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GROUND MOTION CHARACTERISTICS AROUND KOBE CITY DETECTED BY MICROTREMOR MEASUREMENT

– THE GREAT HANSHIN EARTHQUAKE DISASTER –

FUMIAKI UEHAN and YUTAKA NAKAMURA

UrEDAS R&D Promotion Department,
Railway Technical Research Institute,
2-8-38, Hikari-Cho, Kokubunji-Shi, Tokyo 185, JAPAN
e-mail : uehan@rtri.or.jp

ABSTRACT

The investigation tours of microtremor measurement were conducted in and around Kobe City, and the dynamic characteristics of the surface layer and the wood houses were estimated. In this paper, the relationships between the estimated dynamic characteristics and the damages which were caused by the 1995 Hyogo-Ken Nanbu Earthquake are dealt with. Furthermore the efficiency of the evaluation method to grasp the vulnerability using microtremor measurements are discussed.

KEYWORDS

microtremor, surface layer, ground motion, spectral ratio, QTS, vulnerability index, Kobe City, Hyogo-Ken Nanbu Earthquake, wood house, Percentage of collapsed houses

INTRODUCTION

The January 17, 1995 Hyogo-Ken Nanbu Earthquake (The Great Hanshin Awaji Earthquake Disaster) was the most devastating earthquake to hit Japan since the 1923 Great Kanto Earthquake. The earthquake was assigned a JMA magnitude of 7.2 by the Japan Meteorological Agency (JMA), and the moment magnitude M_w was estimated to be 6.8 - 6.9. The major cause of death among approximately 6,000 fatalities was the collapse of old Japanese wood houses. Approximately 200,000 buildings were completely destroyed or half-destroyed, and many people were crushed to death beneath collapsed houses. The building damage was not very severe around Mount Rokko and on the reclaimed seaside land. The severely damaged areas formed an earthquake disaster belt zone in the downtown of Kobe City. From this observation, it was expected that the most severe damage of buildings were related to the dynamic characteristics of the subsurface at the zone. Thus the measurement tours were conducted in and around Kobe City, and the dynamic characteristics of the surface layer were investigated by using microtremors. Furthermore the dynamic characteristics of wood houses were investigated by using microtremors.

ESTIMATION OF DYNAMIC CHARACTERISTICS OF THE SURFACE LAYER

Geological Aspects and the Measurement Points Around Kobe City

Kobe City lies on a narrow coastal plain facing the Inland Sea and backs against Mount Rokko. Mount Rokko is composed primarily of granite, and moderate slopes exist at the foot of the mountain, consisting of series of alluvial fans of decomposed granitic soils. A flat plain is present in the alluvial lowlands between the Holocene coastal line and the present coastline of Osaka Bay. Some areas along the coastline were reclaimed by placement of fill, typically with decomposed granite soils. In order to investigate the changes of the dynamic characteristics of the surface layer from mountain side to sea side, measurement points were arranged as shown in Fig. 1. The measurement points are organized into several measurement lines which run from north to south, and each measurement line starts at the mountain side, and goes through the damage belt zone, and stops at the reclaimed seaside land which suffered damage from liquefaction.

