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Site effects on strong-motion records of the 1985 Chile earthquake and their nonlinear behavior

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ABSTRACT: Site effects on strong-motion records and their nonlinear behavior are discussed using the strong-motion records on a rock site and two soil sites during the 1985 Chile earthquake (M_s7.8) and its aftershocks. The spectral ratios of the records on soil sites with respect to the rock site indicate strong site effects in the records at soil sites. From a comparison of the spectral ratios for the main shock and aftershock records, nonlinear behavior of soil is detected. The relation between shear modulus ratio and shear strain derived from the records is consistent with the laboratory data and the previous results from Japanese strong-motion records.

1 INTRODUCTION

The prediction of strong ground motions from destructive earthquakes is one of the important subjects in earthquake engineering. Earthquake ground motions are affected by source effects, propagation path effects and site effects. Among these effects, the importance of site effects have been frequently emphasized because of their large variation in space (i.e. Kanai, 1983).

In geotechnical engineering field, nonlinearity of site effects during strong shaking has been discussed based on the laboratory tests of sampled soil specimens (i.e. Seed and Idriss, 1970). Computer codes for calculating nonlinear site response have been developed and utilized (i.e. Schnabel et al., 1972).

However, few studies have been conducted on in situ soil behavior based on observed strong-motion records (Abdel-Ghaffar and Scott, 1976; Tokimatsu et al., 1989; Chang et al., 1991). It still seems unclear whether the laboratory data could reproduce in situ soil behavior up to a large strain level. This paper describes site response and its nonlinear behavior using strong-motion records during the 1985 Chile earthquake.

2 STRONG-MOTION RECORDS FROM THE 1985 CHILE EARTHQUAKE

Owing to efforts of strong-motion instrumentation, an excellent strong-motion data set was recovered from the 1985 Chile earthquake (M_s7.8). This earthquake was caused by subduction of the Nazca plate to the South American plate. The occurrence of this earthquake was anticipated because no large earthquake had been occurred since the 1906 Valparaiso earthquake of

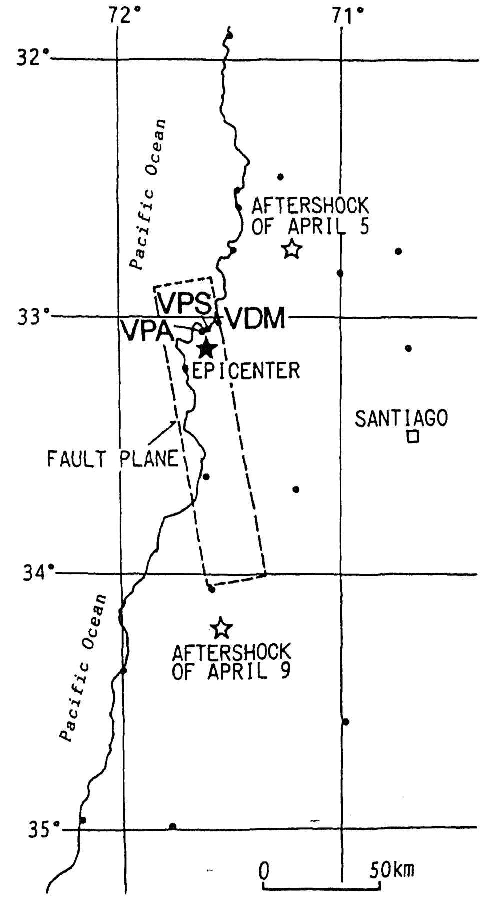

Fig. 1 Locations of epicenter and fault plane of the 1985 Chile earthquake and strong-motion sites.

