A NEW METHOD FOR ANALYZING THE PERIOD-TIME VARIATIONS OF STRONG GROUND MOTIONS

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ABSTRACT :

The purpose of the paper is to provide a new method for analyzing the period-time variations of strong ground motions. The method uses only time domain records such as acceleration, velocity and displacement without any spectral content. It can give the time variations of the central periods of the time domain records in simple form. This paper confirms its validity by application to theoretical wavelets as well as observed motion records.

KEYWORDS: Period-time variation, strong ground motions, nonstationary spectra

1. INTRODUCTION

The time variations of spectra for strong ground motions are generally analyzed by the so-called non-stationary spectral method [Mark]. Such a method is effective to interpret the detailed time–varying characteristics of spectra involved in strong ground motions. But it is too complicated to express the time variations as a single parameter, so further simplified method should be available for some engineering purposes such as detecting pulses due to the asperity of faulting sources. The objective of this paper is to provide a new method for analyzing the period-time variation of strong ground motions. The method is developed by use of the random vibration theory as well as the complex envelope technique. It can give the time variations of the central periods of spectra merely by operating acceleration, velocity and displacement records of strong ground motions.

2. RELATION BETWEEN TIME RECORDS OF STRONG MOTIONS AND THEIR PERIOD CHARACTERS

As is well known, acceleration, velocity and displacement motions are interrelated by means of differential and/or integral operations through their spectral content. In other words, there is a possibility that we can obtain spectral information of motion records merely by investigating the interrelationships between the three motions of acceleration, velocity and displacement. One of the authors derived a theoretical relation between the characteristic periods and peak values of acceleration, velocity and displacement records based on the random vibration theory [Kamiyama]. The theory provides boundary prediction of the central periods of spectra for each motion only using by their peaks in the time records. This paper expands the theoretical relation to obtain the time variation of the central period for each motion record.

In the case of a harmonic motion with a frequency of f, the amplitudes of acceleration, velocity and displacement motions have the well known relations:

$$a / v = 2\pi f \qquad 2.1$$

$$v / d = 2\pi f \qquad 2.2$$

where a, v and d are each the amplitudes of harmonic acceleration, velocity and displacement motions. Random motions like strong earthquake motions, meanwhile, have relations analogous to Eqns. 2.1 and 2.2 in the following form [Kamiyama]:

$$E[a_{\max}]/E[v_{\max}] = 2\pi\sqrt{\bar{f}_a \bar{f}_v} \tag{2.3}$$

$$E[v_{\max}]/E[d_{\max}] = 2\pi\sqrt{\bar{f}_v \bar{f}_d} \tag{2.4}$$

where $E[]$ means the expected value, $a_{\max}$, $v_{\max}$ and $d_{\max}$ are the peak values of acceleration, velocity and displacement motions, and $\bar{f}_a$, $\bar{f}_v$ and $\bar{f}_d$ are the central frequencies of acceleration, velocity and displacement spectra, respectively.

Using Eqns. 2.3 and 2.4, Kamiyama further derived approximate point values of the central periods for acceleration, velocity and displacement spectra as follows:

$$\bar{T}_a \approx 2\pi \frac{{v_{\max}}^2}{\sqrt{{a_{\max}}^3 d_{\max}}} \tag{2.5}$$

$$\bar{T}_v \approx 2\pi \sqrt{\frac{d_{\max}}{a_{\max}}} \tag{2.6}$$

$$\bar{T}_d \approx 2\pi \frac{\sqrt{a_{\max} {d_{\max}}^3}}{{v_{\max}}^2} \tag{2.7}$$

where $\bar{T}_a$, $\bar{T}_v$ and $\bar{T}_d$ are the central periods, respectively, for acceleration, velocity and displacement spectra.