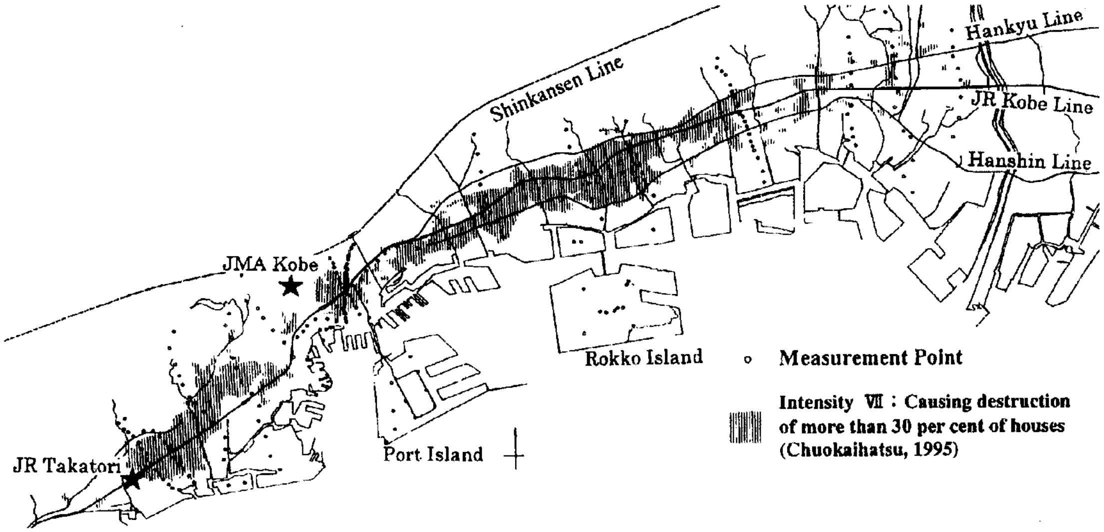

Fig. 1. Measurement points of microtremor in and around Kobe City

Outline of the Measurement and Analysis

Procedures for Measurement An instrument named PIC91 which has been developed by the Railway Technical Research Institute was used for the microtremor measurements. It consists of two sensor units, cables, and a main body made of an aluminum case which contains amplifiers, an A/D converter, and a notebook type personal computer. At every observation point, two horizontal components and one vertical component of microtremor on the ground surface were recorded every 1/100 sec for 40.96 sec. The measurement was repeated three times at each point.

Procedure for Analysis Fourier spectra for the recorded data were calculated and were smoothed 40 times by using the Hanning spectral window. One frequency spectrum of one component of microtremor was estimated by averaging the relevant three Fourier spectra. Furthermore, a spectral ratio between horizontal and vertical components was calculated and the spectral ratio which was named QTS (Quasi Transfer Spectrum) provided the predominant frequency (F_g) and amplification factor (A_g) of the surface ground (Fig. 2).

Vulnerability Index K_g Simplifying the shear deformation of the surface layer as shown in Fig. 3, average shear strain γ_g can be estimated as $\gamma_g = A_g\, d / H$, where A_g is the amplification factor of the surface layer, H is the thickness of the surface layer, and d is the seismic displacement of the basement. Expressing the S-wave velocities of the basement and surface layer as v_b and v_s respectively, the predominant frequency F_g of the surface layer can be expressed as $F_g = v_b / (4 H A_g)$. The acceleration in the basement can be expressed as $\alpha = (2\pi F_g)^2 d$. Then the shear strain γ_g is expressed as follow.

$$\gamma_g = (A_g\alpha/(2\pi F_g)^2)(4A_gF_g/v_b) = (A_g^2/F_g)(\alpha/\pi^2 v_b) = C_gK_g\alpha$$

where $C_g=1/(\pi^2 v_b)$, $K=A_g^2/F_g$. C_g is expected to be almost constant for any site (Nakamura *et al.*, 1990). K_g is a unique value corresponding to the site and can be considered as a vulnerability index of the site, which is expected to be useful in selecting weak points of the ground.

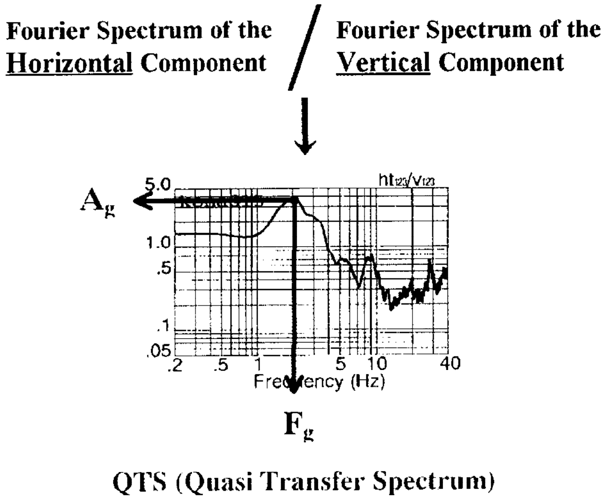

Fig. 2. Spectral ratio (QTS) and A_g, F_g.

