NONLINEAR BEHAVIOR OF SOIL RESPONSE OBSERVED IN STRONG-MOTION RECORDS FROM RECENT JAPANESE EARTHQUAKES

S. Midorikawa[1] and H. Miura[2]

[1] *Professor, Dept. of Built Environment, Tokyo Institute of Technology, Yokohama, Japan*
[2] *Assistant Professor, Dept. of Built Environment, Tokyo Institute of Technology, Yokohama, Japan*
Email: smidorik@enveng.titech.ac.jp, hmiura@ enveng.titech.ac.jp

ABSTRACT :

Nonlinear behavior of soil response is discussed using the strong-motion records from recent Japanese earthquakes. During the 2004 Niigata-ken-chuetsu (M_J 6.8), the 2007 Noto-hanto (M_J 6.9), and the 2007 Niigata-ken-chuetsu-oki (M_J 6.8) earthquakes, large amplitude strong-motion records with peak ground velocity of about 100 cm/s are observed on soft soil sites. The strain level developed in surface soils and shear modulus ratio of soils are estimated from the records by a simple method. The estimated shear modulus ratios are 0.8 to 1.0, 0.4 to 0.6 and 0.2 to 0.3 at strain levels of 0.01%, 0.1% and 1%, respectively. The dependency is consistent with the previous laboratory data, suggesting the validity of the soil response analysis based on the laboratory data.

KEYWORDS: nonlinear soil response, strong-motion record, strain level, shear modulus ratio

1. INTRODUCTION

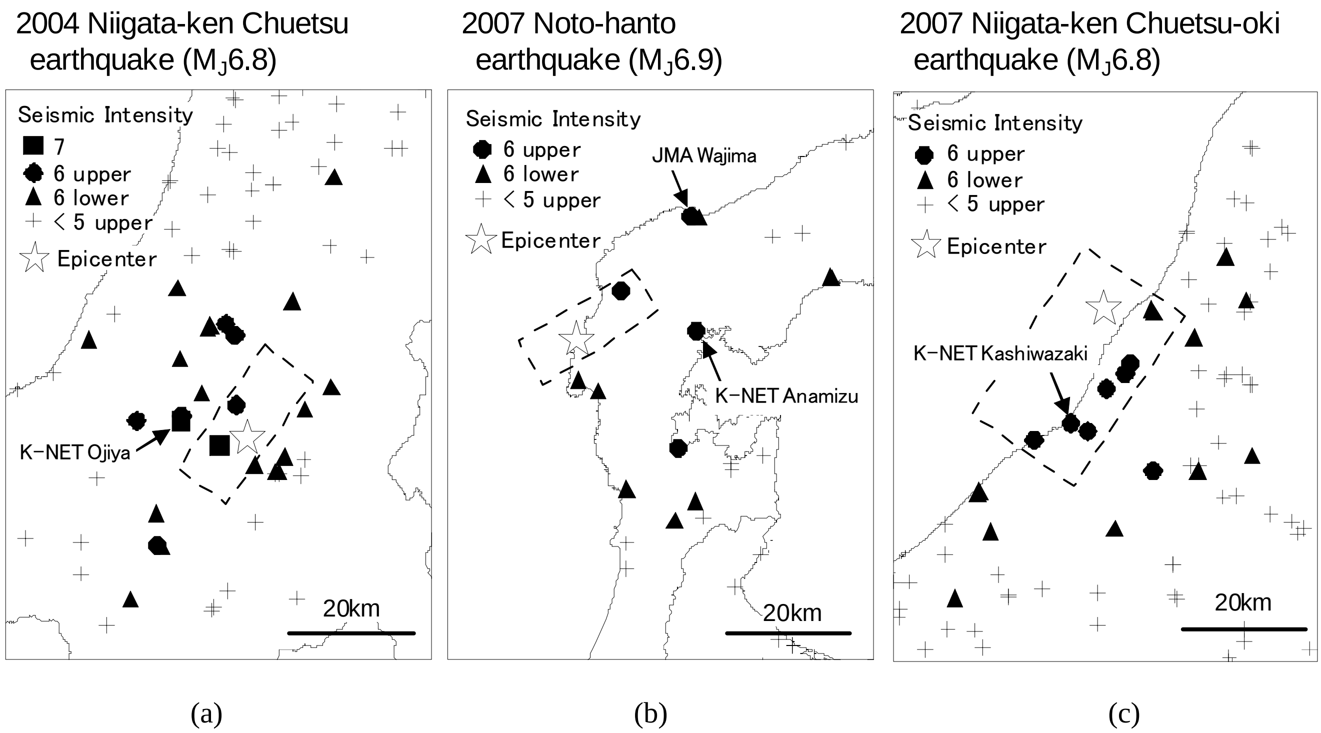
Local site effect on ground motion is one of key issues in strong motion prediction. Nonlinearity of soil amplification has been suggested from geotechnical experiments, and is being discussed by using observed strong motion records (Kawase, 2006). This is because that recent strong motion instrumentation provides better opportunities to examine the nonlinearity in large amplitude records. In Japan, strong motion networks such as K-NET and JMA network have been developed after the 1995 Kobe earthquake. During the 2004 Niigata-ken-chuetsu (M_J 6.8), the 2007 Noto-hanto (M_J 6.9), and the 2007 Niigata-ken-chuetsu-oki (M_J 6.8) earthquakes, large amplitude strong-motion records with peak ground velocity of about 100 cm/s are observed on soft soil sites. This paper discusses nonlinear behavior of soil response using large amplitude strong-motion records from these three earthquakes.

