A Study of Site Effects by Means of Strong-Motion Seismograms from Near-by, Intermediate-Depth Earthquakes

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We study the effects of surface geological conditions on long-period ground motion, that is, the site effects, at various sites in Japan by means of strong-motion seismograms from near-by, intermediate-depth earthquakes. These seismograms represent the site response to nearly vertical incidence of plane S waves; they are simply composed of the primary S wave on rock sites, while they show the long-period scattered waves after the primary S wave at alluvial sites. Then we consider that the strength of scattered wave excitation represents the site characteristics, and define an index of scattered wave excitation by dividing the area of the envelope shape for the scattered waves by that for the primary S wave. The indices are determined at various sites in Hokkaido, Tohoku, Kanto, and Kyushu districts and are compared with a simple geological map. They are low at rock sites, while they vary from low to high values at alluvial sites and are not always in proportion to the size of the alluvial plain. The index defined here has the advantage over the simple geological map to represent the site response of long-period ground motion. Finally we discuss the relation between the index and sedimentary basin structure at some sites.

1. Introduction

One of the most urgent subjects in earthquake engineering is to establish effects of surface geological conditions on long-period (1 to 10 s) ground motion, that is, the site effects, in view of the recent increase of large structures such as high-rise buildings and huge oil tanks. The extensive damage to high-rise buildings in Mexico City during the 1985 Michoacan earthquake has again demonstrated the importance of the site effects on long-period ground motion (e.g., Beck and Hall, 1986).

The deep geological structure is the fundamental information to study the site effects on long-period ground motion. However, the structure is not always known well enough for this purpose. Then, various methods have been proposed to estimate the

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site effects. Okada and Kagami (1978) studied amplification characteristics of long-period ground motion in many parts of Japan by means of maximum amplitude data from a number of shallow earthquakes. They first determined an attenuation curve to approximate the relation between maximum amplitudes and epicentral distances for each earthquake, and then regarded the deviation from this curve at each site as an index to express ground motion characteristics. They finally obtained a map of site amplification factors in Japan, that showed serious regional variation of amplification characteristics. A similar study has been done by Mamula *et al.* (1984), who analyzed a number of surface wave data from the Kita-Mino earthquake of August 19, 1961. They obtained the site amplification factor as a function of period by dividing the observed spectrum by the synthetic one. The amplification factors strongly depended on period at certain sites.

In this paper we take a different method to estimate the site effects on long-period ground motion at various sites in Japan. We analyze strong-motion seismograms from near-by, intermediate-depth earthquakes. The incident wave field to the basement from such an earthquake, which produces strong motion at a ground surface, may be regarded as nearly vertical incidence of plane S waves. Then we can consider that the observed seismogram at each site represents the response to such an incident wave field.

Here we illustrate how the site condition affects the ground motion characteristics. Figure 1 shows a comparison between strong-motion records at different sites from

Fig. 1. JMA strong-motion seismograms on the rock sites (left) and on the alluvial basins (right) from near-by, intermediate-depth earthquakes. M , H , and Δ indicate magnitude, and focal depth of the earthquake, and epicentral distance, respectively. An arrow with S indicates an arrival time of the primary S wave. Hiroo and Hachinohe stations are located at the edge of the alluvial plains, but we refer these to rock site stations because of a simple waveform and the small I_s value defined in the text (see Fig. 8).

intermediate-depth earthquakes. The records on the rock site are simply composed of the primary S wave, while the records on the alluvial basin are more complex and show distinct later arrivals after the primary S wave, resulting in a long duration of the ground shaking. The synthetic seismograms calculated for the simple source and crust-upper mantle models can explain the records on the rock site, but they cannot explain the later arrivals observed on the alluvial basin (Sasatani, 1985, 1987, 1990; Sasatani and Sakajiri, 1989; Ikeda and Sasatani, 1991). According to numerical experiments on seismic response of an alluvial basin to incident plane S waves (e.g., Bard and Bouchon, 1980a, b, 1985; Horike, 1988; Sasatani, 1988), these later arrivals can be considered to be scattered waves generated on the irregular interface (i.e., locally generated surface waves). We measure the excitation strength of the later arrivals (the scattered waves) as an index of the site effect. The index represents the basin characteristics on which mode of excitation of the scattered waves depends.