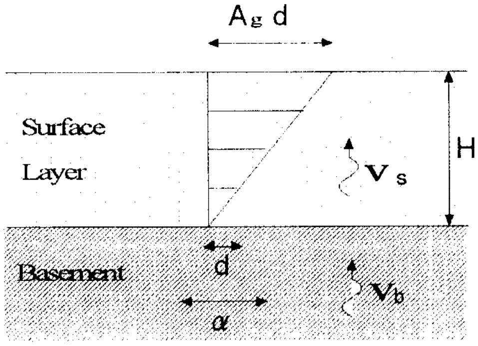

Fig. 3. Shear Deformation of the surface layer.

Comparison Between Estimated Ground Motion Characteristics and Damage Types

Fig. 4 shows the measured points around JR (Japan Railways) Sannomiya Station. The district is near JMA Kobe (the Japan Meteorological Agency Kobe Observatory) which recorded 818 Gal at main-shock, and the district consists of three types of ground (firm ground on the mountain side, flat plain, and reclaimed land). Thus it may be said that the geological features of the Sannomiya district are representative of the geology around Kobe City, and, rephrased, it may said that the damage types of the Sannnomiya district are typical of the damage types around Kobe City. It was confirmed that the predominant frequencies (F_g) were high at the mountain side, but gradually decreased toward the seaside. The predominant frequencies of the reclaimed island were lower than 1 Hz, and the vulnerability indexes (K_g) were great. The results indicate that the potential of the liquefaction can be estimated by using microtremor measurement (Uehan *et al.*, 1995). Fig. 5 shows the relationship between estimated ground motion characteristics and damage types (Sannnomiya). Slight Damage (triangle) corresponds to no damage or slight damage of buildings. The data which were assigned Slight Damage (triangle) were derived from the measurements points on the mountain side, and their predominant frequencies are higher than 2.5 Hz. Severe Damage (circle) corresponds to collapse or severe damage of buildings. The data which were assigned Severe Damage (circle) were derived from the measurement points on the earthquake damage belt zone and their predominant frequencies are distributed between about 1.5 and 2.0 Hz. Liquefaction (square) corresponds to liquefaction damage. The data which were assigned Liquefaction (square) were derived from the measurement points on the reclaimed land, and the buildings standing there did not suffer severe damage from ground shaking. The predominant frequencies of the data are lower than 1.5 Hz. As a result of the investigation of all the measured points shown in Fig. 1, the predominant frequencies of the surface layer were distributed between 1.2 and 2.5 Hz in the earthquake disaster belt zone (Uehan *et al.*, 1995).

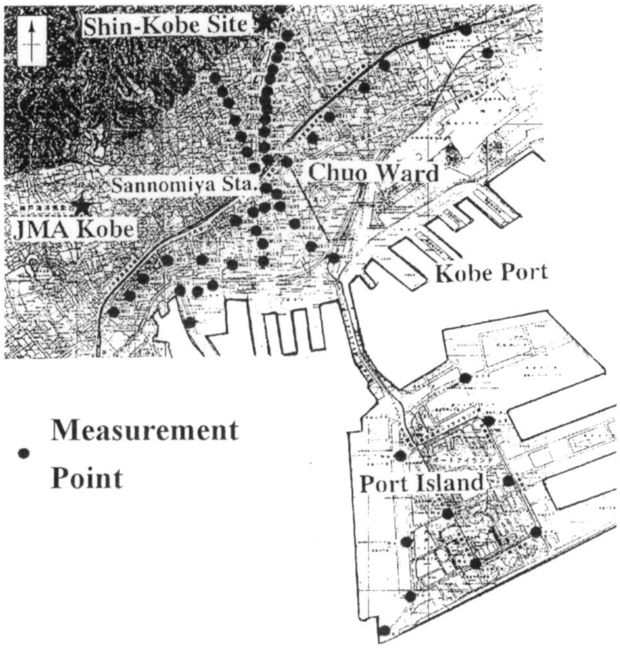

Fig. 4. Measurement points around JR Sannomiya Station.