2. STRONG MOTION RECORDS

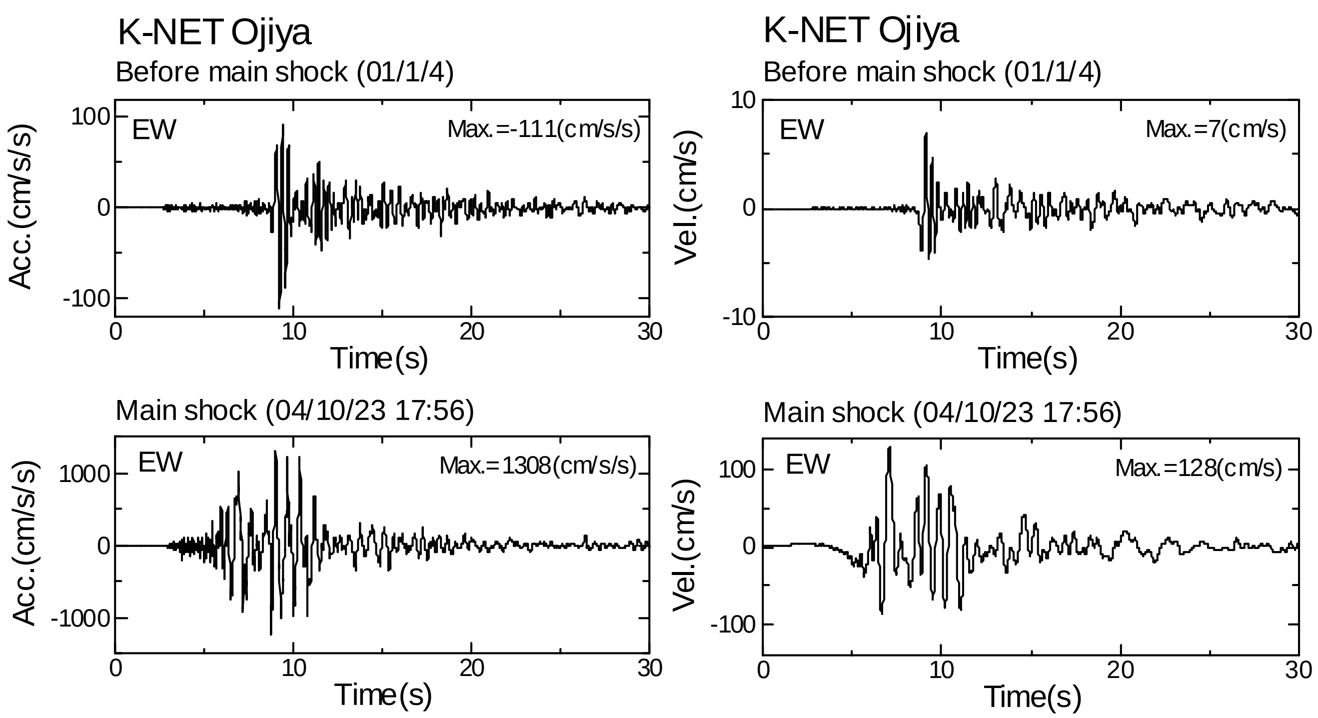
2.1. Records during the 2004 Niigata-ken-chuetsu earthquake

