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BASIN-INDUCED SURFACE WAVES IN THE TOKACHI BASIN, HOKKAIDO, JAPAN

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ABSTRACT

Strong surface waves dominating in the period range of 2 to 5 sec induced at the Tokachi basin were observed for deep earthquakes. Such a surface wave is called "basin-induced surface waves". Analysis of the seismograms recorded at array stations on a basin site using the semblance and polarization technique clearly shows that later phases observed at the basin site are composed of many Rayleigh and Love waves which could be generated by the basin. Snapshots of the wavefield in a basin model calculated by the two-dimensional acoustic modeling clearly demonstrates that surface waves are generated from multiple S wave reflection within the basin. Amplitude and duration of the basin-induced surface waves observed in the Tokachi basin considerably varies with earthquakes. A comparison of observed seismograms for 20 near-by, intermediate-depth earthquakes reveals that excitation strength of the surface waves strongly depends on magnitude and on a distance to depth ratio.

KEYWORDS

Surface waves; Rayleigh waves; Love waves; semblance analysis; polarization analysis; numerical modeling; pseudospectral method

INTRODUCTION

Seismograms observed at basin sites usually have later phases with large amplitude and long duration, even if earthquakes occur at deep depth. Since such a later phase dose extensive harms to the city located on a sedimentary basin, it has long been attempted to investigate the excitation mechanism of the later phases in order to predict amplitude and duration of ground motion.

Characteristics of the later phases for big deep events observed in basins have been studied by many researchers, which suggest that the later phases are mainly composed of surface waves generated at the basin induced by conversions from body waves coming into the basin. For example, Phillips *et al.* (1993) have revealed that the later phases observed in the Kanto basin, Japan, with a predominant period of 1 sec are Love waves generated at the west edge of the basin. Hatayama *et al.* (1995) have demonstrated that the later phases observed in the Osaka basin, Japan, with amplitude larger than S waves and predominant period ranging 2 to 3 sec are Love waves excited at the eastern edge of the basin. Furumura and Sasatani (1996) have revealed that the later phases observed in the Tokachi basin with predominant period of about 2 to 5 sec are composed of many Rayleigh and Love waves excited at edges of the basin. Such a surface wave generated at the basin from body waves are called "basin-induced surface wave" (Kawase, 1993). It has also been discussed that amplitude and

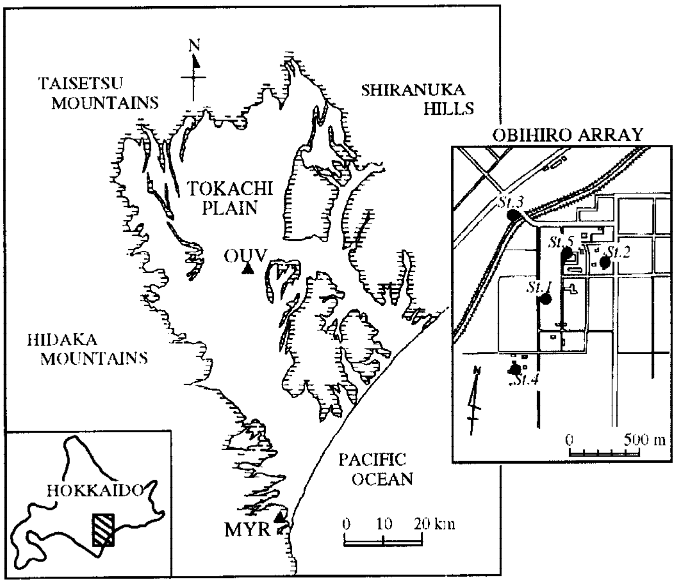

Fig. 1 Station distribution in and around the Tokachi basin. MYR is the rock site, and OUV is the basin site. OUV consists of five stations forming a small-aperture array. Hatch denotes the outcrops of the rocks.

duration of basin-induced surface waves observed at a station varies with earthquakes. Sasatani *et al.* (1992) have found that the excitation strength depends on incident angle of incoming body waves. Kagawa *et al.* (1992) have discussed dependence of amplitude of surface waves on backazimuth to epicenters which are observed in the Osaka basin. These studies demonstrates that the characteristics of surface waves generated for deep events may considerably depend on conditions of source, path and basin structure.