2. Method of Analysis

Figure 2 shows a schematic representation of the site response to incident plane S waves. The incident S wave A is amplified due to low impedance of surface layer and/or resonance of plane layers; the resulting surface motion is represented as B in Fig. 2. This may be the main site effect on the rock site. In addition to the amplification, on the alluvial basin, the scattered waves C are generated on the irregular interface as shown in the inset; the resulting surface motion is D in Fig. 2, corresponding to the observed seismogram. In order to measure the excitation strength of the scattered waves due to incident S waves, it is preferable to compare C with A. However, it is generally difficult to retrieve A from the observed seismogram D because of no information about the deep geological structure beneath many stations. Thus we have to rely on the amplified S wave B instead of the incident S wave A. Even in this case, we cannot

Fig. 2. Schematic representation of the site response to incident plane S waves. A = incident S wave at the basement; B = amplified S wave due to low impedance surface layer and/or resonance of plane layers; C = scattered waves on the irregular interface; D = resulting surface motion due to the amplified S wave and the scattered waves; i.e., $D = B + C$. The primary S motion is shadowed.

Complex Seismic Trace Analysis

Fig. 3. (a) Original seismic trace. (b) Its envelope. Only one side of the envelope is represented because of the symmetry of the shape. T_1 and T_2 are onset and end times of the primary S motion, respectively, and T_3 is appropriate time at which the scattered waves fully diminish. The envelope shape of the primary S motion is shadowed. (c) Averaged time-dependent frequency. This example is taken from the seismogram at Obihiro shown in Fig. 1.

remove S wave reverberations (ground motion after the primary S wave in B) from the observed seismogram D. Fortunately the effect of S wave reverberations is not so severe compared with the scattered waves as shown in Sasatani (1988). Therefore, finally we decided to compare all later phases after the primary S wave with the primary S wave. Of course, this comparison is a rough one to measure the excitation strength of the scattered waves due to incident S waves.

The actual method is shown in Fig. 3. We calculate the envelope shape of the strong-motion seismogram through complex seismic trace analysis (e.g., *Taner et al.*, 1979). Then the area of the envelope shape for the primary S wave, A_s , and that for the scattered waves, A_{sc} , are calculated as

$$A_s = \int_{T_1}^{T_2} f(t) dt, \quad A_{sc} = \int_{T_2}^{T_3} f(t) dt,$$

where $f(t)$ is the envelope shape; T_1 , onset time of the primary S motion; T_2 , end time of the primary S motion; and T_3 , appropriate time at which the scattered waves fully diminish (here we take $T_3 = T_2 + 120$ s). We define an index of the scattered wave excitation, I_s , as

$$I_s = \log_2(A_{sc}/A_s).$$

Figure 4 shows an example of envelope shapes and their I_s values. The envelope shapes at Obihiro and Hiroo are obtained from the records shown in Fig. 1. The

Fig. 4. An example of envelope shapes and their I_s values. Only one side of the envelope is represented because of the symmetry of the shape. The envelope shape of the primary S motion is shadowed. Also shown is the simplified geological map of Hokkaido. The dotted region indicates alluvium and diluvium.

envelope shapes and I_s values vary from station to station depending on the site condition. In general, the envelope shapes obtained on the alluvial basin are complex and for these envelopes the determination of T_2 is somewhat difficult. In these cases, T_2 is determined based on the simple envelope shape obtained on the rock site (for example, Hiroo in Fig. 4).

The lower figure in Fig. 3 shows the time-dependent frequency obtained from complex seismic trace analysis (Taner *et al.*, 1979). It should be noted that we study the site response for seismic waves with a predominant period of a few seconds as shown in this figure.