On October 23, 2004, a major earthquake (M_J6.8, M_W6.6) struck Niigata Prefecture. The earthquake is due to reverse-faulting on a fault striking the northeast and dipping down to the northwest. The rupture area is approximately 25 km in length and 15 km in width. Figure 1(a) shows the seismic intensity distribution with surface projection of the fault plane. The K-NET Ojiya site is located almost above the fault plane. At the site, as shown in the lower part of Figs. 2, the observed peak ground acceleration and velocity are higher than 1*g* and 100 cm/s, respectively. The site is located on soft peat soils with thickness of 3 m and shear-wave velocity of 50 to 70 m/s (Tokimatsu et al., 2006).

The upper part of the figures shows the time histories of the record from the smaller event. The predominant period of the record is much shorter than that of the main shock record. Figure 3(a) shows the spectra of the main shock, its aftershocks and the smaller events before the main shock at the site. For smaller records, the predominant periods are around 0.3 second, which is the same with that for the microtremor at the site. For the larger aftershock the period is about 0.4 second, and 0.7 second for the main shock. The change of the period is considered to be the effect of nonlinear soil response.



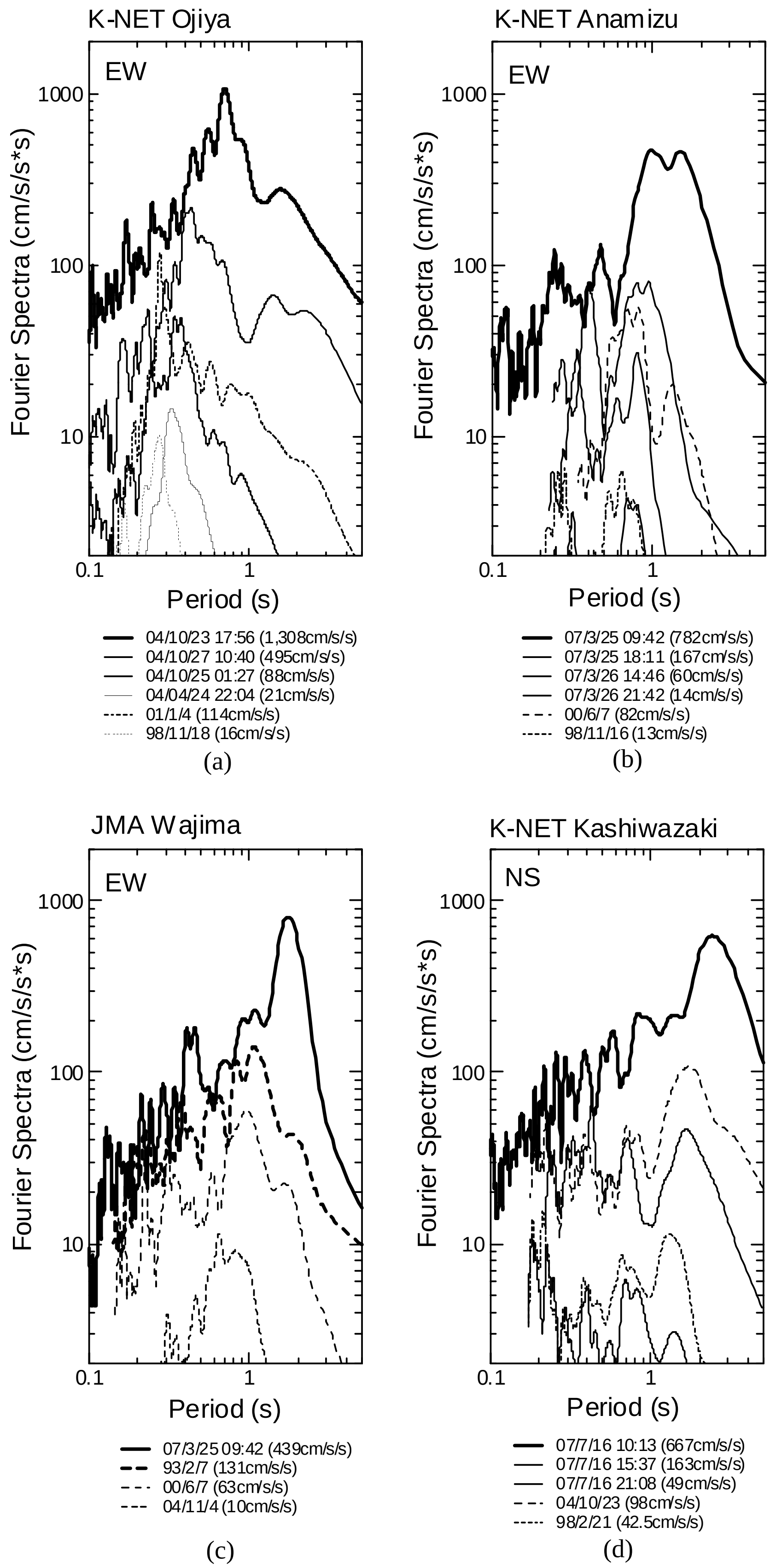
Figures 1 Seismic intensity distributions of the 2004 Niigata-ken-chuetsu, the 2007 Noto-hanto and the 2007 Niigata-ken-chuetsu-oki earthquakes



