Paper No. 1655. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

EFFECTS OF IRREGULAR BEDROCK CONFIGURATION IN A SEDIMENTARY BASIN ON GROUND VIBRATION CHARACTERISTICS

---- POSSIBLE CAUSE OF DAMAGE DISTRIBUTION OF THE 1995 HANSHIN-AWAJI GREAT EARTHQUAKE DISASTER ----

Junpei AKAMATSU[1], Hideo SAITO[1], Mitsuru JIDO[1],
Hitoshi MORIKAWA[2], Keiichi NISHIMURA[3] and Masao KOMAZAWA[4]

[1] Disas. Prev. Res. Inst., Kyoto Univ., Gokasho, Uji, Kyoto 611, JAPAN
[2] Civil Eng. Dep., Fac. Eng., Kyoto Univ., Yoshidahonmachi, Sakyo, Kyoto 606-01
[3] Geophys. Inst., Grad. Sch. Sci., Kyoto Univ., Kitashirakawa, Sakyo, Kyoto 606-01
[4] Geological Survey of Japan, 1-1-3, Higashi, Tsukuba 305, JAPAN

ABSTRACT

Serious damage in the Kobe and Hanshin area caused by the Hyogoken-nambu (Kobe) Earthquake of January 17, 1995 (M=7.2) is distributed in a belt-like zone between Rokko mountain range and Osaka Bay. Across the belt-like zone, we surveyed the distribution of damage to buildings and houses and carried out observation of microseisms (long-period microtremors). Soil-induced amplifications in terms of spectral ratios, soil/rock, of microseisms were studied in relation to the configuration of bedrock, which was estimated from spectral ratio of horizontal to vertical components, H/V, of microseisms. In addition, 3-D bedrock configuration was discussed using bandpass-filtered Bouguer gravity anomaly. As a result, we found unusual vibrational characteristics and their spatial distribution, suggesting some step-like change in depth to bedrock near the belt-like zone. Such change in the bedrock configuration may cause focusing of seismic waves as well as interference between the secondary-generated surface waves and the incident S-waves, thereby bringing amplification of seismic waves responsible for the distribution of earthquake damage. It is demonstrated that comparative analysis of microseisms and gravity data is highly prospective for microzoning of an urban area in a sedimentary basin.

KEYWORDS

Damage distribution of the Hanshin-Awaji Great Earthquake Disaster; effects of irregular configuration of bedrock; vibrational characteristics of microseisms; soil-induced amplification; H/V of microseisms; Bouguer gravity anomaly; microzoning of urban area.

INTRODUCTION

The Hyogoken-nambu (Kobe) Earthquake of January 17, 1995 (M=7.2) brought destructive damage to Kobe and Hanshin area in the northern margin of the Osaka basin (The Hanshin-Awaji Great Earthquake Disaster). The extremely serious damage of JMA(Japan Meteorological Agency) Intensity 7 is distributed on E-W oriented belt-like zone in the narrow urban area between the mountain range to the north and the Osaka Bay to the south. The damage distribution is supposed to be due to the movement of buried active faults or to the amplification by thin Alluvium. It should be noted, however, that the earthquake damage is distributed not only in the Kobe-Hanshin area but also in wide areas including the eastern part of the Osaka basin located more than 30 km from the source region; in this part, severe damage to buildings and houses is distributed along a north-south line where the bedrock is elevated stepwise from about 1,500 m to 700 m in depth (Nakagawa and OCU Team, 1995). This suggests that the bedrock configuration may affect the damage distribution significantly, in addition to the thin Alluvium, and that the belt-like zone of damage in the Kobe-Hanshin area itself may be controlled, at least partly, by the irregular configuration of bedrock in the northern margin of the Osaka basin. In this connection, microzoning based on subsurface structure and ground vibration characteristics related to bedrock configuration is very important. For this, the use of various geophysical data such as microseisms (long-period microtremors) and Bouguer gravity anomaly is advantageous (Akamatsu *et al.*, 1995a, 1996).

In order to study the relation between the damage distribution and the vibrational characteristics of thick soil sediments related to bedrock configuration, we carried out observations of microseisms in the Kobe area, along several observation lines across the belt-like zone, and surveyed the damage to buildings and houses along the observation line. The analyses are based on (1) spectral ratio of microseisms between soil sites and rock sites (soil/rock) for soil-induced amplification factor, (2) spectral ratio between the horizontal and vertical components of microseisms (H/V) observed on soil sites for characteristic frequency of soil ground, which in tem provides the information about the depth to bedrock; and (3) bandpass-filtered Bouguer gravity anomaly obtained by the upward-continuation technique, which enables us to examine 3-D subsurface structure, mainly the relief of bedrock.

