Journal of Zhejiang University SCIENCE A
ISSN 1009-3095 (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Study on the applicability of frequency spectrum of micro-tremor and dynamic characteristics of surface ground in Asia area

CHE Ai-lan[†1], IWATATE Takahiro[2], ODA Yoshiya[2,3], GE Xiu-run[1]

([1]*School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200030, China*)
([2]*Department of Civil and Environmental Engineering, Tokyo Metropolitan University, Tokyo 192-0397, Japan*)
([3]*Department of Civil Engineering, Xi'an Jiaotong University, Xi'an 710049, China*)

[†]E-mail: alche@sjtu.edu.cn

Received Dec. 20, 2005; revision accepted June 21, 2006

Abstract: The dynamic characteristics of ground soil using micro-tremor observation in Asia (Zushi and Ogasawara (Japan), Xi'an (China), Manila (Philippines), and Gujarat (India)) are studied. Ground micro-tremor signals were observed and analyzed by fast Fourier transform method (FFT). The response of ground soil to frequency of ground micro-tremor is revealed, and functions with frequency-dependence and frequency-selection of micro-tremor for different foundation soil strata are also researched. The horizontal to vertical spectral ratio (H/V, Nakamura technique) of micro-tremor observed at the surface ground was used to evaluate the site's predominant period. This paper also discusses the application of micro-tremor on site safety evaluation, and gives the observed calculation results obtained at multiple points. The experimental foundation and the deduction process of the method are described in detail. Some problems of the method are pointed out. Potential use of the technique's good expandable nature makes it a useable means for preventing and reducing disaster's harmful effects.

Key words: Micro-tremor observation, Nakamura method, Predominant period, Earthquake observation, Spectral analysis
doi:10.1631/jzus.2006.A1856 **Document code:** A **CLC number:** TU4

INTRODUCTION

It is well known that micro-tremor observation is one of the most convenient methods for investigating the dynamic characteristics of the surface ground and the affected structure (Bard, 1998; Dowrick, 1997). Micro-tremor is a kind of geophysics information related to soil formation of site, corresponding to engineering geological condition. The frequency characteristics of micro-tremor can be obtained by spectral analyses of its signals, which can be used to probe into the dynamic characteristics of a studied area's soil. The observed signals were analyzed by fast Fourier transform method (FFT) (Guo and Ren, 2005). The horizontal to vertical component spectral ratio (H/V, Nakamura technique) of micro-tremor observed at the surface ground is widely used to evaluate the site's predominant period (Nakamura, 1989; Rodriguez and Midorikawa, 2002). The H/V spectral ratio considers the response of horizontal component of micro-tremor to be the same as that of the vertical component observed, although micro-tremor's vertical component is not amplified by the surface ground. In order to investigate the local site effects on the studied area's seismic vulnerability based on its surface ground motion characteristics, micro-tremor measurements were conducted on the grounds of the typical sites in Asia (Zushi and Ogasawara (Japan), Xi'an (China), Manila (Philippines), and Gujarat (India)) with different soil conditions. Especially, in order to clarify the characteristics of Zushi City's surface ground, which is recognized as anomalous soil layer, earthquake observations were made at five stations on the ground surface and on bedrock (−30 m). From these observation data, the fundamental frequencies and dynamic characteristics of the surface ground were estimated.

GEOLOGICAL CONDITIONS AND MICRO-TREMOR OBSERVATIONS, EARTHQUAKE OBSERVATIONS IN RESEARCH AREAS

Micro-tremor measurements are conducted on the grounds of typical sites in Asia (Zushi and Ogasawara (Japan), Xi'an (China), Manila (Philippines), and Gujarat (India)) with different soil conditions (Fig.1). It was decided to record at one sampling rate of 100 Hz for 5 min, and to record 30000 measurements. Records with the horizontal and vertical components of short-period micro-tremors were obtained using a three components high-sensitivity seismometer, with a natural period of one second. Potential noise sources such as machinery, vehicles traffic or pedestrians, near the seismometer were avoided during the measurement time. And from the recorded data of micro-tremor measurements, five sets of 2048 digital data during lower noise periods were selected for FFT analysis. The Fourier amplitude spectra, spectral ratio and relative variation amplitude were computed.