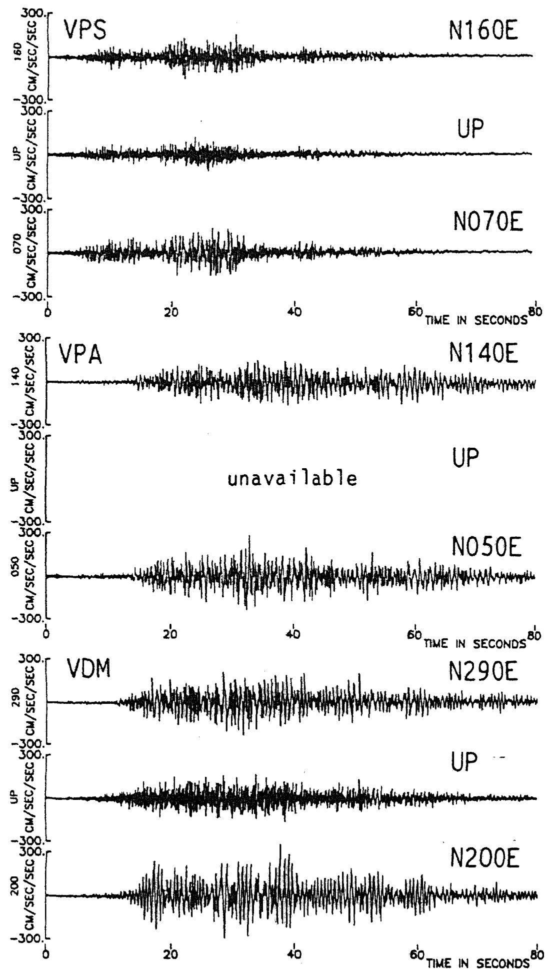

Fig. 2 Acceleration time histories of the 1985 Chile earthquake at VPS, VPA and VDM.

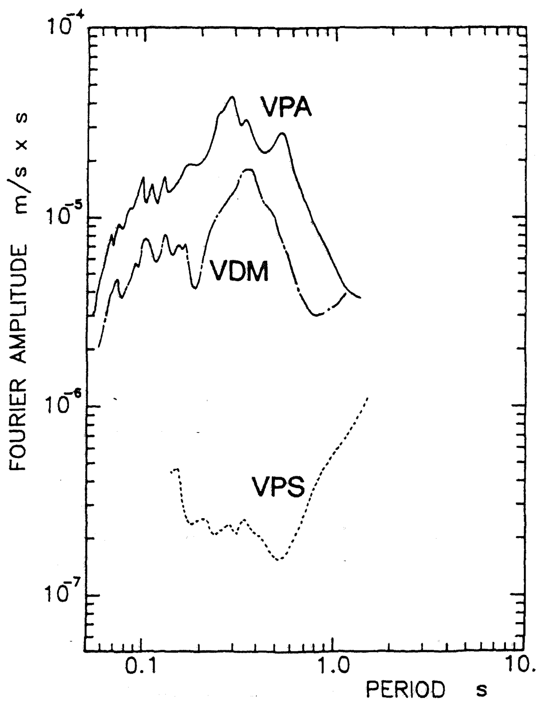

Fig. 3 Comparison of Fourier velocity spectra of microtremors at VPS, VPA and VDM.

M_s8.4 (i.e. Nishenko, 1985). As a result, the installation of strong-motion accelerographs was concentrated in the central part of Chile (Saragoni, 1982).

Locations of the epicenter and the fault plane of the earthquake, and strong-motion sites are shown in Fig. 1. At more than twenty sites, strong-motion records were recovered and digitized (Saragoni et al., 1990; Celebi, 1988). The attenuation relations of peaks of the records have been already investigated (Midorikawa, 1991).

Among these sites, VPS (Univ. of Santa Maria, Valparaiso), VPA (Almendral sector, Valparaiso) and VDM (Vina del Mar) sites are closely situated in the rupture zone with different site conditions: VPS site is on granite rock, VPA is on artificial fills, and VDM is on sandy soil deposits. The distances from VPS to VPA and to VDM are about 1 km and 5 km, respectively.

