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SEISMIC RESPONSE OF SOFT SOIL IN KAMINOKUNI, HOKKAIDO, JAPAN

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ABSTRACT

We study the seismic response of soft soil in Kaminokuni basin, southwest of Hokkaido, by using the reference site technique. The data are strong and weak motion records from aftershocks of the 1993 southwest off Hokkaido earthquake (M_{JMA} 7.8). The S-wave spectral ratios of the soil site to the rock site is about 10 over the frequency range from 0.5 to 1 Hz, about 3 from 4 to 10 Hz and less than 1 at frequencies above 10 Hz. The spectral ratio for strong motion ($\sim$ 120 cm/sec^2) is considerably smaller than those for weak motions ($\sim$ 10 cm/sec^2). This suggests that a non-linear response of soft soil occurred during the strong motion.

Based on well-logging results, one dimensional responses are calculated both in the frequency and time domains. The theoretical frequency domain response is much smaller than observed spectral ratios at frequencies below 4 Hz, but greater at frequencies above 10 Hz. A comparison between observed and synthetic seismograms shows that the observed later phases after S-wave are not explained. These later phases may be secondarily generated waves by a complex three dimensional structure. The observed spectral ratios include effects of these waves and thus cannot be explained by one dimensional response.

KEYWORDS

Soft soil; Seismic response; Non-linear response; One dimensional simulation; Reference site technique.

INTRODUCTION

A large earthquake (M_{JMA} 7.8) occurred southwest off Hokkaido on July 12, 1993. The extensive damage was caused, mainly due to tsunami, in Okushiri Island and southwestern coast of Hokkaido by this large event. Liquefaction also caused damage to many artificial structures in coastal parts of southwest Hokkaido.

We carried out a temporal strong motion observation array after the main shock. KNK station among the array is the special observation site in the Kaminokuni soft basin where liquefaction was observed everywhere during the main shock. KKJ station on the rock site is used as the reference site to study the seismic response of soft soil at KNK.

Recently, artificial fills are widely extended and many large structures such as skyscrapers, bridges, and storage tanks are built there. Because these surface soils are very soft, the amplitudes of seismic waves may be extensively amplified. In this sense, it is very important to know the seismic response of such soft soil.

As well as site amplification, non-linear ground response during strong shaking is in our concern. Non-linear

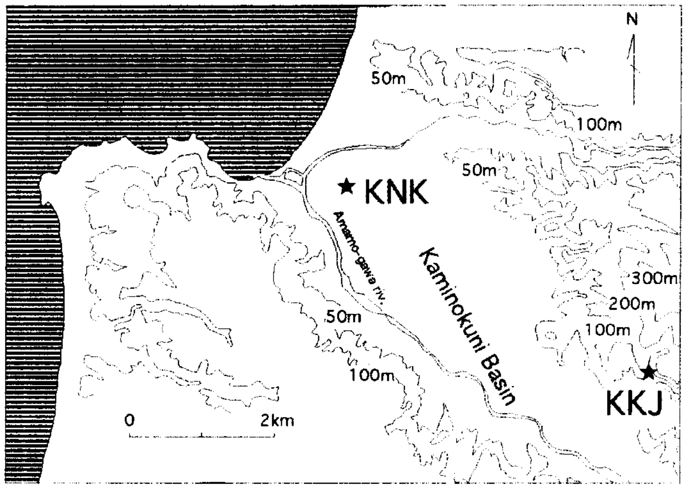


Fig. 1. Local map of Kaminokuni region. Asterisks represent observation sites: KNK is on the soft soil site and KKJ, on the hard rock site.

response is also of the most important issues to be investigated for improvement of strong motion prediction procedures (Aki, 1993). Recently this issue is being discussed by using strong motion records (*e.g.*, Beresnev *et al.*, 1995).

This article analyzes our aftershock recordings to study the site response of soft soil. We investigate the dependence of ground shaking magnitude on the response. Finally, we calculate the theoretical one dimensional response based on well-logging results and compare them with observed ones.