3. Data

JMA strong-motion records from near-by, intermediate-depth earthquakes with a depth (H) of 50 to 260 km and a magnitude (M) of 6 to 7 were used in the analysis. The natural period, damping constant, and static magnification of the strong-motion (displacement) seismographs are 5–6, 0.5–0.6 and 1 s, respectively. After correction of the distortion of the records due to the mechanism of the recording system, these records were digitized at a rate of 0.4 s. In the following analysis, we used horizontal components with large amplitude.

We analyzed mainly the records which satisfy the condition $\Delta/H \lesssim 1$ where Δ is

Table 1. Earthquakes used in this study.

Date (JST)		Epicenter		Depth	<i>M</i>
Hokkaido					
Oct.	26, 1965	43°44'N	145°31'E	160 km	7.1
Jan.	19, 1969	44°33'	143°29'	260	7.1
Aug.	17, 1969	42°35'	141°31'	140	5.9
Nov.	9, 1974	42°29'	141°47'	130	6.5
Dec.	30, 1979	42°14'	143°02'	70	5.7
Jan.	23, 1981	42°25'	142°12'	130	7.1
May	29, 1982	42°43'	143°16'	120	5.8
Mar.	6, 1984	42°31.8'	142°55.6'	118	6.0
June	22, 1984	42°36.3'	142°29.1'	103	5.4
Mar.	29, 1985	40°17.7'	140°35.2'	164	6.5
Jan.	14, 1987	42°32.0'	142°55.9'	119	7.0
Jan.	2, 1988	43°13.8'	142°29.9'	175	6.4
May	7, 1988	42°29.0'	143°51.9'	93	6.3
Tohoku					
Mar.	29, 1985	40°17.7'N	140°35.2'E	164 km	6.5
Jan.	9, 1987	39°50.0'	141°46.8'	72	6.6
Kanto					
July	1, 1968	35°59'N	139°26'E	50 km	6.1
Sept.	25, 1980	35°31'	140°13'	80	6.1
Feb.	27, 1983	35°56.2'	140°09.3'	72	6.0
Oct.	4, 1985	35°52.1'	140°09.5'	78	6.1
Kyushu					
Nov.	28, 1967	32°05'N	130°57'E	130 km	6.2
July	4, 1978	32°40'	131°21'	120	6.2
Aug.	26, 1983	33°33.2'	131°36.4'	116	6.8
Jan.	27, 1985	32°36.0'	131°17.9'	118	6.0

These parameters are after JMA.

the epicentral distance. This condition was imposed on the data to guarantee approximately the vertical incident wave field at the basement (the incident angle at the basement at $\Delta=100$ km for $H=100$ km event is about 20° , based on the Earth structure by Ichikawa and Mochizuki, 1971). The strong-motion seismograms that satisfied the above condition were obtained at various sites in Hokkaido, Tohoku, Kanto, and Kyushu (including a part of Chugoku and Shikoku) districts. Epicenters of earthquakes (Table 1) and stations used are shown in Fig. 5. Unfortunately we could not obtain these seismograms at sites in Chubu and Kansai districts, being far from the deep seismic zone.

4. Results

First we have to note the dependence of the envelope shape and I_s value on the epicentral distance and azimuth. Figure 6 shows an example of I_s values versus Δ/H (a

Fig. 5. Epicenters of earthquakes (×) and stations (●) used in analysis for four districts.

Fig. 6. I_s values versus Δ/H (a ratio of epicentral distance to depth) at four stations in Hokkaido.

ratio of epicentral distance to depth) at four stations in Hokkaido. This figure clearly indicates that I_s values for the data with $\Delta/H > 1$ are much greater than those for the data with $\Delta/H \leq 1$ at stations except Obihiro. The Δ/H value is related to incident angle

Fig. 7. Envelopes and their I_s values for three intermediate-depth earthquakes at the Saga station. Only one side of the envelope is represented because of the symmetry of the shape. The envelope shape of the primary S motion is shadowed.

into the basement, and then Fig. 6 means I_s value dependence on incident angle. Since it is important to examine various I_s values under the common situation (nearly vertical incidence of plane S waves), we take the I_s values with $\Delta/H \lesssim 1$ in analysis as mentioned before. Figure 6 also indicates the accuracy of I_s determination at each site.