The purpose of the present study is to investigate the excitation characteristics of basin-induced surface waves observed in the Tokachi basin. We show characteristics of seismograms observed at a basin site to see site effects of the Tokachi basin on seismograms, comparing with seismograms observed at a rock site. Wave types of later phases observed at the basin site are estimated by a semblance and polarization analysis and physical properties of the surface wave generation are examined by numerical modeling for acoustic wavefield using the pseudospectral method. We also discussed source and path effects on surface wave generation in the basin, by comparing the seismograms observed at the basin site for 20 near-by, intermediate-depth earthquakes.

OBSERVED SEISMOGRAMS IN THE TOKACHI BASIN

The Tokachi basin located in the south-east of Hokkaido, Japan, have thick sediments of terrace deposits, with a size of about 100 km (north-south direction) by 50 km (east-west direction). Matsushima (1990) have estimated S-wave velocity structure in the basin using microtremors, which shows sediment layers with low S-wave velocity of about 1 km/sec have maximum thickness of 2600 m over the basement with S-wave velocity of about 3 km/sec, producing large velocity contrast at the sediment-basement interface.

We have carried out seismic observations in the Tokachi basin at a basin and rock station to see site effects of the Tokachi basin (Fig.1). The basin site, OUV, is located near the central part of the basin and the rock site, MYR, is at the southern edge of the basin. The distance between two stations is about 70 km. In order to investigate wave types of observed waves at OUV, we also installed a small seismic array consisting of 5 stations with the station OUV in the center. A strong-motion seismometer with a flat velocity response in the frequency range of 0.025 to 20 Hz has installed at each station, and the seismic signals are recorded by digital recorders with a sampling frequency of 50 Hz. We could record many seismograms for more than 150 earthquakes from July 1991 to July 1993.