DATA

The Kaminokuni basin is a small, soft sedimentary basin with an area of 2 km x 5 km where liquefaction was observed everywhere during the main shock. KNK station is located on Quaternary alluvium near the mouth of Amanogawa river (Fig. 1). The well-logging up to a 80 m depth was conducted at KNK in 1994 (Nagumo, 1995). According to the core data, the alluvium consists of alternations of strata of sand and silt, whose N-values by penetration tests are less than 10 in the depth range from 0 to 50 m. Below there, it mainly consists of coarse sand with N-values of about 40. Tertiary mudstone emerges at the depth of 67 m and it continues until the deepest depth (80 m). The groundwater table is at the depth of 1.6 m. On the other hand, KKJ station, about 5 km southeast from KNK, is located on Pre-Tertiary hard rock which consists of slate, sandstone and chert. This rock is thought to be the basement in this district.

At KNK, the accelerograph, PDR-1 (Kinemetrics), has an obsevable range of (+/-) 2g with gain-ranging amplifiers (x1/4, x1/16). A tri-axial force balance accelerometer is used as a sensor. The A/D converter of 12 bits/word is used and the recording device is a cassette magnetic tape. The time code generator is automatically adjusted by receiving the radio time signal (NHK) of every one hour. At KKJ, the velocity-type strong motion seismometer, VS-1 (Tokyo Sokushin Co.), is used. A recorder, PDAS-100 (Teledyne), has an obsevable range of (+/-) 4 cm/sec. Its A/D converter is 16 bit/word and recording device is ROM. In this station, time code is adjusted temporary during data acquisition. Because of difference of measured seismic data at each station, we must conduct differential or integral calculus to each of them to compare.

The aftershocks observed at both stations are the largest aftershock with a magnitude of 6.3 and its aftershocks in the magnitude range from 3.8 to 4.1, which occurred east apart from the major aftershock area (Fig. 2, Table 1). The average epicentral distance is about 25 km at KNK and 30 km at KKJ. Since two stations, KNK and KKJ, have approximately the same direction from the epicenters, the effect by seismic source radiation pattern is thought to be nearly equal for both stations.

CHARACTERISTICS OF OBSERVED RECORDS

Figure 3 shows the transverse component accelerograms observed at both stations. The waveforms of M6.3

Table 1. List of earthquakes observed at both KNK and KKJ sites.

No.	Date	Time	Latitude	Longitude	Depth(km)	Magnitude
1	93/8/8	4:42:43.6	41.96°N	139.89°E	24	6.3
2	93/8/8	7:11:17.6	41.97°N	139.89°E	21	4.1
3	93/8/8	9:57:37.5	41.95°N	139.89°E	19	3.8
4	93/8/12	10:02:14.6	41.98°N	139.85°E	15	4.1
5	93/8/15	18:18:14.2	41.92°N	139.88°E	21	3.9

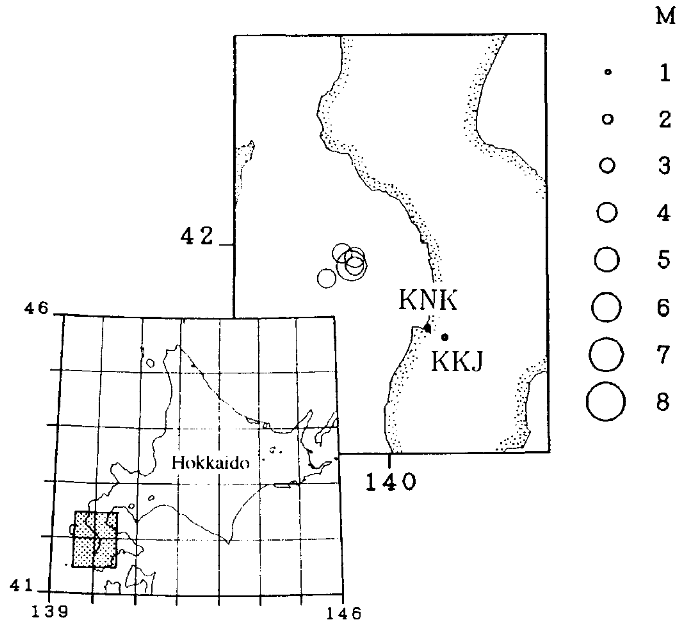


Fig. 2. Epicentral distribution of earthquakes used in this study.