OBSERVATION OF MICROSEISMS

The study area is shown in Fig. 1 with the observation lines of microseisms, A, B and C. Figure 2 shows the location of the observation sites. Along the observation line A, comparative observations of microseisms were made at 16 soil sites and a rock site taken as a reference site. At the rock site a 15-minute recording was repeated every 30 minutes. Along the observation line B, simultaneous 15-min recordings at soil sites and a reference rock site were obtained (9 soil sites). We used 10-s 3-component seismometers at all the sites, with an exception that 1-s seismometer was used at the reference rock site on the line A. The southern 4 sites, MKH, SYH, KYN and KYS, on the line A, and 2 sites, DKT and PID, on the line B are located on the reclaimed lands. Observations on the line C were made at 7 soil sites to study the general characteristics of microseisms in the wider area in the Osaka basin. Examples of the velocity power spectra and the ratio, H/V, are shown in Fig. 3.

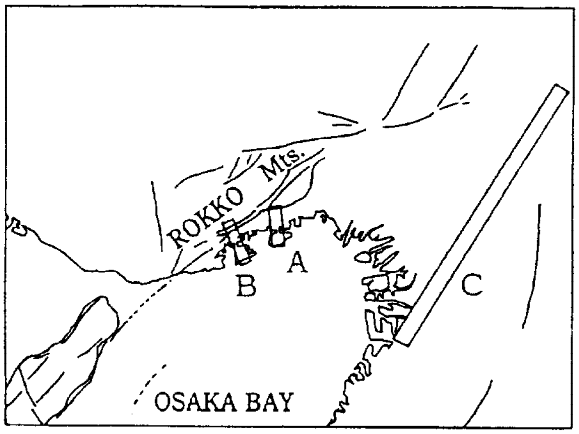

Fig. 1. Location of the study area affected by the 1995 Hyogoken-nambu Earthquake. Microseism observations were carried out in the area A, B and C. Damage to buildings and houses was surveyed in the area A.

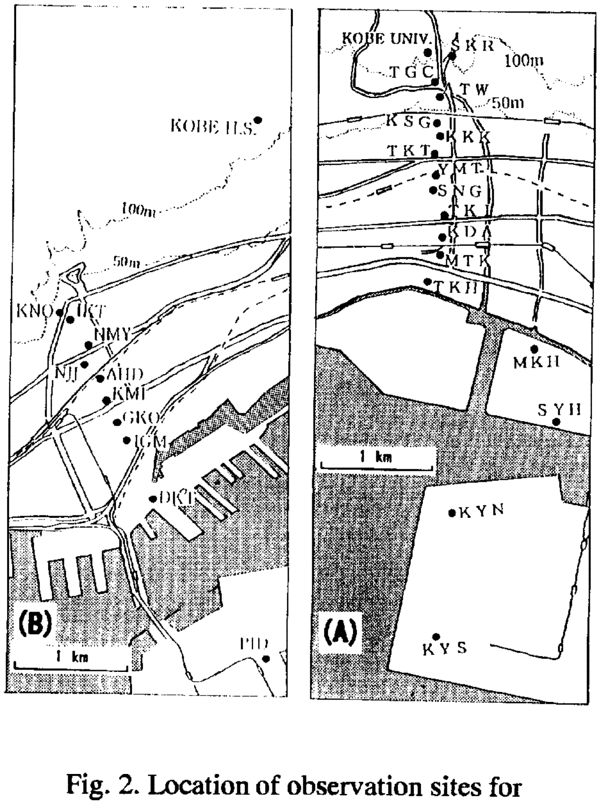

Fig. 2. Location of observation sites for microseisms. KOBE UNIV and KOBE H.S. denote the reference rock sites for observations on line A and B, respectively.