Figure 2 shows the acceleration time histories at VPS, VPA and VDM. The peak ground accelerations are 0.18 *g* at VPS, 0.3 *g* at VPA, and 0.36 *g* at VDM. A large difference of amplitude level among the sites suggests strong local site effects at the sites. Aftershock recordings have been also recovered at the sites (Askew et al., 1985; Celebi, 1988). A comparison of site effects on the main-shock motions and on the aftershock motions can provide quantitative evaluation of nonlinearity of in situ soils.

3 SITE CONDITIONS

The strong-motion accelerographs are installed in a vault at VPS, in a church at VPA, and in a seven-story building at VPA. Effects of soil-structure interaction can be negligible at VPS and VPA, but may be expected at VDM in period of shorter than 0.3 second which is a natural vibration period of the building (Midorikawa and Tokimatsu, 1992).

An outcrop of granite rock whose shear wave velocity is presumably 2 to 3 km/s is found at VPS. At VPA, a boring test and shear wave velocity measurements have been conducted (Saragoni and Carvajal, 1991; Midorikawa and Tokimatsu, 1992). The depth to the rock is 56 meters and shear wave velocity of surface soils is about 350 m/s.

Boring data are available at neighboring points of VDM. The data indicate that sandy deposits with thickness of about 30 meters cover ground surface (Grimme and Alvalez, 1964; Wallace and Moehle, 1990). The depth to the rock is estimated to be approx-

Table 1 Underground models used

Site	Density g/cm³	Thickness m	V_s m/s	Q-value
VPA	2.0	56	360	20
	2.5	–	2000	100
VDM	1.8	15	250	20
	1.8	15	300	20
	2.1	30	800	20
	2.5	–	2000	100

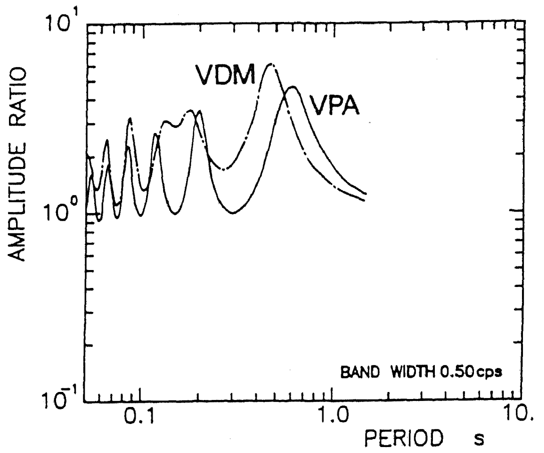

Fig. 4 Theoretical amplification factors of ground.

Table 2 Peak ground velocities of records used

Site	Comp	Main Shock*	Aftershock 1**	Aftershock 2*
VPS	S20E	6.4 cm/s	0.6 cm/s(EW)	2.6 cm/s
	N70E	14.7 cm/s	–	2.4 cm/s
VPA	N50E	28.6 cm/s	0.9 cm/s(EW)	–
	S40E	16.9 cm/s	–	–
VDM	N70W	25.6 cm/s	–	6.1 cm/s
	S20W	30.7 cm/s	–	5.4 cm/s

* Saragoni et al.(1990)
** Askew et al. (1985)

imately 100 m (Riddell et al., 1987). Shear wave velocity of sandy deposits is estimated to be 250 to 300 m/s (Midorikawa and Tokimatsu, 1992).

Microtremors were measured at the sites for evaluating site characteristics. The over-all response of the instrument used for the measurement is proportional to ground velocity in period range of 0.05 to 10 seconds. The measurements were done in day time to avoid daily variation of microtremors.

Figure 3 shows the Fourier velocity spectra of microtremors for horizontal component. The spectrum at VPS is not plotted in short period range where the record should be disturbed by a noise due to heavy traffic. At VPS on rock, the spectral amplitudes are very small and no clear predominant peak is found. At VPA and VDM on soil deposits, the amplitudes are much larger and predominant peaks are found at periods of about 0.6 second and 0.4 second, respectively.