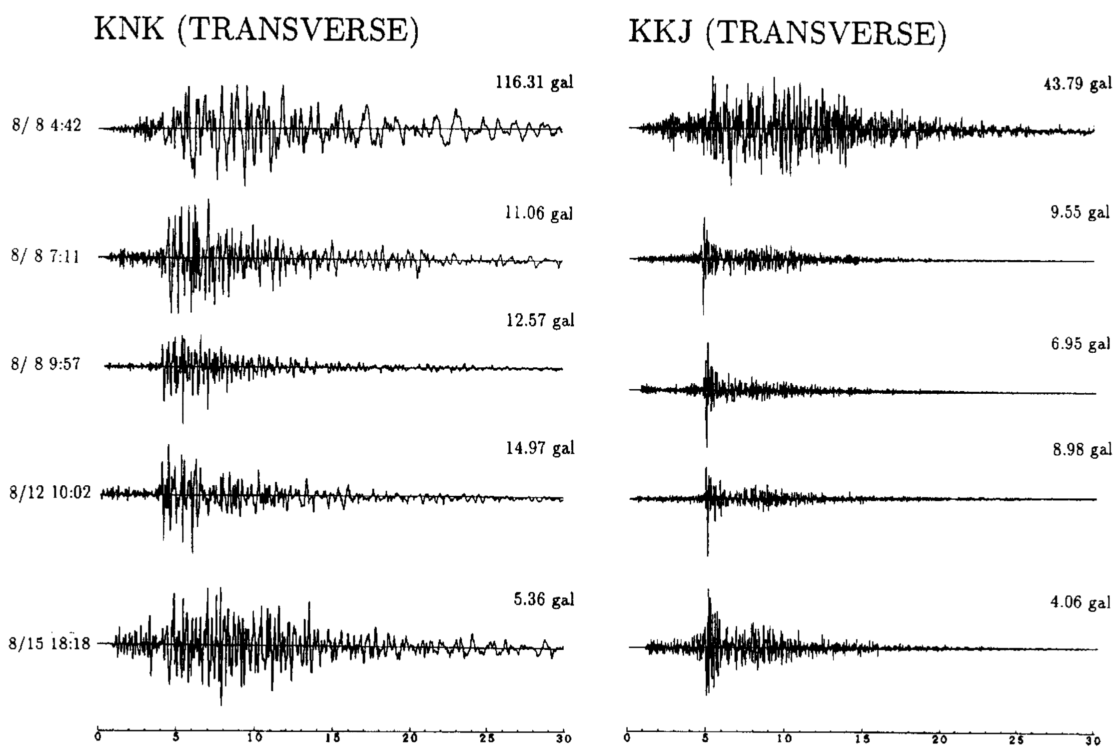
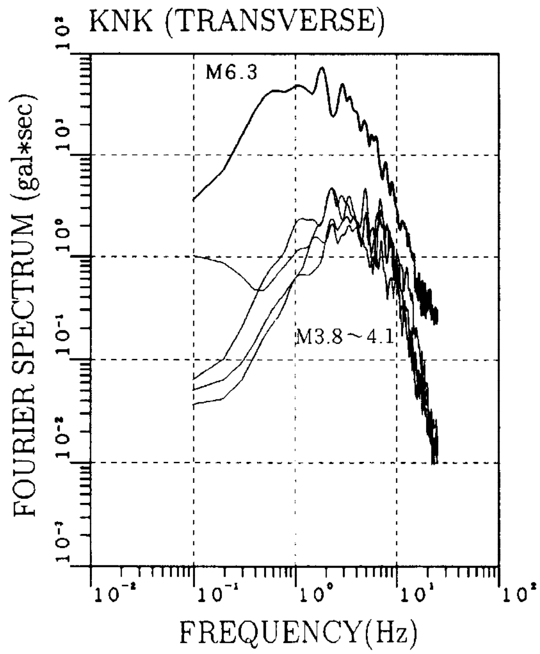