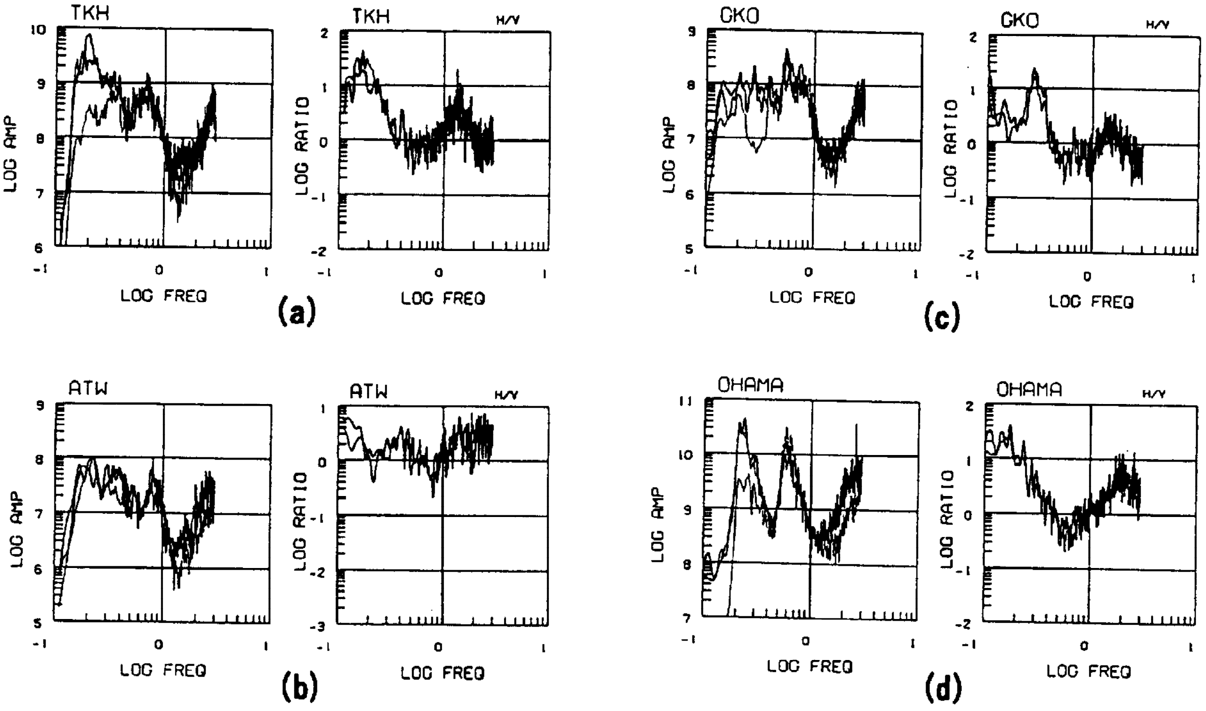

Fig. 3. Examples of velocity power spectra and H/V of microseisms in the observation line A (a, b), line B (c), and southernmost site in line C (d).

DAMAGE SURVEY OF BUILDINGS AND HOUSES

The damage to every buildings and houses was surveyed for a width of two blocks along the observation line A. The total number of surveyed buildings and houses was 1,296. The damage is classified into 4 levels; no damage or slight, light, moderate, and heavy or collapse. We divided the survey area into 9 small subareas to observe the spatial distribution of damage (Akamatsu *et al.*, 1995b). Figure 4 shows the percentage of the highest damage level, heavy or collapse, for the wooden houses in each subarea. It is noted that there is a remarkable contrast between subareas 3 and 4, and between subareas 8 and 9. The severely damaged subareas from 4 to 8 are located within the belt-like zone of JMA Intensity 7.