The above equations: Eqns 2.5 through 2.7 mean that the central periods of each motion spectrum can be estimated only by the peak values of acceleration, velocity and displacement motions. They were originally derived by the random vibration theory using the interrelations between the rms values and peak values of random motions. Therefore, if we can assume that the central period instantaneously defined at each time is related with an instantaneous rms value and its peak value similarly to the interrelations of these values defined for the entire duration of earthquake motions, the above equations become to the time relations depending on instantaneous variations. The key point for such time relations is how to provide the rms value and peak value of motions at each instantaneous time. In this paper, we assumed, with a valid reason, that these values are estimated approximately from the absolute values of the envelopes for motion records. That is, the time dependent values of the central periods of acceleration, velocity and displacement motions result in:

$$\bar{T}_a(t) = 2\pi \frac{Env(v(t))^2}{\sqrt{Env(a(t))^3 Env(d(t))}} \tag{2.8}$$

$$\bar{T}_v(t) = 2\pi \sqrt{\frac{Env(d(t))}{Env(a(t))}} \tag{2.9}$$

$$\bar{T}_d(t) = 2\pi \frac{\sqrt{Env(a(t)) Env(d(t))^3}}{Env(v(t))^2} \tag{2.10}$$

where, $Env(a(t)) = |a(t) + iH(a(t))|$, $Env(v(t)) = |v(t) + iH(v(t))|$, $Env(d(t)) = |d(t) + iH(d(t))|$, $H()$ is the Hilbert transform, $a(t)$, $v(t)$ and $d(t)$ are acceleration, velocity and displacement motion records, and t is time.

3. APPLICATION OF THE METHOD TO THEORETICAL WAVELETS

As shown in Eqns. 2.8 to 2.10, the present method uses the division relations of envelope amplitudes of records, so it gives possibly an abnormally large results when the denominator being extremely small. To avoid such a phenomenon, this paper applied the binominal smoothing method to the divided results [Marchand and Marmet]. In addition, the present method requires simultaneously acceleration, velocity and displacement time records in which the second and third records are numerically obtained from the first one resulting from observation. This paper uses the integral method by Boor and Bommer for the purpose of numerically integrating acceleration records.

To confirm the validity of the method, we first apply it to theoretical wavelets that consist explicitly of some fixed central periods. In this paper, we use the Gabor wavelet because it resembles time-varying amplitudes of actual earthquake motions with a unique value of central period [Marvroeidis and Papageorgiou]:

$$f(t) = Ae^{-(2\pi f_p \gamma)^2 t^2} \cos(2\pi f_p t + \upsilon) \tag{3.1}$$

where A is the peak amplitude, f_p is the central frequency, γ is a parameter controlling the duration, and υ is a parameter representing the phase.