The underground models at VPA and VDM are constructed based on the available data mentioned earlier. The estimated models are shown in Table 1. The amplification factors of ground with respect to baserock surface are computed based on the multiple reflection of SH waves, as shown in Fig. 4.

The fundamental periods of ground are about 0.6 second for VPA and about 0.5 second for VDM, respectively. The amplification factors at these peaks are 5 to 7. The fundamental periods computed from the underground models correspond to the predominant periods of microtremors. This supports the validity of the underground models used.

4 SPECTRAL RATIO ANALYSIS

To extract site effects on the records, the spectral ratio of the motion on soil deposits to that on rock is computed. For the ratio of VPA/VPS, the records during the main shock and the aftershock of April 5, 1985 with m_b5.3 (aftershock 1) are used. For the ratio of VDM/VPS, the records during the main shock and the aftershock of April 9, 1985 with M_s7.2 (aftershock 2) are used. The peak ground velocities of the records are summarized in Table 2. The amplitude level of the main shock records is much larger than that of the aftershock records.

To avoid the effects of polarity of seismic waves, the two-dimensional Fourier spectrum is computed for each record by vector composition of Fourier amplitudes of two orthogonal horizontal components. Then the spectral ratio with respect to VPS is computed. For the spectral ratio of VPA/VPS during the aftershock, however, the ratio of the east-west component motions computed by Askew et al.(1985) is used, because the north-south component motion of the aftershock at VPA was not recorded properly.

The computed spectral ratios are shown in Fig. 5. The ratios from aftershock records are indicated by dashed lines. They show peaks at period of 0.7 second for VPA and at period of 0.5 second for VDM. Although the periods of the peaks are slightly longer than those in the theoretical amplification factors shown in Fig. 4, the ratios are in fairly good agreements with the theoretical amplification factors.

It should be noted that the spectral ratio at VDM is smaller than the theoretical amplification in period of shorter than 0.3 second. This may be due to soil-structure interaction effects of the building at VDM.

The spectral ratios from the main shock records are indicated by solid lines in the figure. Although the ratios for the main shock are similar to those for aftershocks, the peaks for the main shock are found at longer period; 0.9 second at VPA and 0.7 second at VDM.