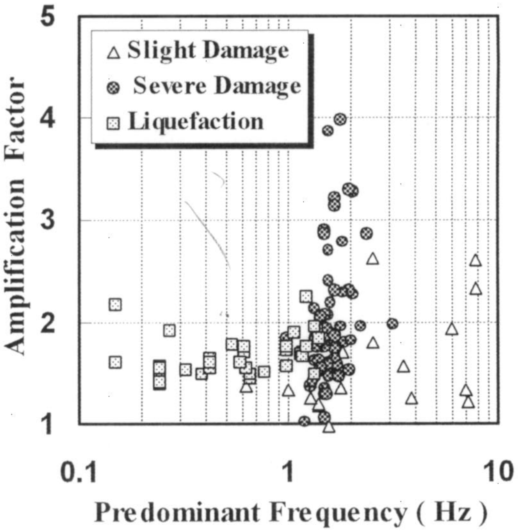

Fig. 5. Relationship between estimated ground motion characteristics and damage levels.

Comparison Between Vulnerability Index K_g and Percentage of Collapsed Houses

Fig. 6 shows the measured points around JR Takatori and Shin-Nagata Stations. The district is near the JR Takatori Site which recorded 616 Gal, and this district was one of the most severely damaged districts around Kobe City. As Fig. 6, detailed investigation about percentage of collapsed houses was enforced nearby the measurement lines of microtremors (Chuokaihatsu, 1995). The result of comparison between vulnerability index K_g and percentage of collapsed houses in Takatori district is shown in Fig. 7.

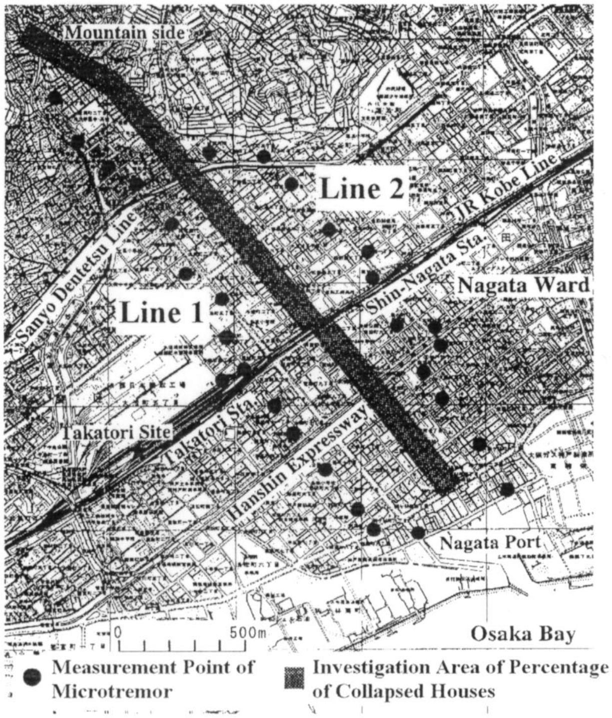

Fig. 6. Measurement points around JR Takatori and Shin-Nagata Station.

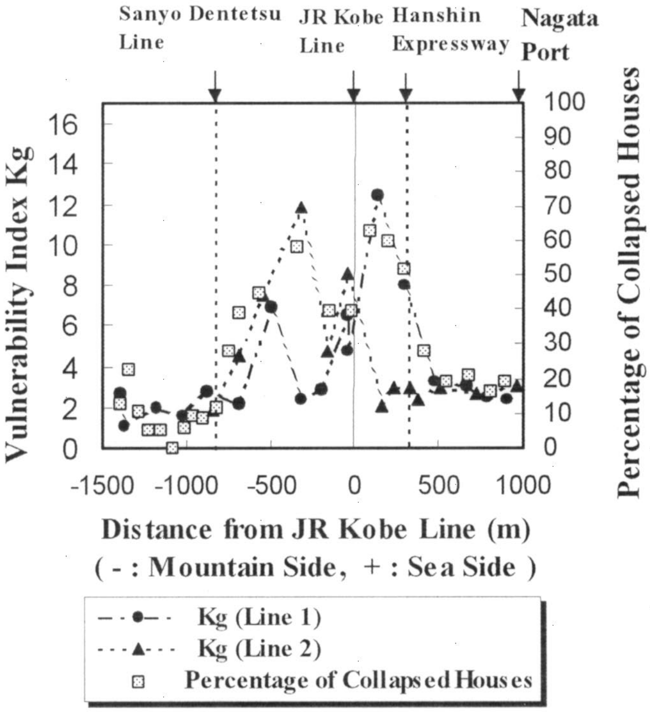

Fig. 7. Comparison between vulnerability index K_g and percentage of collapsed houses.