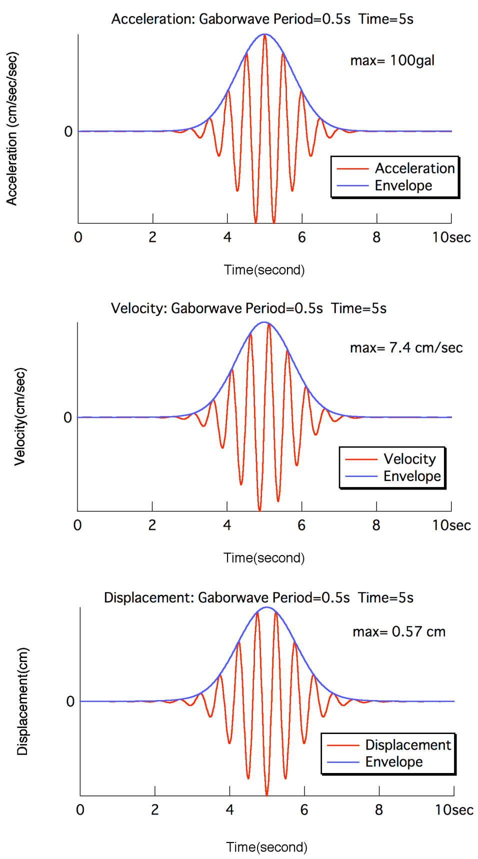

Figure 1 Analyzed Gabor wavelets of acceleration, velocity and displacement

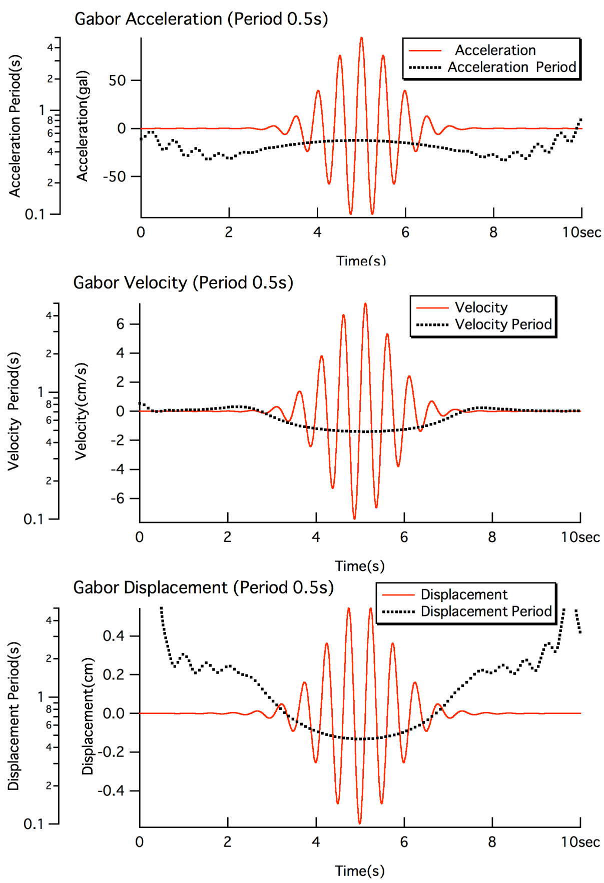

Figure 2 Time variations analyzed for the Gabor wavelets of acceleration, velocity and displacement

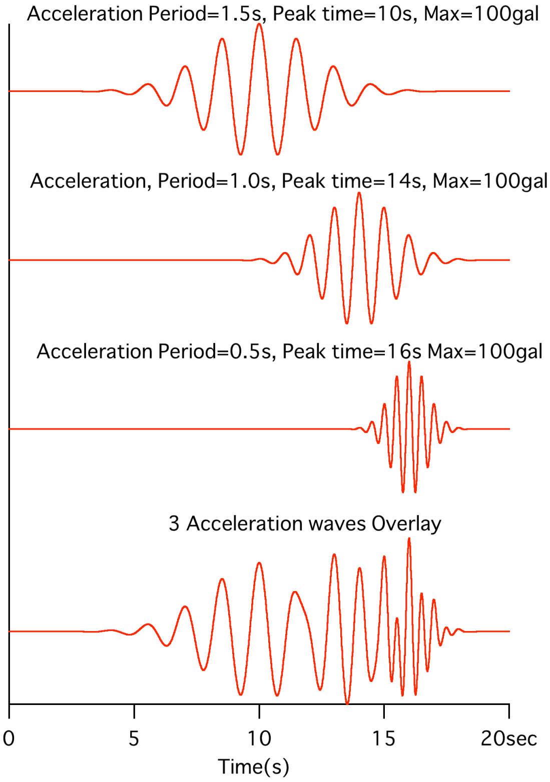

Figure 3 Gabor wavelets with different central periods and different peak times of amplitude and their overlay wavelet