(a) acceleration time histories

(b) velocity time histories

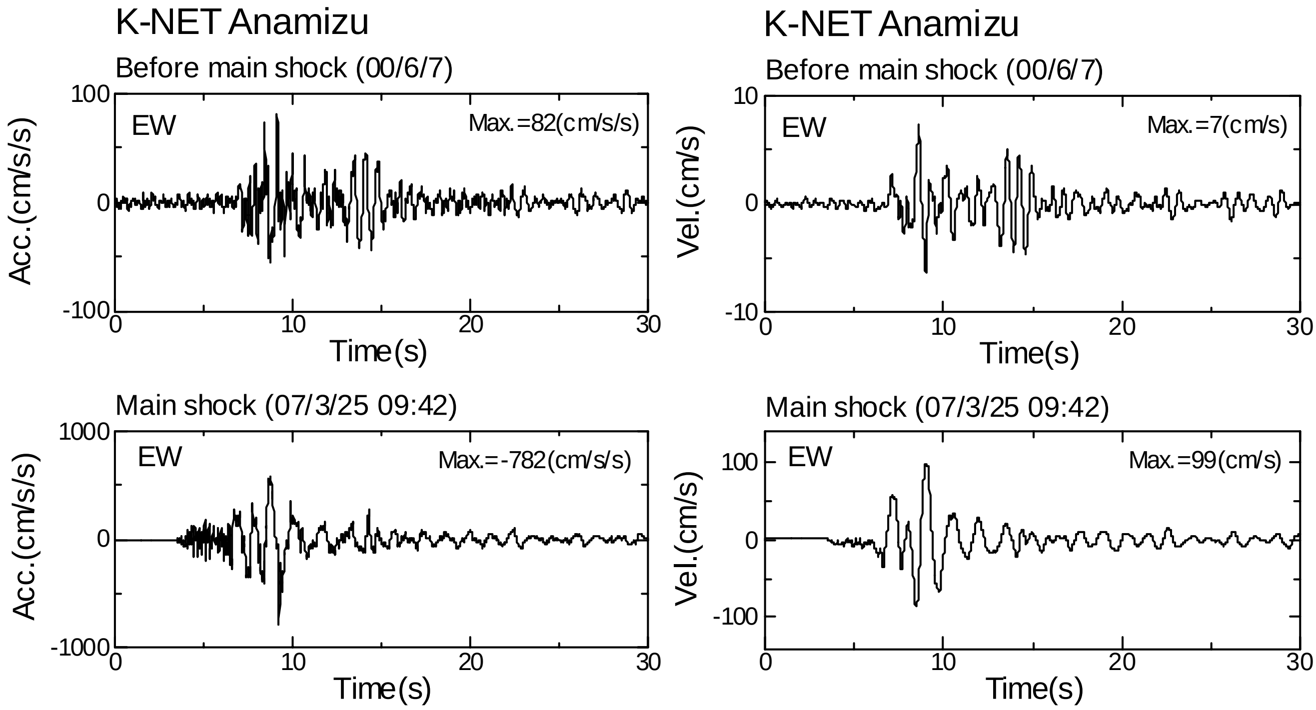
Figures 2 Strong motion records at K-NET Ojiya