Vulnerability index K_g and the percentage of collapsed houses show similar tendencies. Although K_g was developed as the vulnerability index of the deformation of the ground, it is expected that K_g is significantly related to the damage of the houses when the ground is not severely liquefied.

ESTIMATION OF DYNAMIC CHARACTERISTICS OF WOOD HOUSES

Damage level of a structure is related to the relationship among the seismic motion of the basement, dynamic characteristics of the surface layer, and dynamic characteristics of the structure. The acceleration of the basement can be estimated by the strong motion records. The dynamic characteristics of the surface layer can be estimated by microtremor measurements. Here, dynamic characteristics of wood houses were investigated using microtremor measurements.

Outline of the Damage to the Wood Houses

In Japan, two-story wood houses (wood-frame building with weak walls and tile roof) are very popular for single family home construction, and heavy tile roofs in which the tiles are set with thick layers of mud was ordinarily used as a countermeasure against frequent attack of typhoons on the old wood houses around the Hanshin area. As a consequence of the large mass of these roofs, large inertial forces were generated during the earthquake and most of these wood houses collapsed. The dominant failure mechanism of wood houses was the collapse of the first floors caused by the inertial forces (Fig. 8).

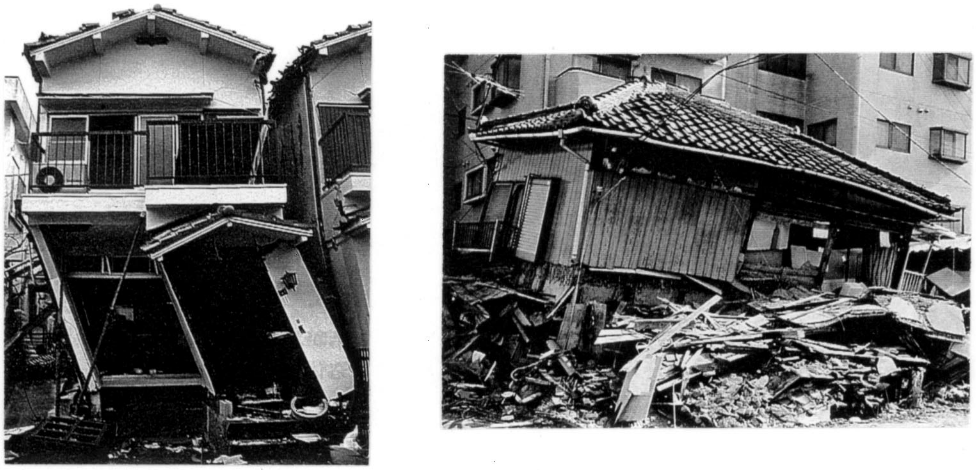

Fig. 8. Collapse of the first floors of Japanese wood houses.

Outline of the Measurement and Analysis

Measured Houses and Their Location The measured area is approximately 40 kilometers away from the epicenter (Fig. 9). In the area, the railway viaducts suffered severe damage, but the houses around the viaducts suffered minor damage. The microtremor measurements of wood houses were conducted on 25 houses with two stories, and the houses suffered slight damage or minor damage. The houses in this area are comparatively new and the roofs of houses are lighter than the roofs using thick mud which were popular in Kobe City. Therefore it is estimated that the natural frequencies of the houses in this area are higher than natural frequencies of old houses in Kobe City.

Procedures for Measurement Basic procedures for measurement were almost the same in the case of ground measurement, but two sensors were used in the case of measurement of structures. One sensor was put on the second floor of each wood house, another was put on the ground near each house and, microtremors of the house and the ground were recorded at the same time (Fig. 10).