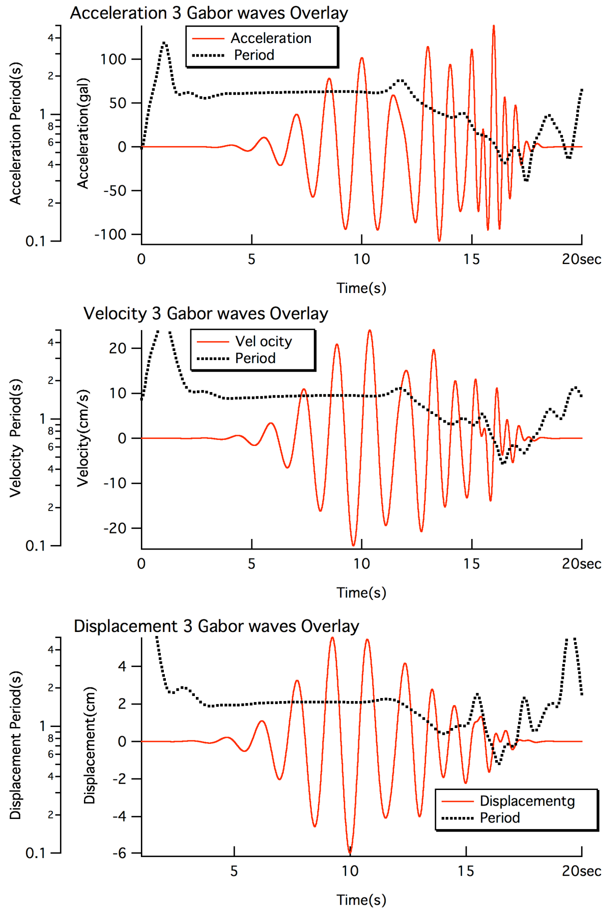

Figure 4 Period-time variations analyzed for the composite Gabor wavelet

We produced various kinds of Gabor wavelets using many parameters. In this paper, we present representative examples: Figure 1 shows Gabor wavelet acceleration, velocity and displacement in which the acceleration wave was produced with A=100 gal, fp=2Hz, γ=50, υ=0 and sampling time of 0.01 s. In Figure 1, we also show the envelope amplitudes that were obtained by the Complex Envelope Method[Fanbach]. Figure 2 shows the time variations of the central period analyzed by the present method together with the original wavelets. We can see from Figure 2 that the present method correctly analyzes the central period involved in the wavelets, though their variations are changeable according to acceleration, velocity and displacement records.

Figure 3 is another example that overlaps with three Gabor wavelets with different central periods and different peak time of amplitudes. Figure 3 shows the three original wavelets together with their composed wavelet, where their central periods, peak times and peak amplitudes are numerically given. We integrated the composed acceleration record to numerically obtain velocity and displacement records, and show their wavelets along with the analyzed time-variations of the central periods in Figure 4. Figure 4 indicates that the present method detects effectively the central periods secretly involved in the wavelets, especially the analyzed period-time results make explicit the starting times of each central period with some characteristic features of variation.

4. APPLICATION OF THE METHOD TO OBSERVED STRONG MOTIONS

We next applied our method to many observed strong ground motions. The strong ground motions observed in the epicentral region during the 2004 Niigata-Chuetsu Earthquake in Japan are exemplified in this paper. The

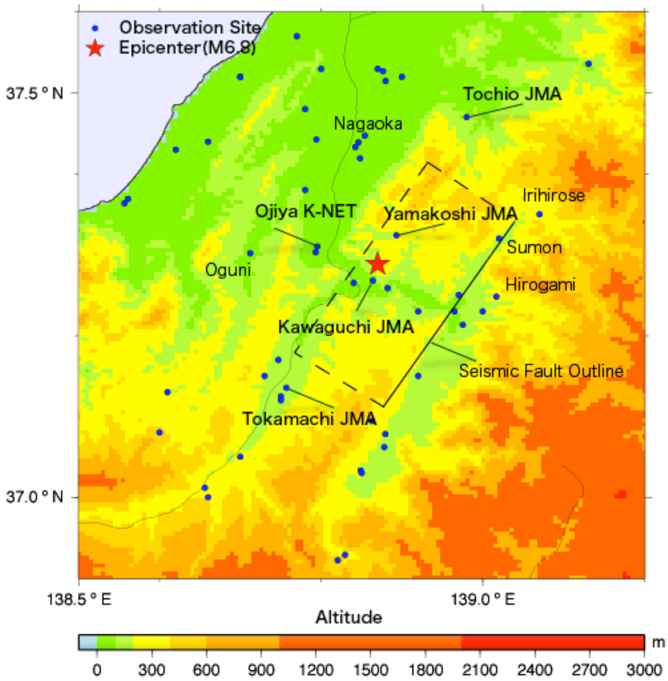

Figure 5 Ovservation sites of strong ground motions during the 2004 Niigata-Chuetsu Earthquake