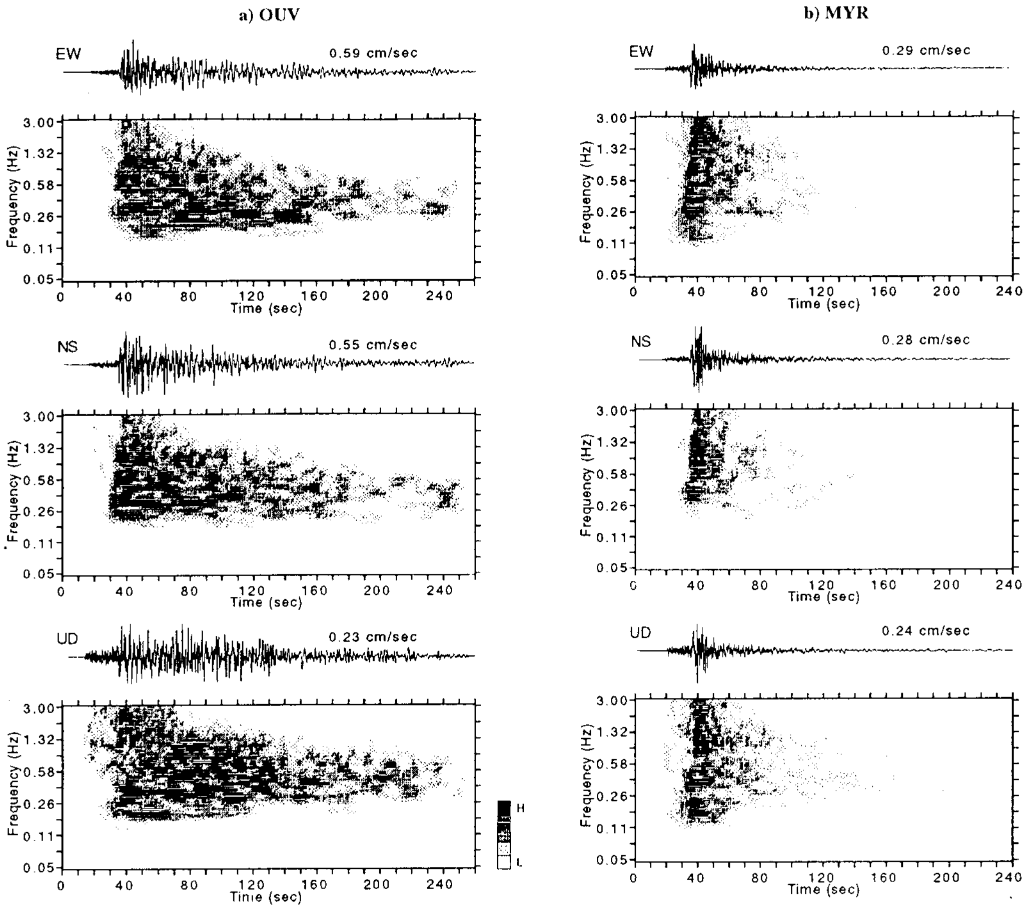

Fig. 2 Velocity seismograms and their instantaneous amplitude spectra for the East off Aomori earthquake. Maximum amplitude of the seismograms is labelled above each trace. The spectra are expressed by logarithm of the ratio of the amplitude to the maximum amplitude and displayed by 5 levels of every -6 dB.

Figure 2 illustrates seismograms of ground velocity with instantaneous amplitude spectra (Dziewonski *et al.*, 1969) for the East off Aomori earthquake (June 12, 1992, M = 6.3, H = 65 km) at OUV and MYR, which clearly show difference in site effects between two stations; The seismograms observed at MYR are very simple and mainly composed of S waves, while the seismograms at OUV are very complex, contaminated by later phases of large amplitude and long duration whose predominant frequency is about 0.4 Hz. This contrast in seismograms may mean that later phases observed at OUV are amplified or excited by the Tokachi basin. We can also find that duration of later phases at OUV on vertical components is longer than the duration on horizontal components and that predominant frequency on vertical components is slightly higher than the frequency on horizontal components. It should be noted that these later phases are also observed at OUV for other deep earthquakes (Sasatani, 1987; Furumura and Sasatani, 1996).

WAVE TYPES OF LATER PHASES OBSERVED AT A BASIN SITE

In order to confirm that the later phases observed at OUV are basin-induced surface waves, we will examine apparent velocity and polarization characteristics of the later phases. We analyze seismograms for three big earthquakes observed at the array stations in which later phases can be seen with large amplitude and long duration (see Furumura and Sasatani, 1996). The seismograms are produced by a Gaussian filter with a central frequency of 0.4 Hz to analyze the surface waves dominant in the frequency.

Figure 3 shows apparent velocity and semblance value of vertical-component seismograms for the East off Aomori earthquake obtained from semblance analysis (Neidell and Taner, 1971). Semblance values for 30 percent of total time windows are greater than 0.9; The high semblance value means that coherent waves are

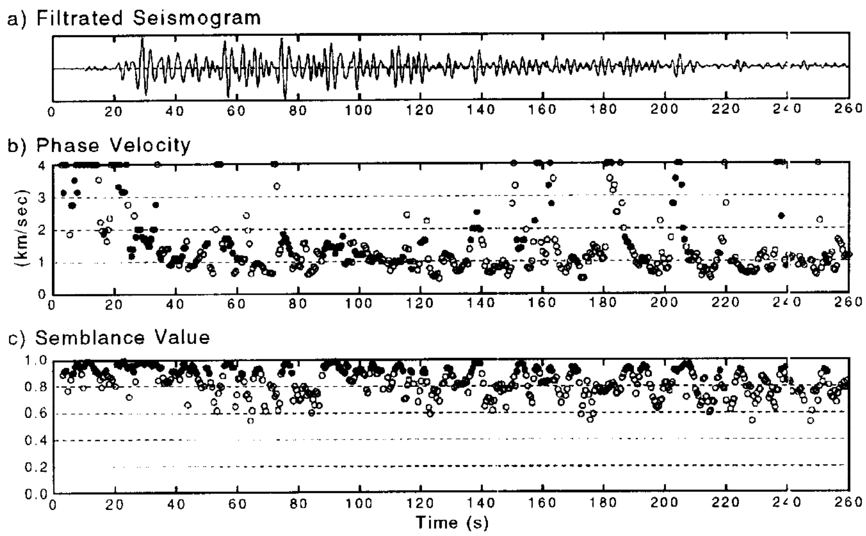

Fig. 3 Apparent velocities (*middle*) and semblance values (*bottom*) obtained from semblance analysis of the vertical-component seismograms for the East off Aomori earthquake. Top shows one of the vertical-component seismograms in the array.

observed in the seismic array. For these coherent waves, apparent velocity of P-coda and S waves is greater than 4 km/sec while apparent velocity of S-coda is about 1.3 km/sec. The low apparent velocity of later phases is good agreement with theoretical phase velocity of the Rayleigh waves with frequency of 0.4 Hz, calculated using S-wave velocity model at OUV (Matsushima, 1990), and in consequence we can conclude that the later phases observed at OUV are mainly composed of many Rayleigh waves.