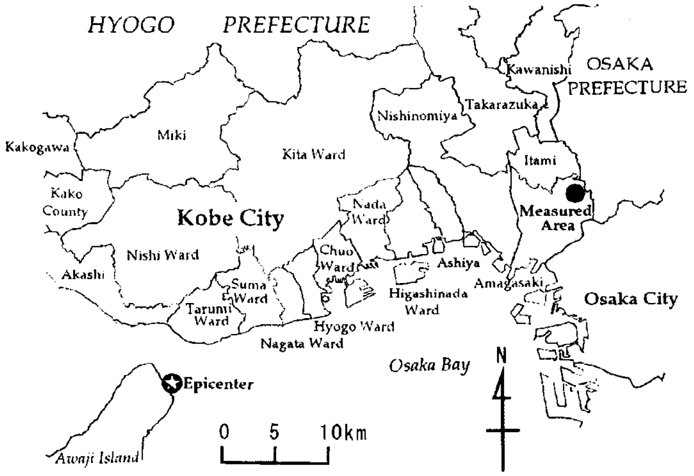

Fig. 9. Location of the measured area and epicenter.

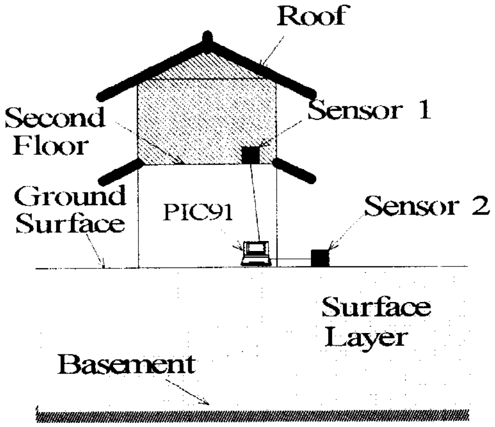

Fig. 10. Microtremor measurements of a wood house using two sensors

Procedure for Analysis Fourier spectra for the recorded data were calculated and were smoothed 20 times by using the Hanning spectral window. One frequency spectrum of one component of microtremor was estimated by averaging the relevant three Fourier spectra. Furthermore, a spectral ratio between horizontal component on the second floor and horizontal component on the ground was calculated, and the spectral ratio provided the predominant frequency (F_w) and amplification factor (A_w) of the wood house. In the same way, a spectral ratio between the horizontal component on the second floor and vertical component on the ground was calculated, and the ratio provided the combined predominant frequency (F_{gw}) and combined amplification factor (A_{gw}) of the entire wood house-surface layer system.

Fig. 11 shows deformation of a wood house during the earthquake. Focusing on the collapse of the ground floor, the wood house was simplified to a system with one degree of freedom. Where δ is the horizontal displacement of the second floor, h is the height of the second floor, W is the total weight of all components on the second floor and above, and g is gravity. Furthermore α_b is the horizontal acceleration of the basement, α_g is the horizontal acceleration of the ground surface, and α_w is the horizontal acceleration of the components on the second floor and above.

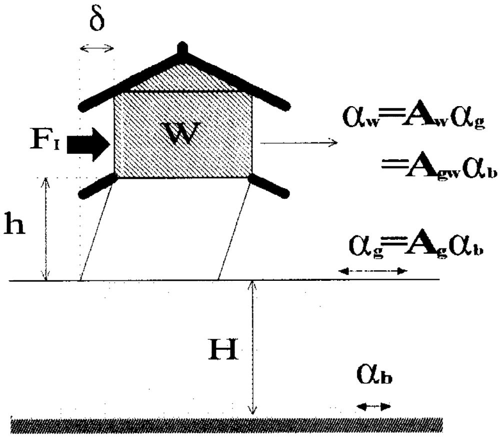

Fig. 11. Shear deformation of a wood house during an earthquake.

Shear strain between the second floor and the ground floor γ_w can be expressed as $\gamma_w = \delta/h$. Inertial force F_I can be expressed as $F_I = (W/g)\alpha_w$, and horizontal displacement of the second floor δ can be expressed as $\delta = F_I/k$, where k is the shear spring constant between the second floor and ground floor. Horizontal acceleration α_w can be estimated as $\alpha_w = A_w\alpha_g = A_{gw}\alpha_b$, where A_w is the amplification factor of the wood house and A_{gw} is the combined amplification factor of surface layer and wood house, and then shear strain γ_w is expressed as follow.

$$\gamma_w = 10000(W/gk)(A_{gw}\,\alpha_b)/h$$
$$= (10000/4\pi^2)(A_{gw}\alpha_b/F_w{}^2h) = K_w\alpha_b$$

where $K_w = 2500A_{gw}/\pi^2F_w{}^2h$. K_w can be considered as a vulnerability index of the wood house. In addition 10000 is a coefficient to adjust the calculated result to be in unit 10^{-6} strain, when seismic acceleration is measured in units of Gal (cm/s^2), and the height of the second floor is measured in units of meters (m).