earthquake, triggered on October 23, 2004 with a JMA magnitude of 6.8, caused severe damages to various kinds of structures in the source region. At the same time, it brought about valuable motion records near the epicenter, as shown in Figure 5. Figure 5 shows observation sites of strong ground motions with the epicenter. In Figure 5, the outline of the seismic fault is also shown for reference, revealing that there are many observation sites within the seismic fault area. The strong motion records observed at these sites were downloaded through the web sites such as the Kyoshin Network, K-NET and the Japan Meteorological Agency Network, JMA.

Figure 6 shows the strong ground motions observed at the Ojiya site of K-NET. The motions were recorded continually for a long time from the mainshock to many aftershocks. We applied the present method to the entire duration to show the availability of the method for such a long duration event. The analyzed time variations of the central period are shown along with the three components of acceleration records for the entire duration. The time variations of the central periods are quite complicated, especially during the aftershock phases, but some detailed comparison between the acceleration records and the time variation of central periods make it clear that the characteristic changes of central periods correspond to pulse-like events of acceleration possibly related with aftershock raptures.

Figure 7, on the other hand, shows the time variation of central periods analyzed by centering on the principal part of acceleration record due to the mainshock. It is clear in Figure 7 that the three components of acceleration have predominance in rather short period range for the initial part corresponding to P-wave while they tend to be predominant in long period range in the later phase of S-wave. Such a tendency for the central period to become longer with the passage of time is rather stronger in the N-S and U-D components of acceleration. Especially, the U-D component of acceleration has some distinctive changes in the time variation of central period at around 14.9 s, 16.9 s and 25.5 s, which seem each to coincide with the arrivals of P-wave, S-wave and Surface waves. The distinctive feature found in the U-D component of acceleration at the Ojiya K-NET site is common in the U-D component records at other observation sites in the epicentral region. Figure 8 shows the time variations of central period for the U-D component accelerations at representative sites in the epicentral