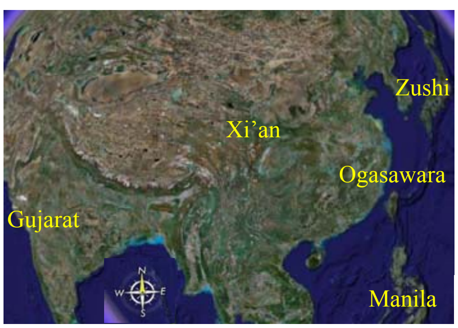

Fig.1 The research area

Earthquake observations were conducted on the grounds of typical sites in Zushi City, Japan. Approximately 108 earthquakes were recorded from 1994 to 2004, including the Chibaken-Nanbu Earthquake (M=5.2), for which Zushi recorded a maximum acceleration of 75 gal (horizontal component). From these observation data, the fundamental frequencies and the dynamic characteristics of the surface grounds are estimated from the spectral ratio of NS component of earthquake motion between ground surface and bedrock. This study will be useful for seismological micro zoning and planning seismic disaster mitigation in these sites.

Research area in Zushi and Ogasawara (Japan)

1. Zushi City

The city of Zushi is located in Kanagawa Prefecture, southern part of Metropolitan Tokyo. Zushi area is a particularly high seismicity area, which suffered severe damages during the 1923 Great Kanto Earthquake (M=7.9). Two major rivers run through the city, the Tagoe River and the Ikego River. Geographically, the city can be divided into three zones based on ground characteristics: the Holocene lowland zones along the banks and mouths of the main rivers, a zone consisting of reclaimed land near the coastline, and a hill zone (Fig.2). The properties of point K_1 are shown in Table 1.

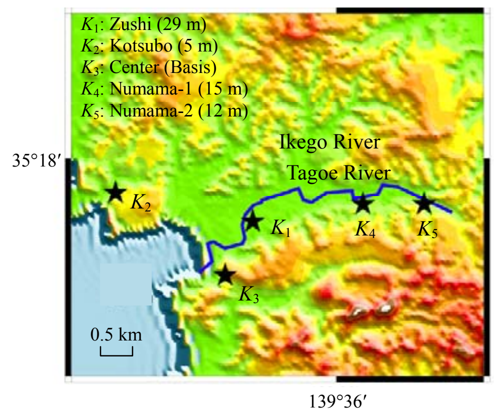

Fig.2 Locations of observation stations at Zushi City (K_1~K_5)

Table 1 Properties of point K_1

No.	Soil	ρ (t/m^3)	Vs (m/s)	h	Depth (m)
1	Loam	1.7	150	0.07	1
2	Sand	1.8	130	0.05	4
3	Clay	1.5	100	0.08	20
4	Clay	1.9	220	0.03	24
5	Clay	2.0	250	0.03	25
6	Weathering soil	2.0	400	0.03	29
7	Basis	2.1	700	0.03	−

Micro-tremor measurements were conducted at the earthquake observation stations (K_1~K_5), and also along the North-South (NS) direction (94 m) on the surface of K_1, spaced approximately 5 m apart in July, 1996. The total number of observation points was 20. Seismic array observation started in June, 1994, at five ground surface stations (designated by K_1~K_5) in Zushi site. In 1998, point K_6 on bedrock in borehole was added. Stations, K_1, K_2, K_4 and K_5 were located on the surface of Holocene lowland along the two rivers, K_3 was located on a rock outcrop, and K_6 was located in bedrock below K_1 (Fig.2). Bedrock with velocity Vs greater than 700 m/s occurs at a depth of −29 m at K_1, −5 m at K_2, −15 m at K_4, and −12 m at K_5.

2. Ogasawara islands

The Ogasawara islands are located about 1000 km south of Metropolitan Tokyo in the Pacific. Chichi Island, the biggest one of the Ogasawara islands, has area of about 24.5 km^2. The east coast of Chichi Island is composed of steep cliff, and the west coast is composed of many gulfs with sandy beaches. The properties of Point 1 are shown in Table 2. Micro-tremor measurements were spaced at representative spot on Chichi Island with 14 observation points in Aug. 1999, and also in the Miyanohama area (1.5 km×2.5 km); the area is subdivided into 250 m square grids, thus summing up to 38 observation points (Fig.3).