Fig. 3. Transverse component accelerograms. The left column shows KNK seismograms and the right column, KKJ seismograms.



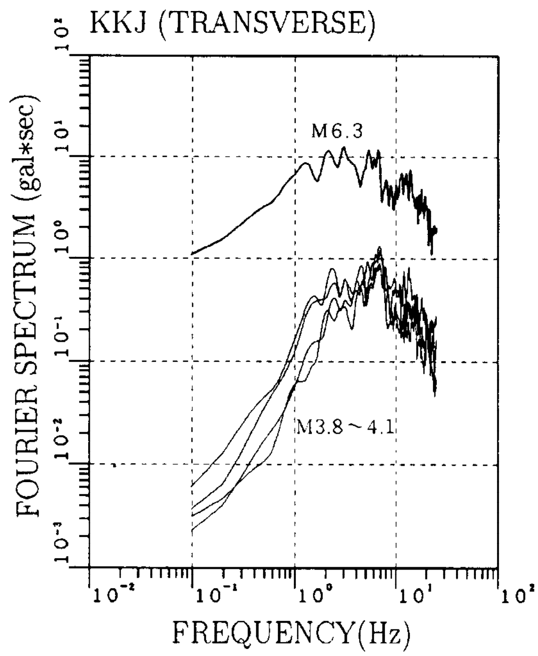


Fig. 4. Fourier amplitude spectra of transverse components at KNK (left) and KKJ (right). Bold curves represent the spectra of M6.3 event (8/8 4:42) and thin curves, those of small events.

event at both sites are different from others; the duration of strong shaking is much longer. This is because M6.3 event is a multiple shock (Iwata *et al.*, 1993). In later part, waves with a frequency of about 2 Hz are dominant at KNK, but not at KKJ. Waveforms for weak motions (M3.8 ~ 4.1) are much different between two stations. Maximum amplitudes at KNK are two or three times larger and the durations of strong shaking following S-wave are much longer than those at KKJ. The shapes of S-wave part at KKJ are impulsive and followed by small amplitude, high frequency waves for 5 seconds. On the other hand, waveforms at KNK show strong shaking for more than 10 seconds after S-wave and entirely lack of high frequency components seen in those at KKJ.

Figure 4 shows S-wave Fourier amplitude spectra of transverse accelerograms of 10 seconds duration at both stations. For weak motions, they are low reliance below 0.5 Hz because of instrumental character. Above 0.5 Hz, they are in good agreement within a factor of 2. Shapes of spectra approximately agree with that of "ω-square" model at both sites; corner frequencies are about 2 Hz and flat levels continue above that frequency. However, the locations of f_{max} are different between two stations; about 7 Hz at KNK and 12 Hz at KKJ. This suggests site-controlled f_{max} (Hanks, 1982). Above these frequencies, spectra fall off at both stations. The ways of decay are much stronger at KNK than at KKJ. It seems that this is due to the difference of underground structure at each site. On the other hand, amplitude spectra for strong motion are greater by about one order than those for weak motions. Shapes of spectra of strong motion do not fit that of "ω-square" model. For lower frequencies, those increase linearly with frequency. In addition, locations of f_{max} are a little shifted to lower part at both stations. These discrepancies are thought to be due to effects of complex source process (multiple shock) and contamination by surface waves.