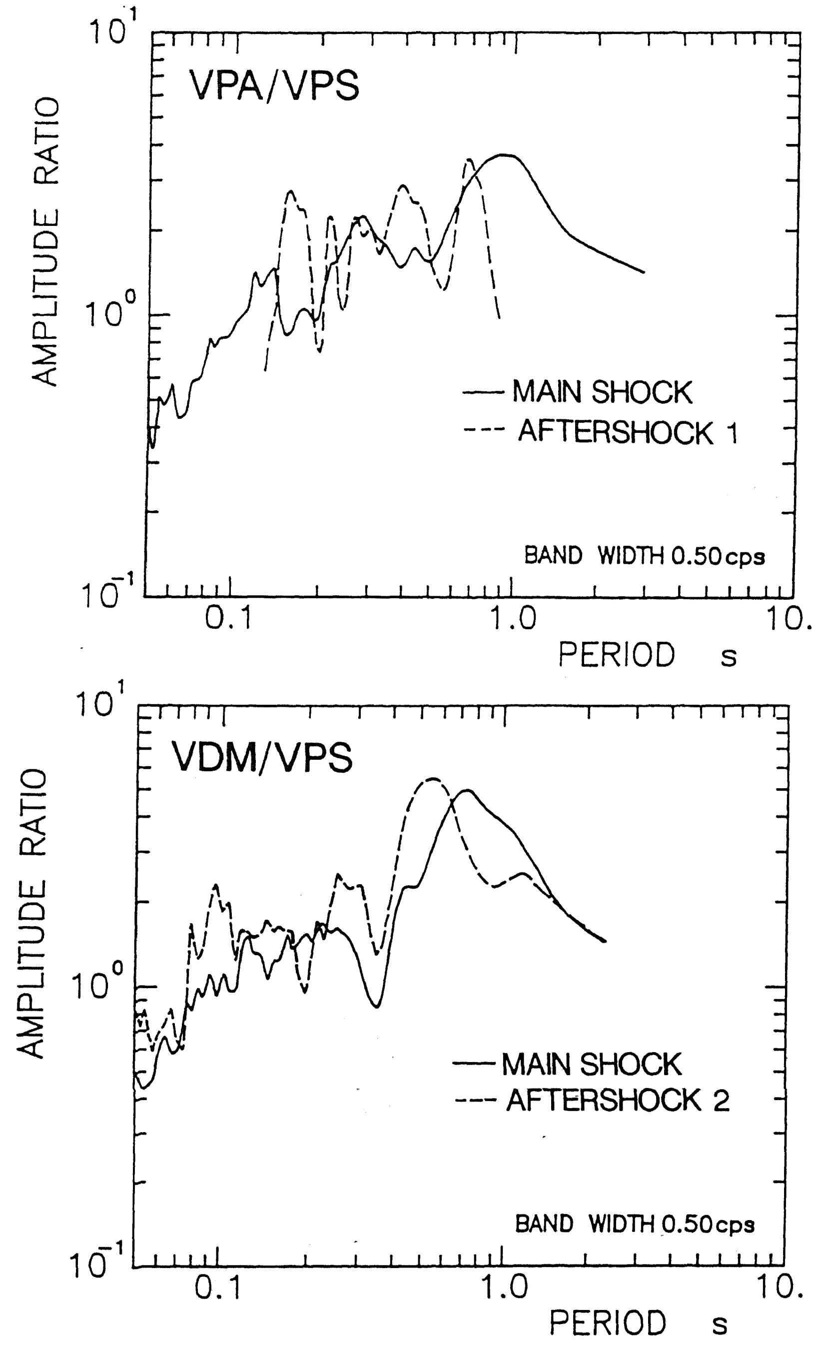

Fig. 5 Fourier spectral ratios with respect to rock site.

These periods are 30 to 40 percent longer than those from the aftershock records and about 50 percent longer than those of the theoretical amplifications. The spectral ratios for the main shock tend to be smaller than those for aftershocks. Thus, the predominant periods of ground become longer and the amplification factors become smaller with increase of amplitude level of ground motion. These facts suggest nonlinear behavior of soil deposits during the main shock.

5 RELATIONSHIP BETWEEN SHEAR MODULUS AND SHEAR STRAIN

The strain level developed in soil deposits and shear moduli of soils are estimated using a simple procedure (Tokimatsu et al., 1989). The effective shear strain, γ_{eff} is roughly estimated by the following equation:

$$\gamma_{eff} = 0.4\ PGV / V_s \qquad (1)$$

where PGV is peak velocity of horizontal ground motion, and V_s is average shear wave velocity of surface layers. The shear modulus ratio, G/G_0 can be obtained as follows:

$$G / G_0 = (T_o / T)^2 \qquad (2)$$

where T_0 is predominant period of ground at small strain, and T is predominant period of ground determined from the records.

Table 3 summarizes obtained effective shear strains and shear modulus ratios for VPA and VDM. During the main shock, shear modulus ratio and effective shear strain are estimated to be 0.4 to 0.5 and 3 to 5 x 10^{-4}, respectively. The relationship between shear modulus ratio and effective shear strain during the main shock and aftershocks is shown in Fig. 6. There is a strong tendency in which shear modulus ratio decreases with increasing shear strain.

For comparison, the relationships from laboratory tests (Kokusho, 1987) and those derived from Japanese strong-motion records (Tokimatsu et al., 1989) are also indicated in the figure. The results from this study are consistent with the laboratory data and the previous results derived from Japanese strong-motion records.