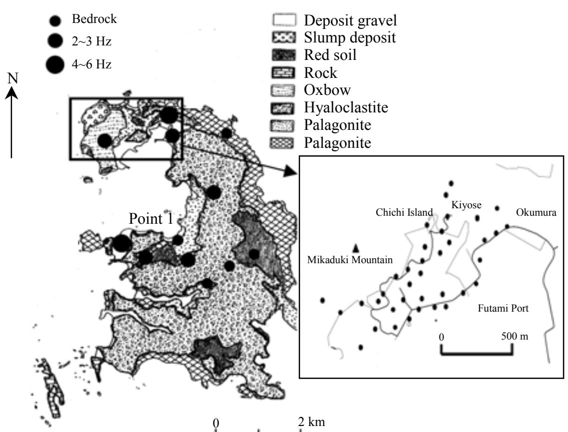

Fig.3 Geological condition and micro-tremor observations at Chichi Island

Table 2 Properties of Point 1

No.	Soil	ρ (t/m^3)	N	Depth (m)
1	Gravel	1.80	15	0.3~4.8
2	Conglomerate	2.25	>50	0~3.6
3	Conglomerate	2.35	>50	0~3.55
4	Andesite	2.00	>50	0~4.4
5	Andesite	2.15	>50	0~6.6
6	Palagonite	2.10	>50	0~8

Research area in Manila (Philippines)

Manila and its immediate vicinity used to be a submerged area with the sea extending to the mountains on the east. Volcanic activities followed intermittently, after which, deposition of volcanic materials occurred. During the intervening periods of inactivity, transported sediments were deposited on the top of the previously deposited volcanic materials. Thus, interbeds consisting of tuff beds and transported sediments became a characteristic feature of the deposit (Dungca, 1989; Tan, 1983). This research project limits the study area with a 1.5 km×4.0 km land area in the western part of Greater Manila (GMA) located in the vicinities of Malate, Ermita, Intramuros, and some parts of Paco and San Andres. The area was selected as it has diverse constructions of buildings from residential (apartments and hotels), government facilities, hospitals, churches, academic institutions, to commercial (malls and office buildings) structures. It is considered that the area has the most growing demand of urbanity within the City of Manila. The area is subdivided into 500 m square grids containing up to 36 observation points (Fig.4). The measurements were conducted in April 1999 (Iwatate and Santos Dy, 2000; Matsuda *et al*., 1998).

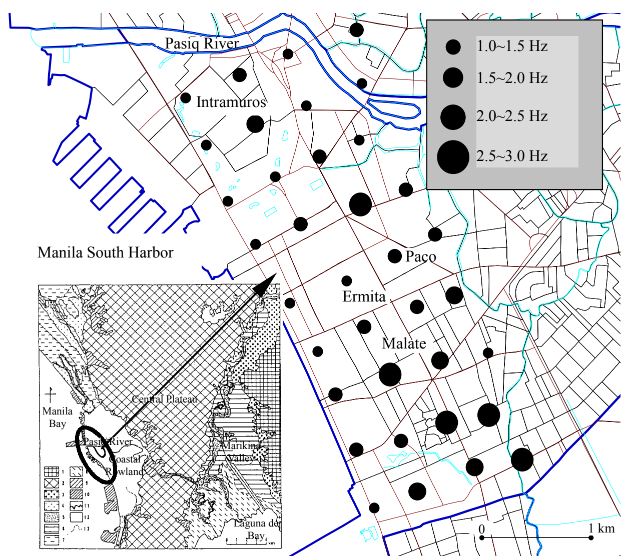

Fig.4 Map with the distribution of predominant frequencies from Fourier spectral ratio (H/V) for each of the measurement points in Manila (Philippines)

Research area in Xi'an (China)

Xi'an City in central China is important for its politics, economy, culture and northwest traffic. In the past, not a few earthquakes (Shanxi-Huaxian

Earthquake, Ninxia-Haiyuan Earthquake) that occurred in the area caused significant damages. The geological conditions of Xi'an area are resulted from loess soil. The loess soil ground was laid in Q_1 (730000~250000 years), Q_2 (130000~730000 years), Q_3 (10000~130000 years, 10~15 m depth), Q_4 (0~10000 years, 0~5 m depth) (Table 3). Micro-tremor measurements project in Xi'an City was conducted in collaboration with Department of Civil Engineering, Xi'an Jiaotong University in Sept. 2001. This research project limits the area to a 1.0 km×0.8 km land area in Xi'an Jiaotong University located in the eastern part of Xi'an City with total of 30 points, and the center of Xi'an City with total of 6 points (Fig.5).