Figures 3 Change of spectra with amplitude level at four sites

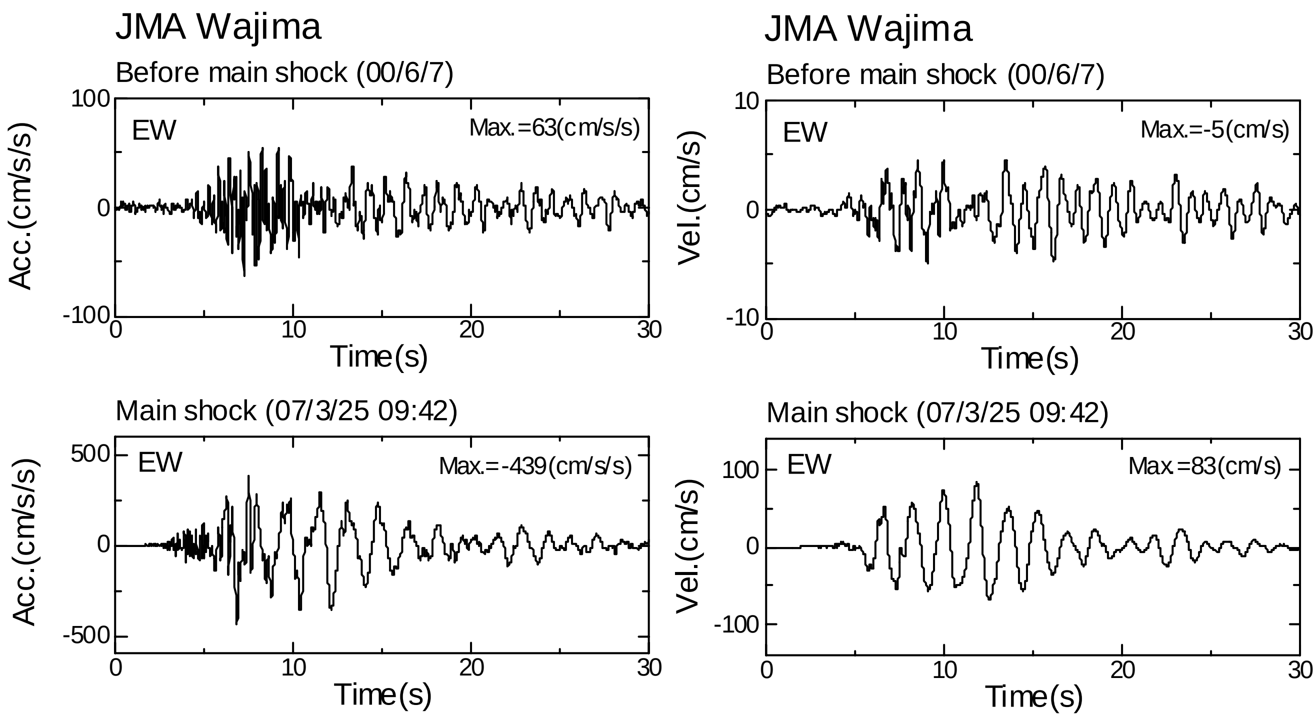
2.2. Records during the 2007 Noto-hanto earthquake

On March 25, 2007, a major earthquake (M_J6.9, M_W6.7) struck Ishikawa Prefecture. Figure 1(b) shows the seismic intensity distribution with surface projection of the fault plane. The intensity 6+ was observed at several sites. Among the sites, the JMA Wajima and K-NET Anamizu are located on soft soil deposits.