Table 3 Effective shear strain and shear modulus ratio

Site	Event	γ_{eff}	G/G_0
VPA	Main shock	3 x 10^{-4}	0.46
	Aftershock 1	1 x 10^{-5}	0.92
VDM	Main shock	5 x 10^{-4}	0.43
	Aftershock 2	1 x 10^{-4}	0.68

6 CONCLUSIONS

On the basis of the spectral ratio analysis of the strong-motion records on soil and rock during the 1985 Chile earthquake and its aftershocks, the following conclusions may be drawn:

(1) Strong site effects are found in the records at soil sites.

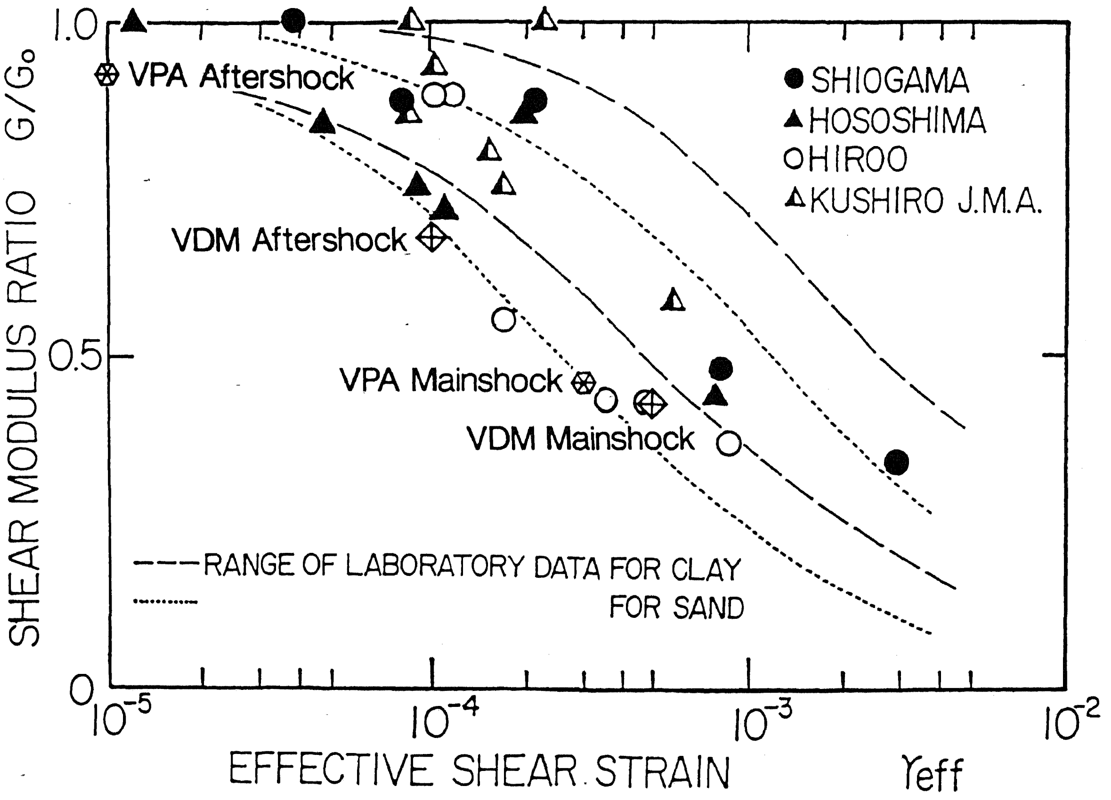

Fig. 6 Relationship between shear modulus ratio and shear strain.

(2) Nonlinear behavior of soil is detected from a comparison of spectral ratios for the main shock and aftershock records.

(3) The relation between shear modulus ratio and shear strain estimated from the records is consistent with the laboratory data and the previous results derived from Japanese strong-motion records.

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