On horizontal components, Rayleigh and Love waves may be observed in the seismograms. Here, we try to find Love waves in later phases on horizontal components using polarization analysis (Vidale, 1986) with the semblance analysis. Few Love waves could be discerned from high linearity of wave motion and perpendicularity between the polarization and arrival directions of the waves. Obtained phases velocity of the Love waves are about 1.1 km/sec and are good agreement with theoretical phase velocity of Love waves at OUV.

Arrival directions of most of the Rayleigh waves observed at OUV, obtained from the semblance analysis, are quite different from backazimuth to the epicenter, which suggests there are many generation area of Rayleigh waves surrounding OUV. The large difference of arrival directions of the Rayleigh waves from the backazimuth may be explained by three-dimensional heterogeneity of the Tokachi basin.

EXCITATION MECHANISM OF BASIN-INDUCED SURFACE WAVES

In order to gain further insights into the understanding the surface wave generation in the basin, we undertake a numerical modeling for two-dimensional acoustic wavefield in a sedimentary basin using the pseudospectral method (e.g., Furumura and Takenaka, 1996). A sequence of wavefield snapshots are utilized to see seismic wave propagation within the basin in time and space (Furumura *et al.*, 1993).

The model we employed here is a two-dimensional basin model having a width of 36.4 km and thickness of 2.0 km, consisting of a low-velocity sedimentary layer of an S-wave velocity of 0.8 km/sec and density of 2.0 g/cm^3, over the basement of a homogeneous half-space with an S-wave velocity of 3.0 km/sec and density of 2.3 g/cm^3. A plane SH-wave having a source time function of Gaussian function with a predominant frequency of 0.4 Hz is vertically impinged on the basin.

The sequence of wavefield snapshots shows that the SH wave is repeatedly reflected between the free-surface and the sediment-basement interface (Fig.4). The energy of the SH wave gradually decreases by leaking away from the sediment-basement interface and horizontal slowness gradually increases. In the T=7.3s snapshot, we can see the plane S-wave travelling almost horizontally, which propagates towards the center of the basin along the free surface. The wave propagating along the free-surface with the energy concentrating almost near the free-surface is a Love, because the wave have vertical seismic wavefront and its amplitude decreases with depth almost decaying at the sediment-basement interface. Synthetic seismograms of ground velocity motion are displayed in Fig.5 which also shows a Love wave generated at the east edge of the basin and propagating towards west. The Love wave appeared in the seismograms has a predominant frequency of about 2.5 sec and is dominant in the seismograms with the large amplitude as almost the same as the S wave. Phase velocity of the Love waves is changed gradually in the range of 0.8 to 1.3 km/sec according to sedimentary thickness at the sites.

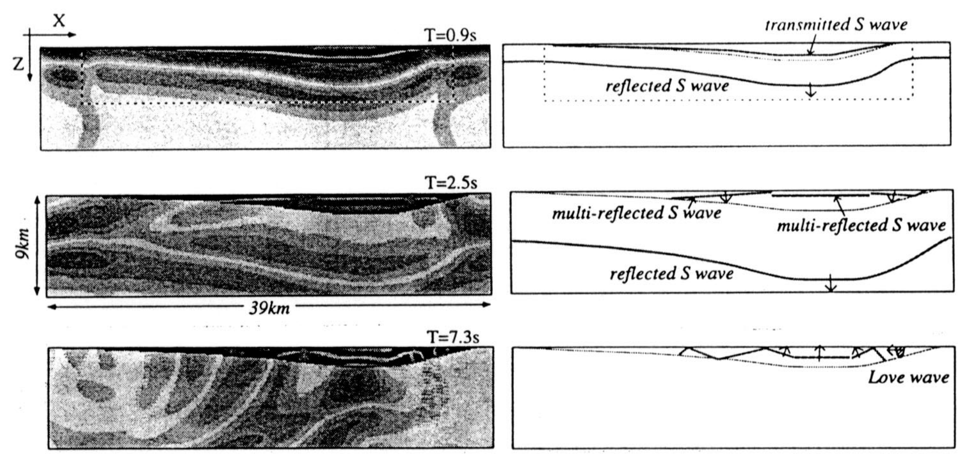

Fig. 4 Snapshots (*left column*) and schematic wavefront of main phases (*right column*) of SH-wavefield for vertical incidence of a plane S wave. They are enlarged for the region shown in the T=0.9s snapshot by a rectangle of broken line.