SEISMIC RESPONSE OF SOFT SOIL

In this study, we define the site response of soft soil in terms of spectral ratios of Fourier amplitude spectra at KNK to those at KKJ. Each earthquake is characterized by the source spectrum and wave path effects. In the site response study, recording of different events can be directly comparable if source and path effects that may overshadow the site response are removed. The spectral ratio method is a straightforward way to isolate the relative site effect (*e.g.*, Beresnev *et al.*, 1995).

To obtain the relative site response, we must correct for the differential path effects between KNK and KKJ caused by the attenuation and geometrical spreading. We use following expression (*e.g.*, Jarpe *et al.*, 1988)

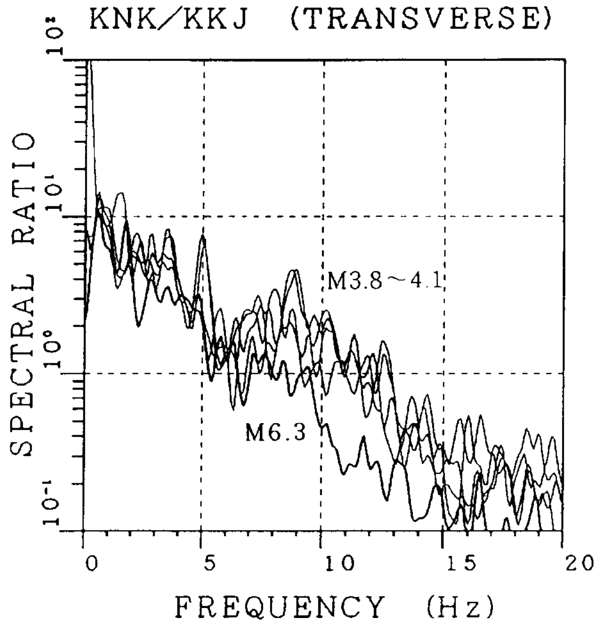


Fig. 5. Seismic responses of transverse components of KNK station with respect to KKJ station. Bold curve represents the result of M6.3 event.

$$\frac{R_1}{R_2} = \frac{g_1}{g_2}\frac{r_1}{r_2}\exp\frac{\pi(r_1 - r_2)f}{vQ}$$

Where R_1/R_2 is the site response, g_i is the spectrum of the recorded motion, r_i is the hypocentral distance, f is the frequency, v is the shear-wave velocity and Q is the quality factor. We assume v = 3.5 km/sec and Q = 200 as average values. These values are estimated by travel times and spectral decay at high frequencies at KKJ which deviate from ω-square model, respectively. Generally, the choice of v and Q affects the spectral ratio estimates, but the effects are not so severe in this case.

Figure 5 shows the site response of KNK relative to KKJ. As stated before, it is low reliance below 0.5 Hz because of instrumental character. The soft site amplification is a factor of about 10 over a frequency range from 0.5 to 1 Hz and a factor of about 3 from 2 to 5 Hz, while the soil site is strongly deamplified at high frequencies above 10 Hz. Boatwright *et al.* (1992) analyzed the aftershock recordings from 1989 Loma Prieta earthquake to determine site response in the Marina district, Los Angeles, where extensive damage of building, the ground failure and liquefaction of hydraulic fill occurred in part of there during main shock. The trends over frequency range below 10 Hz are similar to those in the Marina district.

The amplification factor for strong motion (M6.3) is considerably smaller than those for weak motions (M3.8 - 4.1). Especially at the high frequencies above 7 Hz, it is predominant. The locations of small peaks for weak motions shift to a little low frequency part during strong motion. Maximum ground velocity during M6.3 event reached at 13.6 cm/sec on radial component and 12.2 cm/sec on transverse component. Effective shear strain of KNK during M6.3 event, calculated from relationship between shear wave velocity in the surface layer and maximum ground velocity (Tokimatsu *et al.*, 1989), is 4.1×10^{-4} and 3.7×10^{-4}, respectively. Midorikawa (1993) concluded that shear strain value of 3×10^{-4} is threshold whether non-linear effect is become significant or not. In this case, shear strain during strong motion is a little greater than that value. Then we attribute these discrepancies between weak and strong motion amplifications to the non-linear response at soil site although we cannot deny the possibility due to the effect of multiple shock and contamination by surface waves.