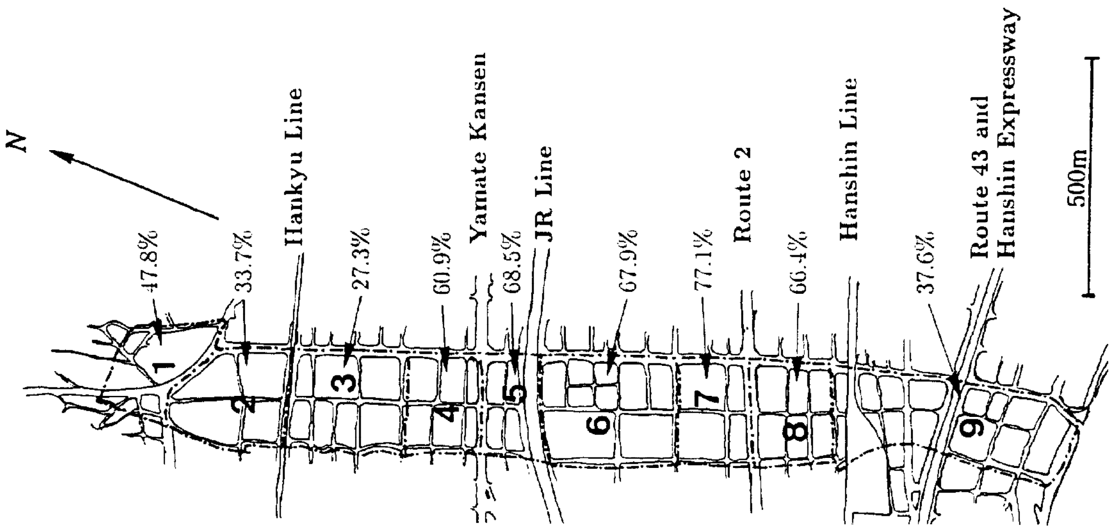

Fig. 4. Distribution of heavy damage to wooden houses along the line A.

Spatial Distribution of Soil-Induced Amplifications

The power spectra at all the sites show remarkable troughs around 1.5 Hz. In the frequency range lower than these troughs, the observed microseisms are considered not to be largely affected by artificial ground noise. Therefore, we can discuss the soil-induced amplification factors with the spectral ratios, soil/rock, in the frequency range from 0.2 to 1.3 Hz (Akamatsu *et al.*, 1992). Figure 5 shows the spatial change in the ratios of spectra averaged over the various frequency bands at a one-octave width. The notable features are: (1) the soil-induced amplifications in the frequency range of 0.2 - 1.3 Hz, both for the horizontal and vertical components, becomes large from north to south with a remarkable increase in amplification in the region south to the middle of the belt-like zone; (2) the amplification of vertical component is nearly equal to or even larger than that of horizontal component in the range of 0.4 - 1.3 Hz, while in the lower frequency range of 0.2 - 0.4 Hz, the horizontal amplification is larger than vertical one as usually observed in the soil sediments (Akamatsu et al., 1991, 1992, 1996).

