when using the nonlinear soil properties determined for the sites but also how the difference in nonlinear soil properties between the two sites affect the ground motions observed at the two stations during earthquakes of different intensity.

Figure 12 schematically shows the layer model for the analysis, the shear wave velocity profiles of which are those shown in Fig. 10 in solid line. The ground motions recorded at SSI was used as the input outcrop motions at a depth of 13 m (the top of the rock) or 3 m (the top of the gravel layer) of the two sites since the shear wave

Fig. 11. Relations of shear modulus, shear modulus ratio, and damping factor with shear strain for samples obtained at K-NET and JMA

Fig. 12. Schematic diagram showing soil layer model for dynamic response analysis

velocity of either layer is almost the same as that of the outcrop rock at SSI. Figure 13 shows the nonlinear dynamic soil properties used for the analysis, most of which are based on the laboratory test results shown in Fig. 11. Only exceptions are those of gravel that are based on the study by Imazu and Fukutake (1986).

Figure 14 compares the time histories of the ground surface acceleration computed for the input motion at a

Fig. 13. Representative relations of shear modulus ratio and damping ratio with shear strain used for dynamic analysis

Fig. 14. Comparison of computed acceleration and shear strain time histories with observed acceleration time histories at K-NET and JMA for the main shock

depth of 13 m with those observed at the three stations for the main shock, together with the computed shear strain time histories within the top 3-m layer. Although the effective shear strains, 0.65 times the maximum shear strain, are quite high (1.5–3%) and appear to exceed the acceptable limit of the equivalent linear analysis, the computed time histories are generally consistent with those observed at the sites. They however neither reproduce spiky waves such as observed at K-NET at 9–11 s correctly nor are necessarily in phase with the recorded motions, probably because of the limitations of the equivalent linear analysis.

Figure 15 compares the velocity response spectra with a damping ratio of 5% for the computed and observed motions during the main shock and the aftershock on 11/10/2004 03:43 hrs for the input motions at depths of 13 m and 3 m. The velocity response spectra of the computed motions also agree fairly well with the observed ones for both stations, irrespective of the depth of input motion. This suggests that the observed ground motions at K-NET and JMA were insignificantly affected by the dynamic properties of gravelly soils at depths greater than 3 m, even though they exhibited nonlinear behavior, and significantly governed by those of the soft soils at depths smaller than 3 m.

Figure 16 compares computed PGA between K-NET and JMA. The computed PGA at K-NET during small

Fig. 15. Comparison of velocity response spectra for computed and observed motions at K-NET and JMA

Fig. 16. Comparison of computed peak ground accelerations between K-NET and JMA

intensity earthquakes tends to be generally smaller than but that during the main shock is almost equal to or greater than that at JMA, the trend of which is consistent with that observed in Fig. 5(a). The major cause of this difference is due probably to the difference in nonlinear surface soil properties between the two sites.

Figure 17 shows the relations between spectral peak period and PGA of the computed ground motions at K-NET and JMA. There is a definite trend in which the spectral peak period increases with increasing PGA at both stations but the elongation of the spectral peak period is less significant at K-NET than at JMA, reflecting the weaker nonlinearity of surface soil at K-NET. The trend is consistent with that observed in Fig. 6.

The above finding and discussions indicate that the near-surface soils to a depth of 3 m including the difference in nonlinear soil properties between K-NET and JMA and particularly the weaker nonlinearity of peat at

Fig. 17. Relations between spectral peak period and computed peak ground acceleration at K-NET and JMA

K-NET significantly affected the strong ground motions at K-NET and JMA during the 2004 Mid Niigata Prefecture earthquakes.

CONCLUSIONS

The effects of local site conditions on the strong ground motions during the 2004 Mid Niigata Prefecture earthquakes were examined based on the observed strong motion records at three stations in Ojiya together with field investigation, laboratory tests and subsequent analysis. Based on the results and discussions, the following conclusions can be drawn:

- (1) The soil profile at K-NET consists of a 3-m thick soft surface layer of silty clay and peat with V_s about 50 m/s that is underlain by a stiff gravel layer with V_s about 400 m/s, while that at JMA of a 3-m thick soft layer of sandy silt with a shear wave velocity of about 100 m/s that is also underlain by a stiff gravel layer of almost the same V_s value. Despite its very low shear wave velocity, the near-surface peat at K-NET shows weaker non-linearity with larger damping at small strains but with smaller damping at large strain than does the near-surface sandy silt at JMA.
- (2) The equivalent linear analysis can simulate reasonably well the strong motions observed in the 2004 Mid Niigata Prefecture earthquake although the effective shear strains to be developed in the surface layer are extremely high (1.5–3%) and appear to exceed the acceptable limit of the analysis. The computed acceleration time histories, however, neither reproduce spiky waves associated with cyclic mobility correctly nor are necessarily in phase with the recorded motions, probably because of the limitations of the equivalent linear analysis.
- (3) The difference in nonlinear properties of surface soils between K-NET and JMA and, in particular, the weaker nonlinearity of peat at K-NET might have had strong effects on the extremely large peak acceleration at K-NET during the main shock as well as on the variation in relative magni-

tude of PGA between K-NET and JMA during earthquakes of different intensity.

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