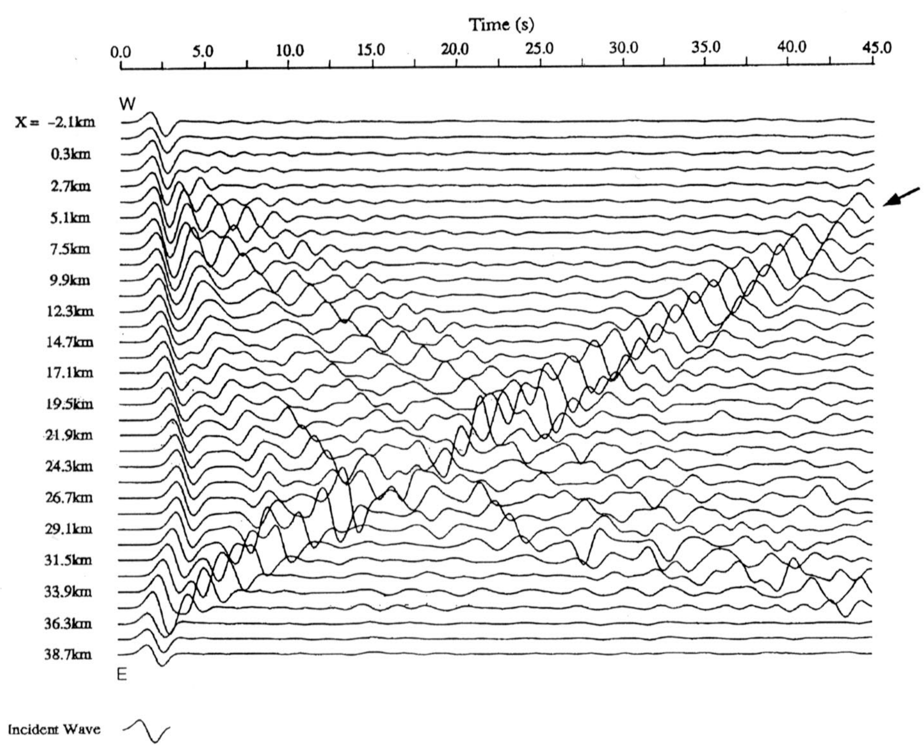

Fig. 5 Synthetic seismograms at stations on free surface. A trace in the bottom of the figure indicates incident waves. An arrow denotes excited Love wave.

It should be noted that excitation strength of basin-induced surface waves in the Tokachi basin considerably varies with events. In order to see the properties of the excitation strength, we compare the seismograms observed at OUV and MYR for 20 near-by, intermediate-depth earthquakes (Table 4-1 in Furumura (1994)). These earthquakes have magnitude range of 4.1 to 7.8, epicentral distances of less than 220 km, and focal depth of 40 to 120 km. Incident angle of impinging S waves into OUV is less than 26 degree, for which body waves are considered to be dominant in the incoming waves into the basin.

Figure 6 compares the seismograms and their instantaneous amplitude spectra at MYR and OUV for the 1993 Kushiro-Oki mainshock (Jan. 15, 1993, M = 7.8) with those for its aftershock (Feb. 4, 1993, M = 4.9), which shows the difference in excitation strength of the basin-induced surface waves. We can find that a large later phase is observed at OUV for the mainshock, while such a phase is not observed and S waves are dominant at OUV for the aftershock. Since hypocentral locations are nearly the same between two earthquakes, the difference in the later phases may be caused by difference in magnitude. On the other hand, the seismograms and spectra at MYR clearly show that only S wave is dominant for both earthquakes, but that S wave for mainshock has much lower frequency contents than that for aftershock, reflecting the difference in magnitude. Then we will examine the magnitude effects on the excitation strength of basin-induced surface waves using the lowest frequency of S wave observed at MYR (denoted by *LF*) for which instantaneous spectral amplitude is larger than -12 dB of its maximum.