The shear-wave velocities and the quality factors in the sediments at KNK have been determined by Nagumo (1994) from well-logging up to 80 m. We divide the sedimentary layer into three parts with the shear-wave velocities of 130, 190 and 320 m/sec overlying Tertiary mudstone. The quality factors are approximately constant in a range from 30 to 50 throughout sediments. We investigate the amplification due solely to the vertical velocity structure using the one dimensional multiple reflection theory. The assumed densities are taken from results of similar rock types. To model the amplification of KNK relative to KKJ, we calculate the one dimensional transfer function for the underground structure shown in Table 2.

Table 2. Velocity structure of KNK site derived from well-logging.

Thickness (m)	V_S *(m/sec)*	$\rho^{\star}(g/cm^3)$	*Q*
23.5	131.2	1.8	30
26.5	191.0	1.9	30
14.0	325.7	2.0	30
∞	560.5	2.2	–

$\star$ Assumed value

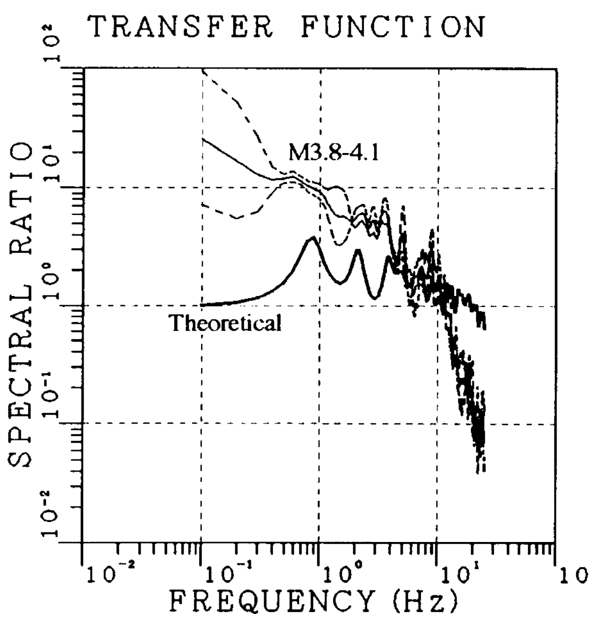


Fig. 6. Transfer function calculated by 1-D method (bold curve) and mean spectral ratio for weak motions of M3.8~4.1 events (thin solid curve). Dashed curves represent ± 1 s.d. of the mean spectral ratio.

Theoretical transfer function fits the observed amplification for frequencies from 4 to 10 Hz (Fig. 6). For frequencies below 4 Hz, however, it substantially underestimates the observed one and for frequencies above 10 Hz it conversely overestimates. The response at high frequencies basically depends on Q structure. But the shape of strong decay for frequencies above 10 Hz is too steep to attribute it to Q structure. It is likely that observed records at KKJ are somewhat amplified at high frequencies by weathering of rock, as stated by Kawase (1993).

To study the causes of the discrepancy at low frequencies, we calculate theoretical velocity seismograms using one dimensional theory and compare them with observed ones in the time domain. We use impulsive S-wave part observed at KKJ as an input wave. The result of 8/8 7:11 event (M4.1) is presented in Fig. 7. Synthetic S-wave fits well observed one in amplitude and shapes, but observed later phases after S-wave are not reproduced by synthetic one at all. It is well known that secondary surface waves can be generated by two or three dimensional geometry of basin boundary (*e.g.*, Bard and Bouchon, 1980). These secondary waves make the duration of shaking longer. Taking into account a scale of the Kaminokuni basin, such waves arrive just after direct S-wave. Predominant frequencies in this part at KNK are from 0.5 to 4 Hz. These waves seem to have brought discrepancies between the spectral ratios and the transfer function at low frequencies below 4 Hz. This leads to a conclusion that observed ground motion of 10 seconds S-wave portion at KNK includes not only direct S-wave but also secondarily generated waves by complex basin structure.