Fig.5 Micro-tremor observations in Xi'an City

Table 3 Properties of Point 1

No.	Soil	ρ (t/m^3)	*Vs* (m/s)	Depth (m)
1	Q_4	1.7	233	0~5
2	Q_3	1.8	256	10~15
3	Q_2	1.5	300	23
4	Sand	1.9	450	3.5
5	Q_2	2.0	300	6
6	Sand	2.0	450	1.4
7	Q_2	2.1	450	10

Research area in Gujarat (India)

Gujarat State of India was severely shaken by a powerful earthquake (M=7.9) at 8:46 a.m. on 26, January 2001 (India Standard Time), which was the most damaging earthquake in the last five decades in India. The state of Gujarat is largely barren except for a fertile band along the Gulf of Kachchh in the Arabian Sea. It was the scene of major border disputes between India and Pakistan in 1965 and 1971. Kachchh or Kutch is an erstwhile princely state of India. It is the largest district of the state of Gujarat and the second largest district in India and covers an area of 45612 km^2. The land is virtually an "island" resembling a tortoise "Katchua or Kachbo", surrounded by seawater. Kutch was also known as the Kutchdweep or Kutchbet. "The Great Rann of Kutch" dominates a major portion of the district. The Great Rann of Kutch and the Little Rann of Kutch respectively are uninhabitable deserts which during the monsoon season (June to October) are often completely submerged by floods (JSCE, 2001). Micro-tremor measurements were conducted at several locations in Gujarat State in March 2001 (Fig.6).

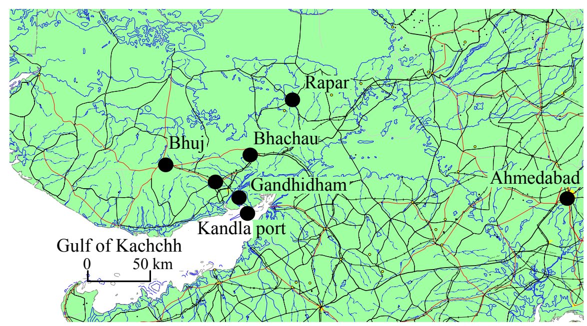

Fig.6 Geomorphic map and observation points in Kutch region

THE APPLICATION OF MICRO-TREMOR H/V METHOD AND SOME PROBLEMS OF THE METHOD

The application of micro-tremor H/V method

Approximately 108 earthquakes were recorded at the six stations between June 1994, and July 2003, including the Chibaken-Nanbu Earthquake (M=5.2), Vladivostok (M=7.6), the Hyogoken-Nanbu Earthquake (M=7.2), the Sagami-Bay Earthquake (M=5.6), the Tokyo-Bay Earthquake (M=4.9). The epicenters of the earthquakes are indicated by dots in Fig.7, the diameter of the dot indicates the earthquake magnitude. The highest peak acceleration recorded on the Holocene lowland (K_1) was 75 gal in the horizontal direction. The highest at the outcrop (K_3) was 28 gal in the horizontal direction, recorded during the Sagami-Bay Earthquake. Fig.8 shows the acceleration time histories of NS component of Tokyo-Bay Earthquake (M=4.9, 1998/11/08) recorded at K_1 and K_6 (bedrock) stations. The response of the surface at K_1 was approximately three times that at bedrock (K_6), and the response at the outcrop (K_3) was approximately equal to that at bedrock (K_6).

In Zushi area, earthquake observation data and micro-tremor observation data estimated the surface ground seismic characteristics. Fig.9 shows the spectral ratio of NS component of earthquake motion between ground surface and bedrock. From the results, the predominant frequency of the surface ground was examined (Enomoto and Iwatate, 2002).