We can see an example of the azimuthal dependence of the envelope shapes in Fig. 7: The envelope shapes of the 1978 and 1985 events are somewhat similar to each other, but they are different from those of the 1983 event. The azimuthal dependence of the envelope shapes may be related to three-dimensional basement structure (Horike *et al.*, 1990) and causes scatter in I_s values as shown here and in Fig. 6.

We calculated the average of I_s values, denoted by $\bar{I}_s$, to obtain the index of the scattered wave excitation at each station. The results are listed in Table 2, and shown in Fig. 8 together with a simple geological map (the distribution of alluvium and diluvium). At some stations, $\bar{I}_s$ values are less reliable because of few number of data, and they are denoted by the number with a parenthesis. Figure 8 shows that (1) $\bar{I}_s$ values obtained at rock sites are less than 1.5 (for example, Urakawa, Miyako, Chichibu, Shimonoseki, and Asosan), while (2) those at alluvial plains vary from 0 to 4.6. The Saga station has the greatest $\bar{I}_s$ of 4.6 in this analysis. On the other hand, the Tokyo station has the relatively low value ($\bar{I}_s = 1.7$) in spite that it lies within the Kanto Plain,

Table 2. $\bar{I}_s$ values obtained in this study. S.D. and N_s are the standard deviation and number of data used.

Station	$\bar{I}_s$	S.D.	N_s	Station	$\bar{I}_s$	S.D.	N_s
Hokkaido				Tohoku			
Obihiro	2.9	0.70	8	Akita	2.4	0.01	2
Hiroo	0.35	0.50	5	Aomori	2.4	0.23	2
Sapporo	2.2	0.19	4	Hachinohe	0.86	0.02	2
Tomakomai	2.1	0.43	6	Miyako	1.2	0.06	2
Urakawa	1.1	0.44	6	Morioka	0.27	—	1
				Ohfunato	1.0	0.54	2
				Sakata	3.1	0.40	2
Kanto				Kyushu			
Chichibu	0.78	0.23	2	Asosan	1.0	0.34	2
Choshi	0.79	—	1	Fukuoka	1.2	0.81	2
Kumagaya	2.9	—	1	Hiroshima	1.5	0.32	2
Mito	3.0	0.48	2	Kumamoto	2.8	0.35	4
Tokyo	1.7	0.62	3	Matsuyama	-0.20	—	1
Utsunomiya	2.1	0.35	3	Nobeoka	1.0	0.57	3
Yokohama	2.5	1.33	2	Oita	3.1	0.96	3
				Saga	4.6	0.79	6
				Shimonoseki	0.45	0.91	2
				Uwajima	0.81	0.13	2

the biggest plain in Japan; this can be seen directly in Fig. 9. The $\bar{I}_s$ value is not always in proportion to the size of the plain. On the basis of above statement (1), we believe that stations with $\bar{I}_s$ less than 1.5 in the alluvial plains (for example, Hiroo, Hachinohe, Ohfunato, and Fukuoka) have the same response as on the rock site; the sedimentary layer at these stations may be very thin. The wide range of $\bar{I}_s$ values at alluvial plains implies that the simple geological map is not enough to represent the site response of long-period ground motion.

5. Discussion

Recent numerical experiments on seismic response showed that local surface waves (the scattered waves) were excited inside the alluvial or sedimentary basin due to incident plane S waves (e.g., Bard and Bouchon, 1980a, b, 1985; Horike, 1988; Sasatani, 1988). The excitation of surface waves strongly depends on the shape ratio (sediment thickness to basin half-width ratio), the velocity contrast between the sediment and the underlying basement, and the characteristics of the incident wave field (the frequency contents and angle of incidence of the incoming wave). Since the $\bar{I}_s$ values were obtained under approximately common incident wave field (nearly vertical incidence of plane S wave with a predominant period of a few seconds), they represent such basin characteristics as the shape ratio and the velocity contrast; qualitatively the higher $\bar{I}_s$ value indicates that the basin has the higher shape ratio and velocity contrast.