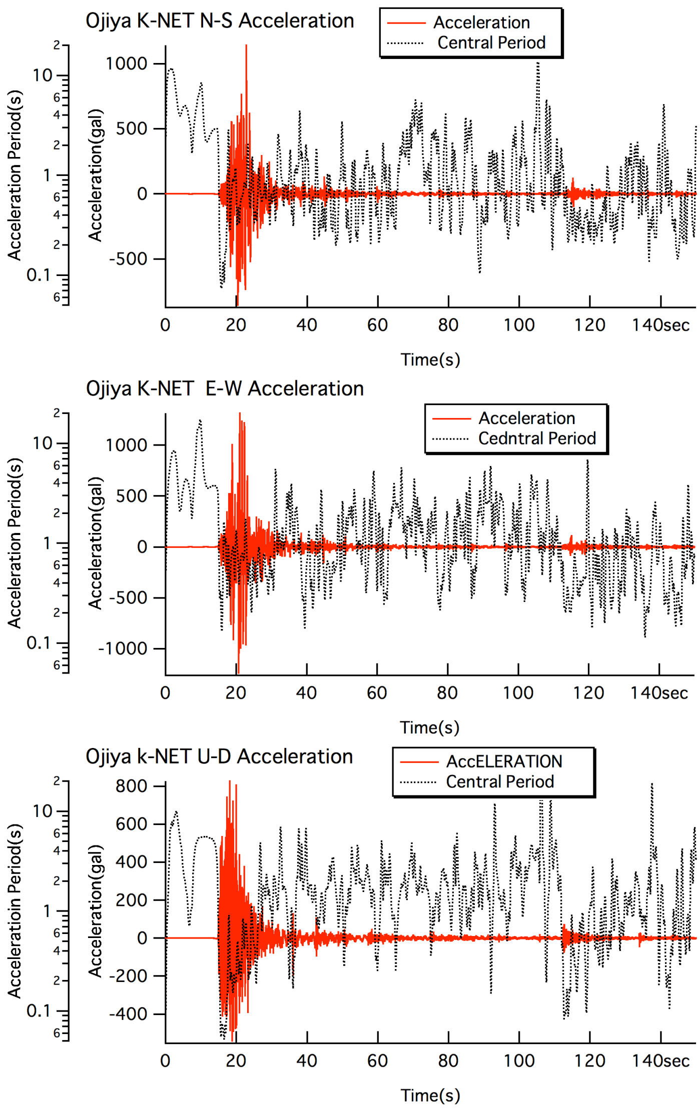

Figure 6 Time variations of central period analyzed for the strong motion records at the Ojiya K-NET site for the entite duration

region: the Ojiya K-net site, the Yamakoshi JMA site, the Kawaguchi JMA site, Tokamachi JMA site and the Tochio JMA site, all indicated in the map of Figure 5. These time variations of central period behave almost similarly to the one at the Ojiya K-NET site so that they gradually lengthen in the later phases. The phenomena found in the U-D component records might have a close relation with various causes such as faulting process of source, wave characters of propagation and so on. It should be emphasized here that the present method clearly detects characteristic variations of central period involved in acceleration records. For example, the original acceleration records demonstrate little difference in period characteristics with the passage of time, but the present method, on the contrary, analyzes the remarkable time variations of period characters in time. We can confirm the appealing point of the method by applying it to velocity component records. Figure 9 shows the time variations of central period analyzed for the velocity component of records in the U-D component at the same observation sites shown in Figure8. The velocity records themselves visibly show some clear period variations of period in time as opposed to the acceleration records, indicating the validity of the present method found in the application to acceleration.

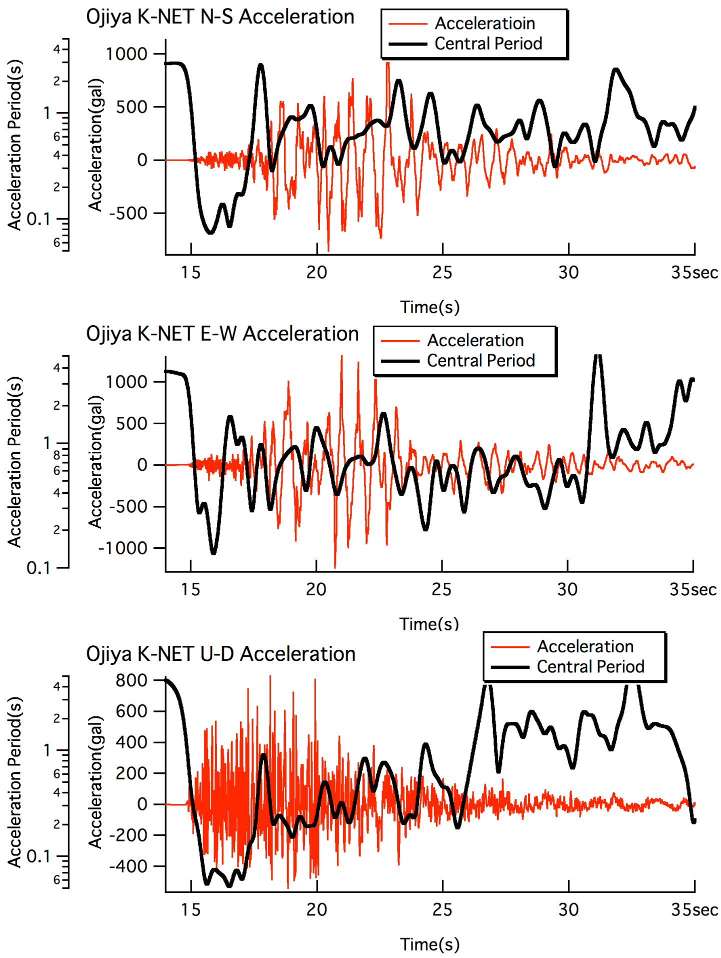

Figure 7 Time variations of central period analyzed for the strong motion records at the Ojiya K-NET site for the main motion part of duration