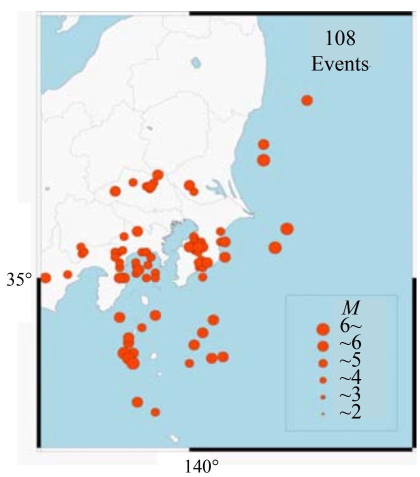

Fig.7 Location of epicenters of observed earthquakes

Comparison with the predominant frequency values from H/V of micro-tremor measurements and seismic array observations, showed good agreement. Therefore, it can be considered that the seismic characteristics of the surface ground in the Zushi area can be evaluated by the spectral ratios (H/V) from micro-tremor measurements.

The local site conditions of Ogasawara Chichi Island, Western Manila and Gujarat (India) were also evaluated using H/V spectral ratio from micro-tremor measurement data (Fig.10). In Ogasawara area, the predominant frequency obtained from the micro-tremor data showed a peak of 2~6 Hz and no peak correspondence to the bedrock ground, which is in good agreement with its soil conditions (Fig.3).

In Western Manila area, the predominant frequency obtained from the micro-tremor data showed a peak of 1~3 Hz which indicated that the site's soil layer is of generally soft sediments. This is true to all lowland areas in the whole National Capital Region (Metropolitan Manila) compared to highland areas that may consist of rock sites. A map with distribution of predominant frequencies is shown in Fig.4.

In Gujarat (India), the predominant frequency obtained from the micro-tremor data showed a peak of 1~3.6 Hz which indicates that the soil layer of the site is comprised of generally soft sediments.

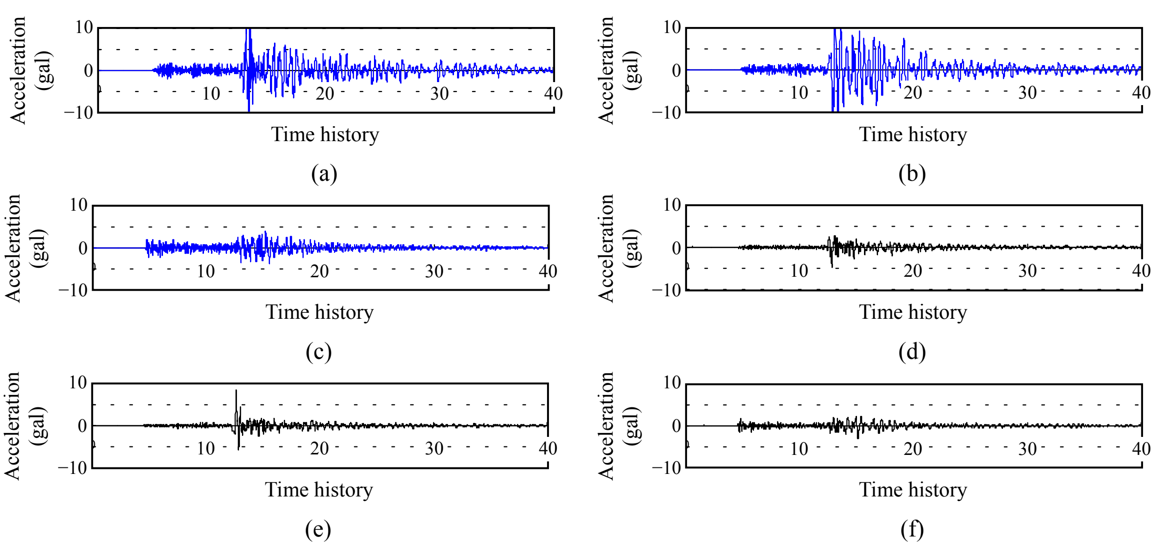

Fig.8 Acceleration time histories of the earthquake motion recorded at K_1 and K_6 (Tokyo-Bay Earthquake, NS component). (a) NS surface; (b) EW surface; (c) UD surface; (d) NS base; (e) EW base; (f) UD base