(a) acceleration time histories (b) velocity time histories

Figures 4 Strong motion records at K-NET Anamizu



(a) acceleration time histories (b) velocity time histories

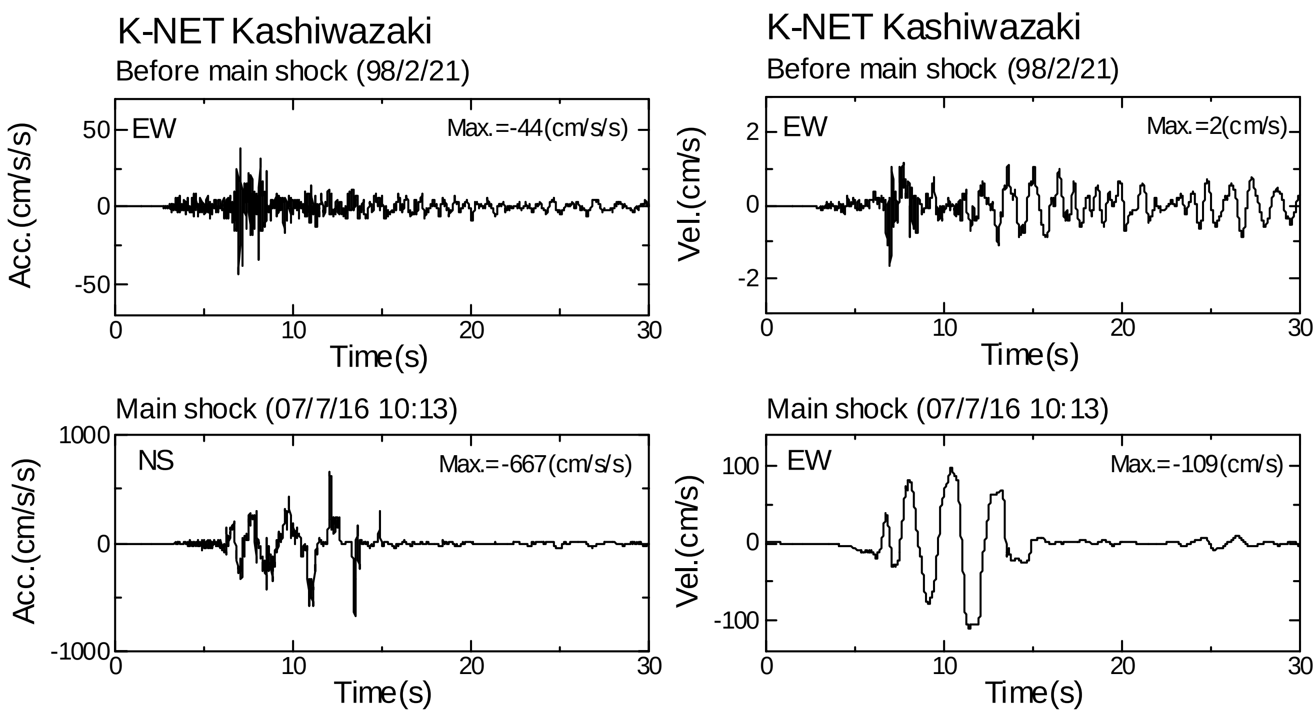
Figures 5 Strong motion records at JMA Wajima

Figures 4 and 5 show the acceleration and velocity time histories at the K-NET Anamizu and JMA Wajima sites, respectively. The upper and lower parts of the figures show the records of the smaller event and the main shock, respectively. At the K-NET Anamizu site, basement rock is overlaid by soft peat soils with thickness of about 15 m and shear-wave velocity of about 100 m/s. At the JMA Wajima site, sand stone rock is overlaid by soft silty soil deposits with thickness of about 25 m and shear-wave velocity of about 100 to 200 m/s. Figure 3(b) and (c) show the spectra of the main shock and the smaller events at the sites. At JMA Wajima, for example, the predominant period is 0.8 second for the smaller records, 1 second for the records with peak acceleration of about 100 cm/s^2, and 1.8 second for the main shock record. The amplitude dependency of the predominant period is observed in the figure.

2.3. Records during the 2007 Niigata-ken-chuetsu-oki earthquake

On July 16, 2007, a major earthquake (M_J6.8, M_W6.6) struck again Niigata Prefecture. Figure 1(c) shows the seismic intensity distribution with surface projection of the fault plane. The intensity 6+ was observed at the sites just above the fault plane. Among the sites, the K-NET Kashiwazaki site is located on sandy soil deposits with thickness of about 60 m and shear-wave velocity of about 200 m/s.

Figures 6 show the acceleration and velocity time histories at K-NET Kashiwazaki. The upper and lower parts of the figures show the records of the smaller events and the main shock, respectively. The effects of cyclic mobility of sandy soils are observed on the main shock record. Figure 3(d) shows the spectra of the main shock and the smaller events before the main shock at the site. The amplitude dependency of the predominant period is observed as well as at the other sites mentioned before.