5. CONCLUDING REMARKS

This paper presents a new method for analyzing the period-time variations of strong ground motions. The method is simple and essential in analyzing the period-time variations of strong ground motions because it is given as a single parameter only from time-series records. The main concluding remarks of the paper are summarized as follows:

As opposed to non-stationary techniques, the method presented by this paper is simple to deal with and sophisticated to analyze the time-variations of central period of strong motions. The method was developed, as shown in Eqns.2.8 through 2.10, by use of the random vibration theory as well as the complex envelope technique. It can give the time variation of central periods of spectra for each time merely by operating acceleration, velocity and displacement records of strong ground motions. That is, the present method can give period-time variations of strong motions only based on the time domain records such as acceleration, velocity and displacement. The method was first applied to some theoretical waveforms of the Gabor wavelet to confirm its validity. The application showed that the present method could analyze the central periods involved secretly in the original Gabor wavelets. The method was also applied to strong motion records observed at the epicentral region during the 2004 Niigataken-Chuetsu Earthquake, Japan. It was shown that some wave-events related with the asperity faulting appear visually in the period–time variation of strong motions. This means that the method can analyze the faulting process of earthquake, especially the number and positions of asperities in

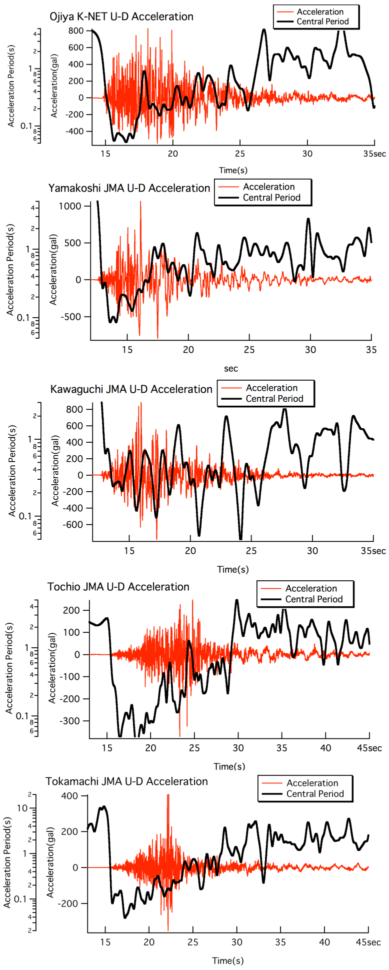

Figure 8 Time variations of central periods analyzed for acceleretaion U-D component records in the epicentral region

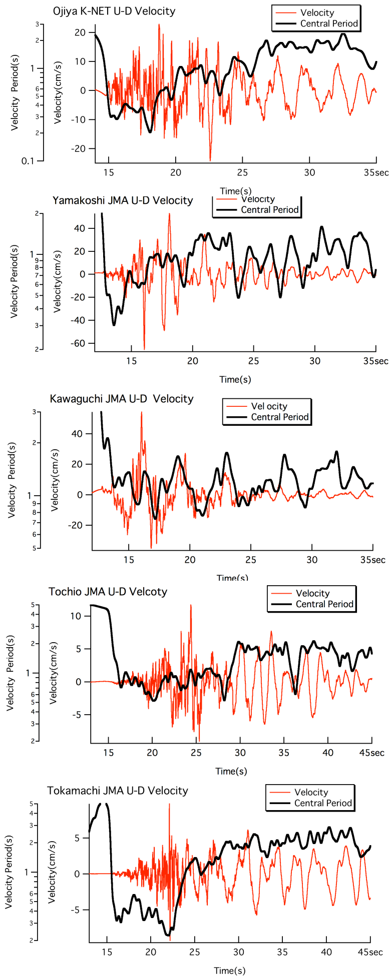

Figure 9 Time variations of central periods analyzed for velocity U-D component records in the epicentral region

seismic sources. In addition to such interesting phenomena related with source faulting, the method succeeds in detecting characteristic variations of central periods associated highly with the difference in the propagation of body waves and surface waves.

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