Variance in the excitation strength of the basin-induced surface waves cannot be explained by the magnitude effects only. For example, later phases observed at OUV for the East off Aomori earthquake show long duration of about 120 sec, while those for the 1993 Kushiro-Oki mainshock have relative short duration of about 80 sec (Fig.7), although the magnitude of the former event is smaller (M6.3) than that of the latter event (M7.8) (In this study, excitation strength of basin-induced surface waves are defined by duration of later phases for which instantaneous spectral amplitude is large in the frequency range of 0.26 to 1.0 Hz). Remarkable difference between two earthquakes is in radiation pattern of the sources, path and incident angle of incident S waves on the basin. The difference in the radiation pattern of sources and the ray path affects of the incident S waves rather than excitation of surface waves within the basin, and those effects on the incident S waves may be

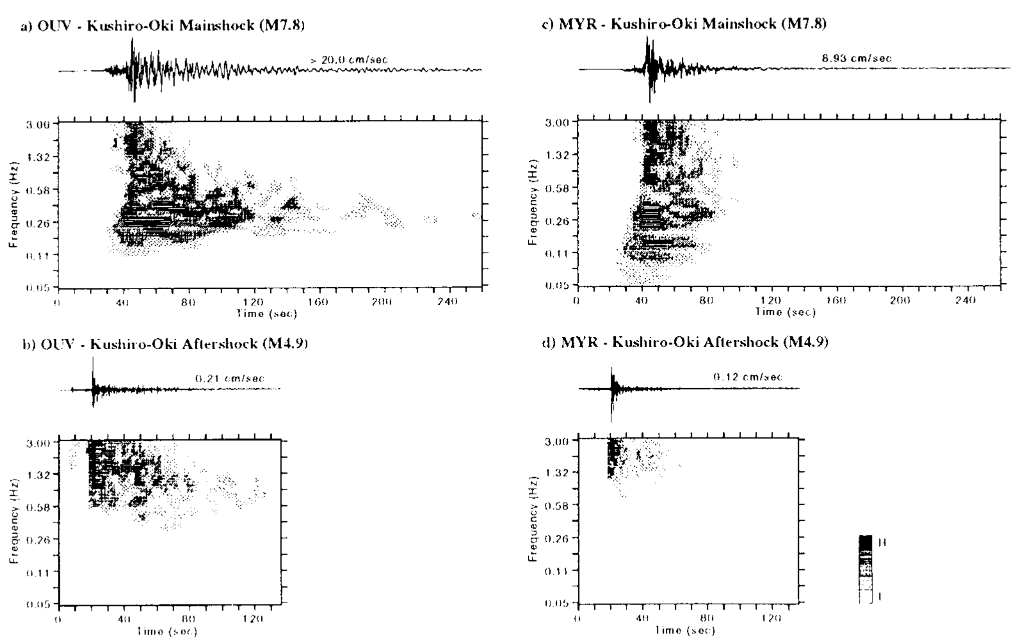

Fig. 6 Observed seismograms and their instantaneous amplitude spectra on east-west components at OUV and MYR for the 1993 Kushiro-Oki earthquake ((a) and (c)) and for its aftershock ((b)and (d)).