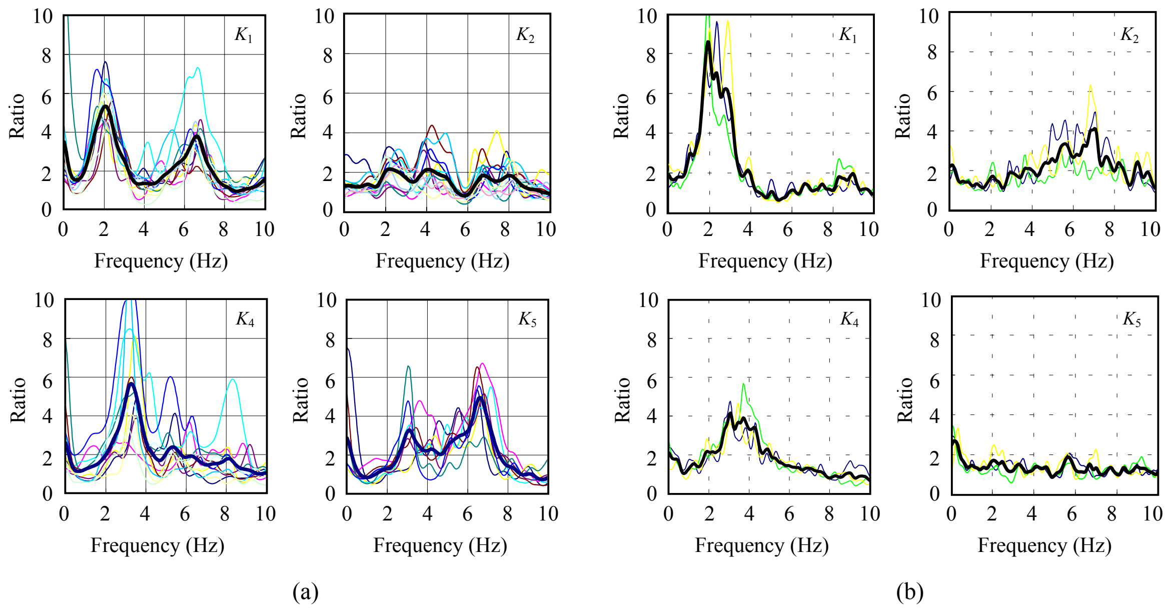

Fig.9 Comparison with the predominant frequency from seismic array observations (a) and H/V of micro-tremor measurements (b)

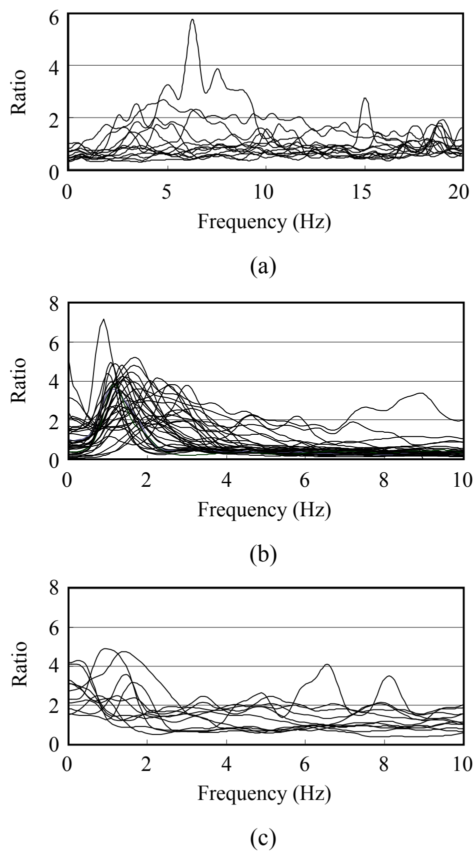

Fig.10 Transfer function (H/V) based on micro-tremor measurements. (a) Ogasawara (Japan); (b) Manila (Philippines); (c) Gujarat (India)

Some problems of the H/V method

The geological conditions of Xi'an (China) are different from Zushi and Ogasawara (Japan) and Manila (Philippines) (which have soft deposits in the surface ground), and are constructed from eolian soil. And there are few contrasts between the surface grounds (Fig.5). The predominant frequencies (NS, EW, UD component) of all the observation points in Xi'an are shown in Fig.11. The result shows that the predominant frequencies of NS, EW, and UD component of the same observation point are almost the same. The predominant frequencies obtained from the micro-tremor data showed peak of 2.5~3.5 Hz, which demonstrated that the soil layer of the site is generally uniform. It can be considered that the engineering geological property of the area soil is good.