(a) acceleration time histories (b) velocity time histories

Figures 6 Strong motion records at K-NET Kashiwazaki

3. ESTIMATION OF SHEAR MODULUS RATIO AND STRAIN

The shear modulus ratio of soils and strain level developed in surface soils are estimated from the record by a simple method (Tokimatsu et al., 1989). The soil profile is modeled as a two layer model composed of the surface soil layer with thickness of H and the bedrock. The shear wave velocity of the surface layer, Vs, can be estimated from the predominant period of the observed ground motion, T ;

$$Vs = 4\,H / T \tag{3.1}$$

The shear modulus of the surface layer, G, becomes ;

$$G = 16\,\rho\,(H/T)^2 \tag{3.2}$$

where ρ is the density of the surface soil. Letting T_0 be the predominant period at a low strain level, the shear modulus ratio is given by ;

$$G/G_0 = (T_0/T)^2 \tag{3.3}$$

Assuming that f(t) and g(t) are particle velocities of the upward and downward shear waves at the top of a soil layer, shear strain $\gamma(t, z)$ at a depth of z can be given by;

$$\gamma(t, z) = [f(t+z/Vs) + g(t-z/Vs)]/Vs \tag{3.4}$$

where t is time and Vs is the shear wave velocity determined by Eq. (1). Considering the boundary conditions at ground surface leads to the following equation:

$$v(t) = 2f(t) = -2g(t) \tag{3.5}$$

where v(t) is the particle ground velocity. Thus the shear strain developed at any depth can be given by;

$$\gamma(t, z) = [v(t+z/Vs) - v(t-z/Vs)]/2Vs \tag{3.6}$$

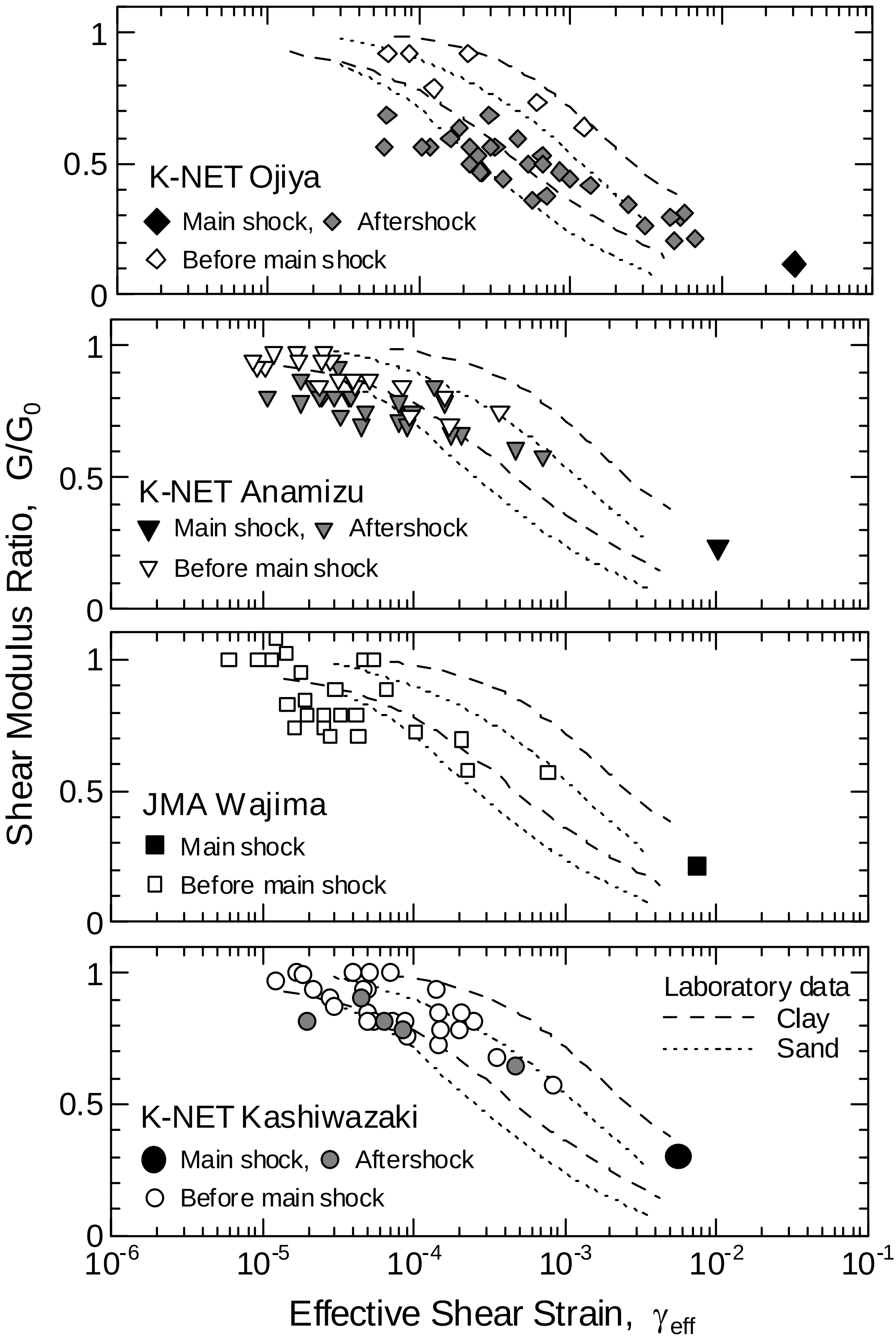
From which the maximum shear strain at any depth, $\gamma_{max}(d)$, can be determined. The effective strain in a surface soil layer, γ_{eff}, can be defined from the concept in the equivalent linear analysis (Schnabel et al., 1972);