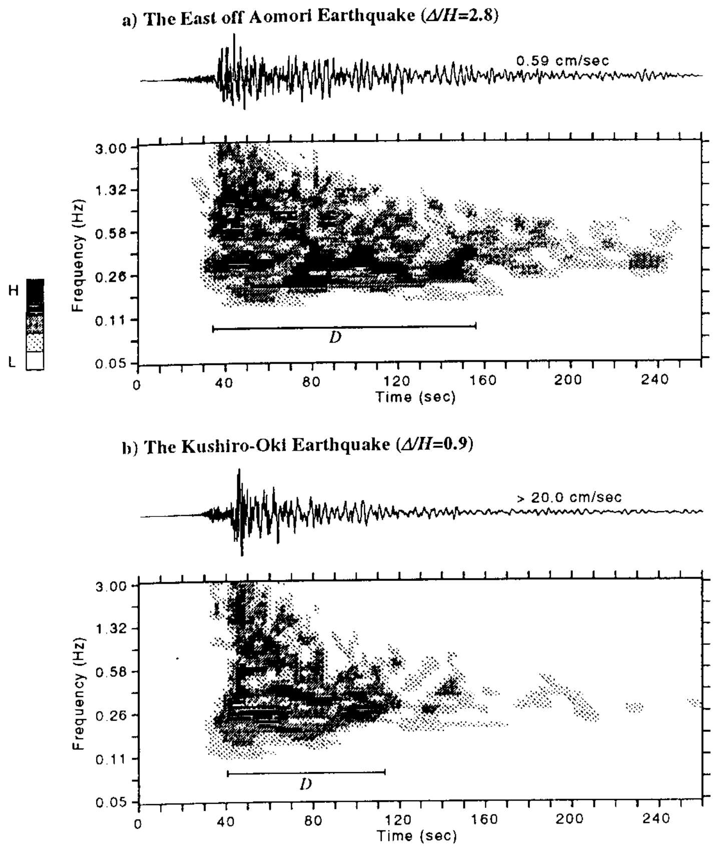

Fig. 7 Observed seismograms and their instantaneous amplitude spectra on east-west components at OUV. (a) The East off Aomori earthquake and (b) the 1993 Kushiro-Oki earthquake. Duration of later phases (D) is defined as time interval in which instantaneous spectral amplitude is large.

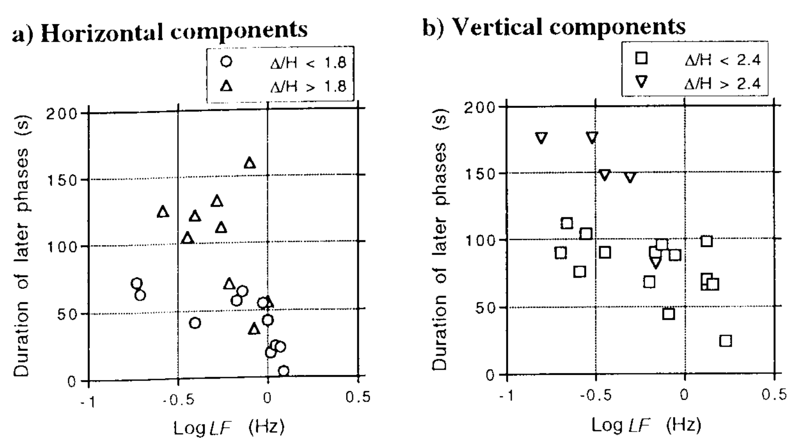

Fig. 8 Relation between two parameters, *LF* and Δ/*H*, and duration of later phases. (a) Horizontal components. (b) Vertical components.

included in *LF*. A ratio of epicentral distance to focal depth (Δ/*H*) standing for the incident angle is 2.8 for the East off Aomori earthquake and 0.9 for the 1993 Kushiro-Oki mainshock. Then we can consider that the discrepancy in the duration of later phases for those two events are caused by the incident angle the incoming S waves into the basin.

The relation between two parameters, *LF* and Δ/*H*, and duration of later phases examined for 20 selected earthquakes reveals that the duration of later phases becomes long for low *LF* and large Δ/*H* (Fig.8). Later phases on horizontal components becomes very long for Δ/*H* of larger than 1.8 and for *LF* of lower than 0.6 Hz, while the phases on vertical components becomes very long for Δ/*H* of larger than 2.4 and for *LF* of lower than 0.5 Hz. The dependence of excitation strength of basin-induced surface waves on *LF* and Δ/*H* suggests that magnitude and hypocentral locations of the earthquakes are very important factors to predict ground motion at basin sites.

RESULTS

In this study, we clarified that later phases observed at a basin site in the Tokachi basin are mainly composed of Rayleigh and Love waves using the semblance and polarization analysis of the observed seismograms at array stations which are located at the basin site. Snapshots and synthetic seismograms calculated from two-dimensional numerical modeling of acoustic wavefield using the pseudospectral method clearly demonstrates that Love waves are excited at edge of the basin from multiple SH-wave reflections. Many seismograms recorded at the basin clearly show that the amplitude and duration of later phases observed at the basin site strongly depends on the lowest frequency of instantaneous amplitude spectra of S waves observed at a rock site and on a distance to depth ratio Δ/H.

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