The predominant frequency obtained from the micro-tremor data, using Nakamura's method (H/V) of micro-tremor measurements at each site, did not show clear peaks (Fig.11). As a result, the predominant frequency of the surface ground, which has no clear boundary to its substratum, cannot be estimated by H/V method from micro-tremor data. On the other hand, when the surface layer has a sharp impedance contrast to its substratum, the predominant frequencies showed clear peaks.

The purpose of our research is to clarify the dyn-

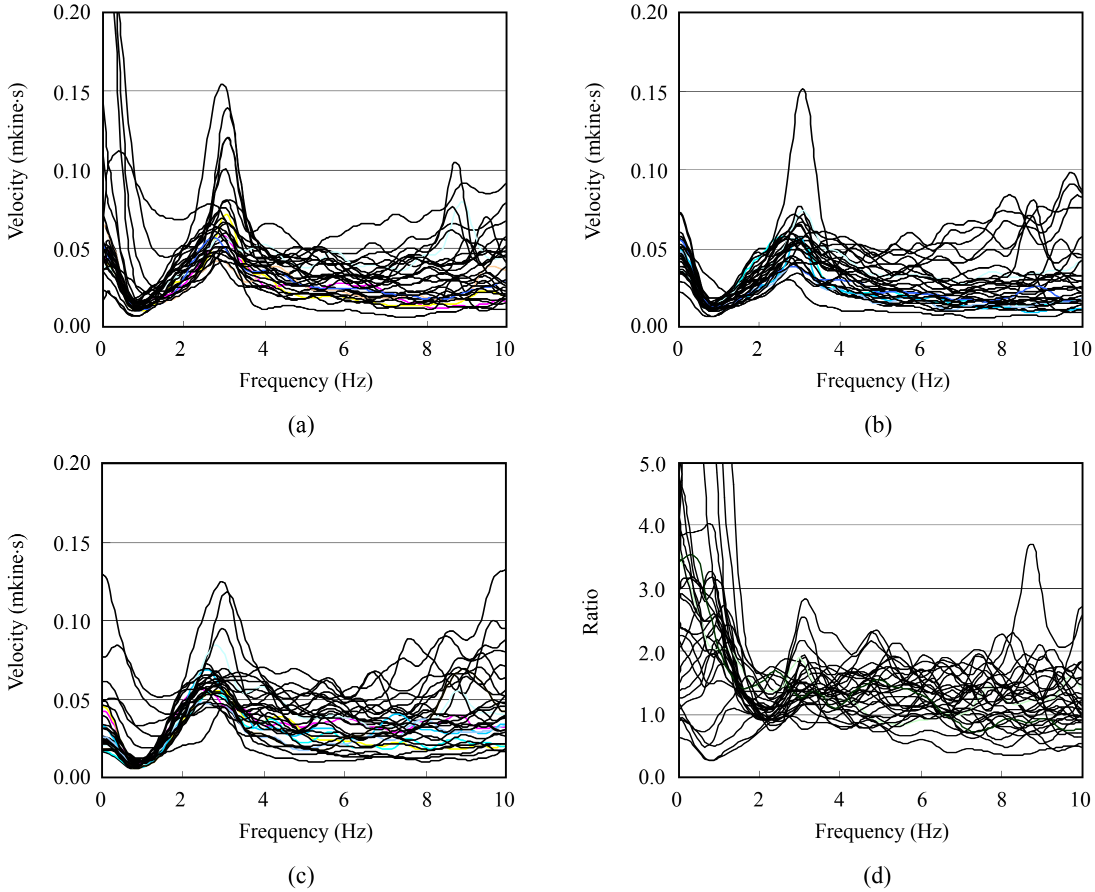

Fig.11 Predominant frequency values based on micro-tremor measurements
(a) NS; (b) EW; (c) UD; (d) H/V

amic behaviors of the surface ground, which is important for studying the seismic response of the structure. The fundamental characteristics of micro-tremor can be used to study the local site conditions of the study area. Fourier spectral ratio using Nakamura's H/V method of micro-tremor at each site was used in analyzing the results.