$$\gamma_{eff} = 0.65\,[\,\gamma_{max}(d)]_{ave} \tag{3.7}$$

The simple soil profile models are constructed for the sites from the PS logging and microtremor data, as shown in Table 1. The shear modulus ratio and effective strain are estimated for each record. The relationship of the shear modulus ratio and effective strain are shown in Figures 7. In the figures, the results from the laboratory tests (Kokusho, 1987) are also plotted. For the main shock record at K-net Ojiya, the estimated strain and shear modulus ratio are 3 % and 0.1, respectively. For the main shock records at the other sites, the estimated strain and shear modulus ratio are approximately 1 % and 0.2 to 0.3, respectively.

Table 1 Soil profile models

Site	Soil	H (m)	Vs (m)	T_0 (s)
K-NET Ojiya	Peat	3	50	0.24
K-NET Anamizu	Peat	16	90	0.71
JMA Wajima	Silt	24	120	0.80
K-NET Kashiwazaki	Sand	56	170	1.32



Figures 7 Relationship between shear modulus ratio and effective shear strain

The results from the smaller events show the larger shear modulus ratio with the lower strain. It should be noted that the results for the aftershock records show smaller shear modulus ratio than that for the events before the main shock at K-NET Ojiya. This may suggest that the reduced shear modulus ratio by the main shock is not fully recovered after the earthquake. The results at four sites, however, show the general relationship that the shear modulus ratios are 0.8 to 1.0, 0.4 to 0.6 and 0.2 to 0.3 at strain levels of 0.01%, 0.1% and 1%, respectively. The dependency is consistent with the previous laboratory data. This may suggest the validity of the soil response analysis based on the laboratory data.

4. CONCLUSIONS

Nonlinear behavior of soil response is discussed using the strong-motion records from recent Japanese earthquakes. During the 2004 Niigata-ken-chuetsu (M_J 6.8), the 2007 Noto-hanto (M_J 6.9), and the 2007 Niigata-ken-chuetsu-oki (M_J 6.8) earthquakes, large amplitude strong-motion records with peak ground velocity of about 100 cm/s are observed on soft soil sites. In the Niigata-ken-chuetsu earthquake, for example, the peak ground acceleration and velocity at the K-net Ojiya site are 1.3 g and 130 cm/s, respectively. The predominant period of the record is 0.7 sec whereas those of the smaller records at the same site are 0.25 sec, indicating nonlinear behavior of soil response. The strain level developed in surface soils and shear modulus ratio of soils are estimated from the record by a simple method. The estimated strains and shear modulus ratios are approximately 3 % and 0.1, respectively. The strains and shear modulus ratios are also estimated from the large amplitude records from the other earthquakes for larger strain level and from the aftershock records for smaller strain level. The estimated shear modulus ratios are 0.8 to 1.0, 0.4 to 0.6 and 0.2 to 0.3 at strain levels of 0.01%, 0.1% and 1%, respectively. The dependency is consistent with the previous laboratory data, suggesting the validity of the soil response analysis based on the laboratory data.

ACKNOWLEDGMENTS

This study is supported by the 21st Century COE Program "Evolution of Urban Earthquake Engineering" sponsored by Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan.

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