Dynamic Characteristics of Wood Houses

Predominant frequencies of measured houses are shown in Table 1. The predominant frequencies of wood houses in this area range between 3.4 and 7.0 Hz, and the average is 4.4 Hz. Generally, the natural frequencies of two-storied wood houses ranged between 2 and 5 Hz (Hisada *et al.*, 1974). Therefore the results seem to be adequate. It can be estimated that the natural frequencies of old houses around Kobe City was rather lower than the frequencies of the houses in this area because of their deterioration and heavy roofs. It seems that the natural frequencies of the old houses around Kobe City were distributed approximately between 2 and 3 Hz .

Table 2 shows the vulnerability of houses estimated by microtremor measurements. House-A is the oldest house of all measured houses, House-B is the house which seemed to be at the average level in this area, and House-C is an RC two-storied building for comparison. House-A has the largest vulnerability and House-C has the smallest vulnerability as shown in Table 2. The basement acceleration is estimated to be approximately 100 Gal in this area, and it is about 1/2 of the basement acceleration of Takatori (Nakamura *et al*, 1996). The shear strain γ_w of House-A is almost the same as the strain defining the horizontal resistance (strength) of the wood house, and the damage of House-A (minor damage: Distress observed in the exterior finishes, but no visible residual inter-story displacement or structural damage, with the exception of minor localized cracking) supports the adequacy of the result.

Table 1. Predominant frequencies (F_w) of the measured houses

No.	F_w (Hz)	No.	F_w (Hz)	No.	F_w (Hz)	No.	F_w (Hz)	No.	F_w (Hz)
1	3.39	6	3.66	11	3.96	16	4.15	21	5.08
2	3.47	7	3.66	12	4.00	17	4.22	22	5.25
3	3.49	8	3.91	13	4.03	18	4.88	23	5.30
4	3.52	9	3.96	14	4.08	19	4.96	24	6.71
5	3.56	10	3.96	15	4.10	20	5.08	25	6.98

Max. = 6.98 Hz, Min. = 3.39 Hz, Ave. = 4.37 Hz

Table 2. Estimated dynamic characteristics, vulnerability index and share strain of the houses ($h = 2.8$ m, $\alpha_b = 100$ Gal)

	Damage Level	F_w (Hz)	A_w	F_{gw} (Hz)	A_{gw}	K_w	γ_w (10^{-6})
House-A (No. 1)	Minor damage	3.39	14.0	3.34	21.6	170	17000
House-B (No. 13)	Slight damage	4.03	6.82	3.66	8.14	45.4	4540
House-C (RC)	No damage	8.45	2.91	4.20	3.52	4.46	446

CONCLUDING REMARKS

It was considered that the severe damage of the buildings caused by the 1995 Hyogo-Ken Nanbu Earthquake was significantly related to the ground motion characteristics of the surface layer. The building damage was not very severe around Mount Rokko and on the reclaimed seaside land, and the severely damaged areas formed an earthquake disaster belt zone between them. According to the analysis of the microtremors, the dynamic characteristics of the surface ground were distinctly different among the three areas.

The predominant frequencies of the surface layer were estimated to be about 1.2-2.5 Hz in the area which suffered severe damage of wood houses. The natural frequencies of old wood houses were estimated to be about 2-3 Hz in and around Kobe City. These frequency ranges were dominant on the strong motion record at JMA Kobe. It was expected that the resonance among the three factors (old wood houses, surface layer, and the earthquake motion of the basement) was significantly related to the damage of the houses.

It was confirmed that the proposed evaluation methods using microtremors (QTS and Vulnerability Index K_g and K_w) were available to grasp the vulnerability of the surface ground and wood houses.

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