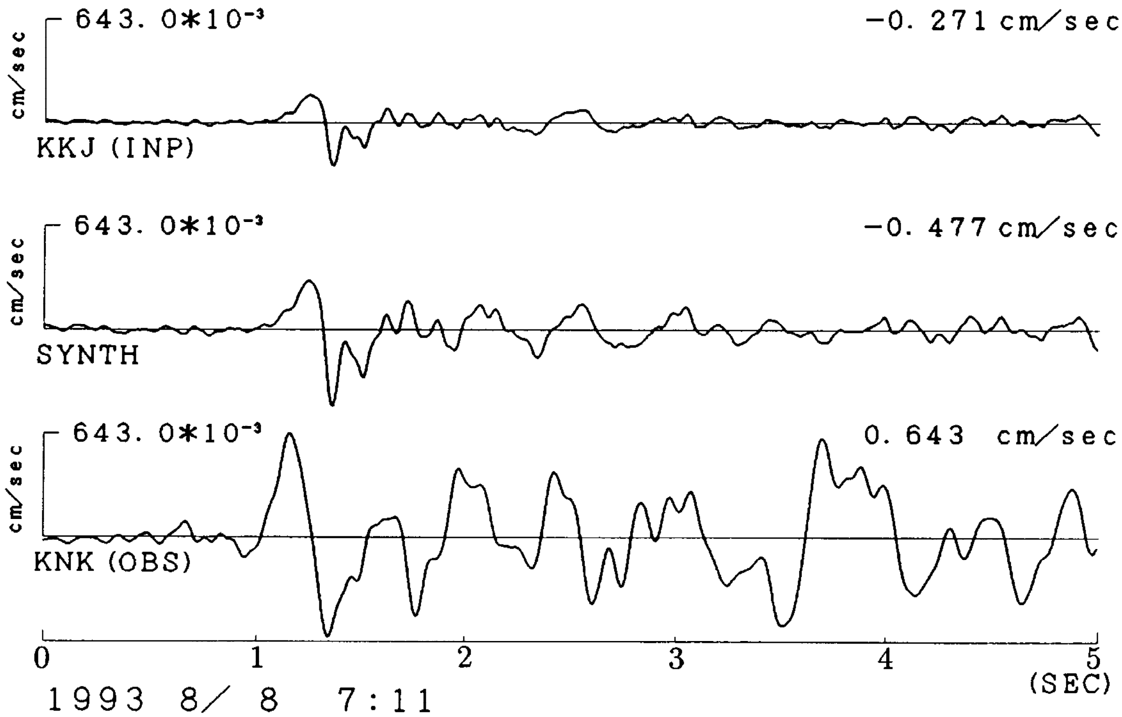


Fig. 7. Comparison between observed and synthetic waveforms for 8/8 7:11 event (M4.1). INP, SYNTH and OBS represent input (S-wave pulse at KKJ), synthesized results and observed record at KNK, respectively.

CONCLUSION

We studied the seismic response of soft soil in the Kaminokuni basin, where liquefaction was observed during the 1993 southwest off Hokkaido earthquake, by using the reference site technique. The data were strong and weak motion records from its aftershocks. The S-wave spectral ratios of the soft soil site to the hard rock site showed the strong amplification at low frequencies (0.5 to 4 Hz) and the deamplification at high frequencies (larger than 10 Hz) on the soft soil site. These were not well explained by one dimensional simulation based on well-logging results at the soft soil site. We attributed the low frequency amplification to effects of secondarily generated waves by a complex three dimensional basin structure. Non-linear soil response was suggested by comparing the spectral ratio during strong motion with those during weak motions.

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