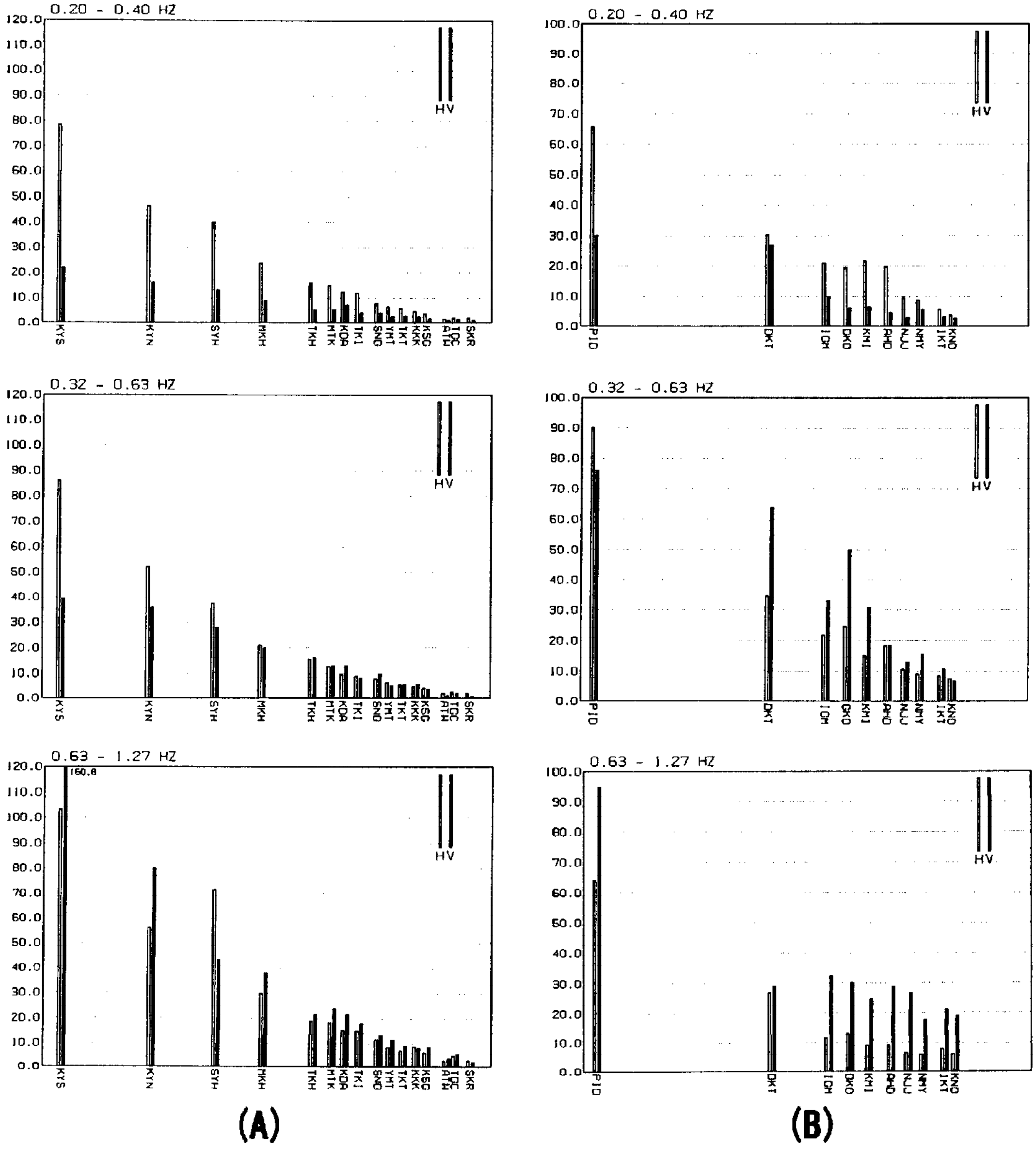

Fig. 5. Spatial distribution of soil-induced amplifications in term of power ratios, soil/rock, for microseisms in the observation line A and B.

Spatial Change in Peak Frequency of H/V

Both on the observation lines A and B, H/V has a sharp peak in the coastal region, though the peak value is lowered and its frequency becomes higher toward inland area. At the southern sites on the line A, sharp peak of H/V appears around 0.17 Hz, and shifts slightly to 0.22 Hz from the coastal region to the middle of the severely damaged belt-like zone, while to the north of the zone the peak of H/V almost disappears. On the line B, the peak frequency varies gradually from 0.19 Hz to 0.4 Hz. At the two rock sites, spectral shapes of the horizontal components are nearly the same as those of the vertical one, and H/V is almost 1 in the frequency range lower than 0.15 Hz. Figure 6 shows the spatial change of the peak frequency (in term of period). On the observation line C, all the sites show the remarkable peaks; the peak frequency varies from 0.26 Hz at the northernmost site to 0.16 Hz at the southernmost site. At the southernmost site the depth to bedrock is considered greater than 1,400m.

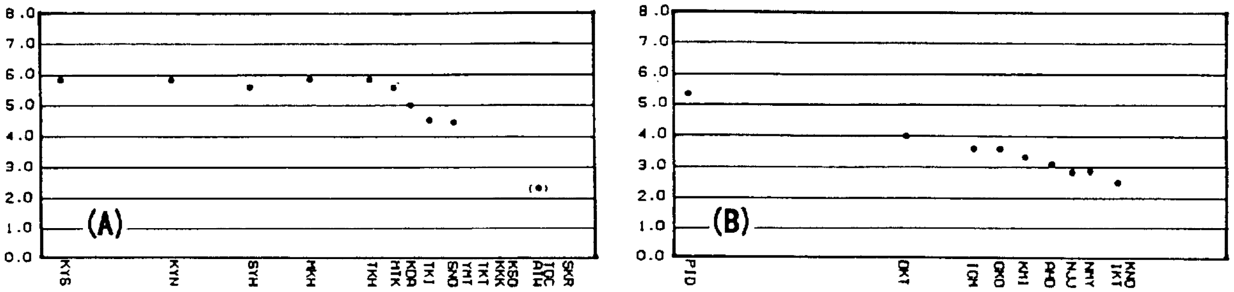

Fig. 6. Spatial change in peak period of H/V of microseisms along the observation lines A and B.

CONFIGURATION OF BEDROCK

Depth to Bedrock Inferred from Peak Frequency of H/V

Figure 7 shows a relation between peak period of H/V and depth to bedrock. This figure uses the data sets obtained both in the Kushiro plain, Hokkaido, Japan (Akamatsu et al., 1994a) and the Shanghai plain, China (Akamatsu *et al*., 1994b). There is a linear relation in the depth range greater than about 100m, in spite that the geological condition of the soil sediments seems to be different between the two plains. This means that, as long as the Pleistocene soil-sediments are much thicker than the Alluvial sediments, the mean velocity of the soil sediments is nearly the same and the impedance ratio is the largest between the soil sediments and the bedrock. Therefore, it seems reasonable to consider that, an empirical linear-relation between the peak period of H/V and the depth to bedrock exists generally for an area on thick soil-sediments. We used this relation to estimate the depth to bedrock from the observed peak frequency of H/V.