It is worthwhile to check the above statement. However, the basin structure is not known well enough at many plains. We can cite the Tokachi Plain in Hokkaido as an

Fig. 8. $\bar{I}_s$ values at stations and distribution of alluvium and diluvium for four districts. The $\bar{I}_s$ value within a parenthesis indicates that it is less reliable because of few number of data.

illustration. The Tokachi Plain is a sedimentary basin extending about 100 km in the north-south direction and about 50 km in the east-west direction. Figure 10 shows an S-wave velocity structure along East-West profile in the Tokachi Plain. Each velocity column was obtained by an array observation of microtremors (Matsushima and Okada, 1990; Matsushima, 1990). We may assume that the layer having an S-wave velocity of about 3 km/s is the basement. Then the shape ratio and velocity contrast are approximately 0.2 and 3, respectively. These values are large enough to excite local surface waves due to incident plane S waves as shown by numerical experiments (Bard and Bouchon, 1980a, b; Sasatani, 1988). Actually, the Obihiro station that lies at roughly central part of the Tokachi Plain has a high $\bar{I}_s$ value of 2.9. This may indicate that stations with a high $\bar{I}_s$ such as Sakata, Saga, and Oita (see Fig. 8) lie within the similar sedimentary basin shown in Fig. 10.

Next we examine the Kanto Plain, the biggest plain, where many explosion experiments have been done and fine basement structure has been obtained (e.g., Shima *et al.*, 1981). It is well known that ground motion with a period of about 8 s predominates in the Kanto Plain (e.g., Tanaka *et al.*, 1979; Yamanaka *et al.*, 1989). Comparing with

Fig. 9. Original seismograms and their I_s values for three intermediate-depth earthquakes at Tokyo. Note the weak excitation of the scattered waves compared with large amplitude of the primary S wave.

Fig. 10. S-wave velocity structure along an East-West profile in the Tokachi Plain. Each velocity column was obtained by an array observation of microtremors (Matsushima, 1990). The profile and array locations (solid triangles) are shown in the inset. The Tokachi Plain is covered mainly by Terrace deposits.

the Tokachi Plain, the Kanto Plain has approximately the same velocity contrast but the lower shape ratio. We believe that this low shape ratio and relatively short period (less than 4s) of incoming wave (see Fig. 9) are causes of low I_s at Tokyo in this analysis. These facts indicate a good evidence of ground motion dependence on period

Fig. 11. Amplitude spectra of seismograms at Saga and Obihiro. The spectra at Saga have a common, relatively sharp peak at 0.2–0.3 Hz regardless of earthquakes. The spectra at Obihiro are shown for the sake of comparison; they have no common sharp peak. Amplitude is normalized.

as pointed out by Mamula *et al.* (1984).

We may consider that the envelope shape of the scattered waves has some information about site characteristics. The envelope shapes of the scattered waves at Saga have much larger amplitudes than those of the primary S waves and very long durations as shown in Fig. 7. This feature is unique and might indicate that the Saga Plain exhibits the two-dimensional resonance as numerically shown by Bard and Bouchon (1985); the resonance occurs for the deeper (the higher shape ratio) basin with the higher velocity contrast. In fact, the spectra of Saga seismograms have a common, relatively sharp peak at 0.2–0.3 Hz regardless of earthquakes as shown in Fig. 11. However, it is considerably difficult to obtain the quantitative relation between the envelope shape and the basin structure at the present time.

6. Conclusions

We studied site effects at various sites in Japan by means of strong-motion seismograms from near-by, intermediate-depth earthquakes. These seismograms represent the site response to nearly vertical incidence of plane S waves. We compared the site characteristics based on the index to express the strength of scattered wave excitation due to the incident S waves. The indices provide some information about deep geological structure, but the quantitative relation between the indices and structures is not yet obtained.

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