CONCLUSION

Based on the observation data, the micro-tremor feature and the relationship between its spectrum character and relevant parameters in the site were studied. The results showed that the predominant periods of the micro-tremor are related to the site's soil formation, corresponding to engineering geological condition. The results are shown as follows:

(1) The ground micro-tremor is geophysics information with abundant intension. The frequency characteristic of ground micro-tremor can be obtained by spectral analyses of its signals, which can be used to probe into dynamical characteristics of rock and soil of a studied area.

(2) There exists a frequency-dependent and frequency-selective function for the response of site soil to micro-tremor. The change of predominant period of ground micro-tremor is closely related to the formation of site soil layers, and mutually corresponds to the change of the site's engineering geological conditions. Therefore, the structure and feature of different foundation soil strata can be used to distinguish different kinds of frequency response of site.

(3) The structure of rock and soil layers directly influences the spectral structure characteristics of ground micro-tremor. The site overburden layer with the structure of different foundation soil strata and different rigidity of soil layer transforms to different degree frequency structure of ground micro-tremor.

The thickness of site overburden layer is an important factor affecting the predominant period of ground micro-tremor.

(4) The correlations between predominant period of ground micro-tremor and predominant period of strong earthquake motions were established.

The results are of important theoretical and practical significance for deeply understanding the characteristic of ground micro-tremor, and developing project application of ground micro-tremor.

ACKNOWLEDGEMENT

The authors thank Department of Civil Engineering, Manila's De La Salle University, and Xi'an Jiaotong University, China, for cooperation and providing us useful data. Special thanks are extended to Professor Maohong Yu of Xi'an Jiaotong University, Mr. Shigeo Aoki of Hokuto Institute and all the members of our group for their valuable assistance in micro-tremor measurements.

References

Bard, P.Y, 1998. Micro Tremors Measurements, a Tool for Site Effect Estimation. ESG 98 Symposium.

Dowrick, D.J., 1997. Earthquake Resistant Design for Engineers and Architects (Second Ed.). John Wiley & Sons.

Dungca, J.R., 1989. Liquefaction Potential Map of Manila. Graduate Thesis, De La Salle University.

Enomoto, T., Iwatate, T., 2002. Site-effects Evaluation H/V Spectra Comparing Micro-tremor with Strong Motion Records Observed at Ground Surface and Basement Using Borehole. 12th European Conference on Earthquake Engineering.

Guo, M.Z., Ren, F.H., 2005. The microtremor methods for dynamics measurement of sites. *World Earthquake Engineering*, **21**(4):139-142.

Iwatate, T., Santos Dy, S., 2000. Seismic Response Evaluation of Surface Ground of Western Manila. Philippines 6ICSZ, Palm Springs, CA, USA.

JSCE (Japan Society of Civil Engineers), 2001. The 2001 Kutch Earthquake, Gujarat State, India—Investigation into Damage to Civil Engineering Structures.

Matsuda, I., Enomoto, T., Banganan, E.L., Narag, I.C., 1998. Regional division of metro manila on the basis of geological and geomorphologic conditions. *Bulletin of Institute of Science and Technology*, (25):101-112.

Nakamura, Y., 1989. A method for dynamic characteristics estimation of subsurface using micro tremor on the ground surface. *OR or RTR1*, **30**:25-33.

Rodriguez, V.H.S., Midorikawa, S., 2002. Applicability of the H/V spectral ratio of microtremors in assessing site effects on seismic motion. *Earthquake Engineering & Structural Dynamics*, **31**(2):261-279. [doi:10.1002/eqe.108.abs]

Tan, R., 1983. Engineering Properties of Manila Subsoil. Graduate Thesis, University of the Philippines.