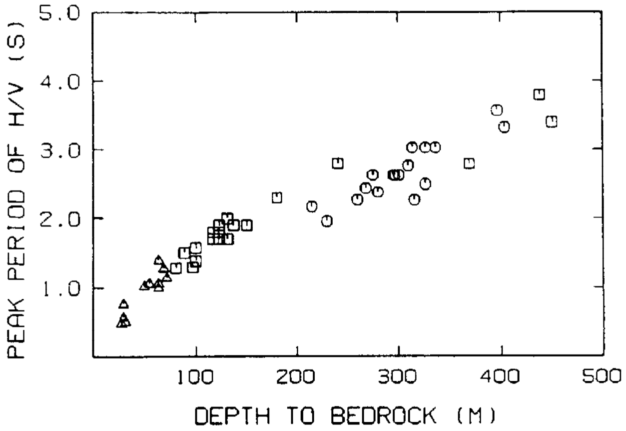

Fig. 7. Relation between peak period of H/V and depth to bedrock. Data were taken from the Kushiro plain, Hokkaido, Japan and the Shanghai plain, China.

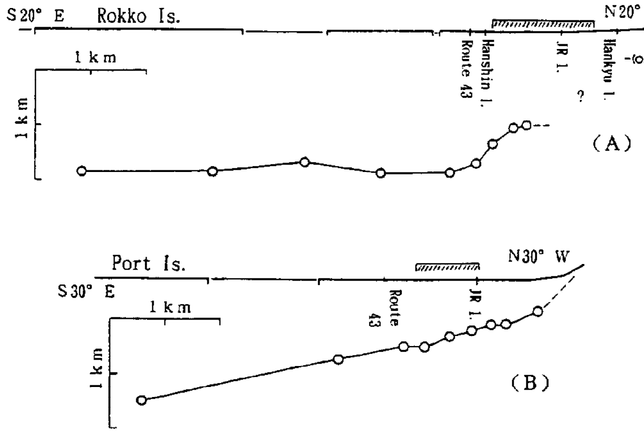

Fig. 8. Depth to bedrock inferred from H/V of microseisms. Shadows show the seriously damaged area. Note that the damage area is located where the depth to bedrock changes abruptly.

The result is shown in Fig. 8 for the observation lines A and B. The main features of the bedrock configuration are: (1) the bedrock subsides from 0 m at the foot of the mountains to 1,000m or more under the reclaimed lands; (2) the increase in depth to bedrock is abrupt in the northern part of the lines, while it is gradual or not determined in the southern parts; and (3) there is some difference in the spatial change in the depth to bedrock between the lines A and B. It should be noted that, the abrupt changes of (2) occur under the belt-like zone and/or between the belt-like zone and the foot of the mountains, although it is difficult to clarify whether the increase in depth is stepwise or gradual.

Comparison with Bandpass-Filtered Bouguer Gravity Anomaly

To discuss 3-D configuration of bedrock, we analyzed the gravity data. The data set was provided by Japan Geological Survey. The analyzing procedure is as follows: (1) calculation of the Bouguer gravity anomaly as mesh data with 500 m grid interval; (2) separation of the residual component from the regional one with combined use of upward-continuation filters (Gupta and Ramani, 1980). The original Bouguer gravity anomaly was calculated with a reduction density of 2.45 gr/cm^3, focusing on the shallow structure. The residual component of gravity anomaly was obtained as the difference between the anomalies continued to the heights of 50 m and 2,000 m. This means that the gravity anomaly was bandpass filtered so as to suppress both the regional component with the horizontal wavelength longer than about 6 km and the so-called noise with extremely short wavelength. According to Komazawa(1984), the bandpass-filtered anomaly thus obtained are due to the density distribution down to the depth of 1.5 km. In this depth range the difference in density is largest between the soil sediments and the bedrock, therefore it is highly probable that the bandpass-filtered anomaly reflects the configuration of bedrock.

Figure 9 shows the map of bandpass-filtered Bouguer gravity anomaly and its profiles along the observation line of microseisms. The contour intervals are 0.5 m Gal. The white and dotted areas show negative and positive anomaly, respectively. The anomaly changes rapidly from the mountain area to the sedimentary region with the positive to negative change near the foot of the mountain range. It should be noted that, along the observation lines of microseisms, the positive to negative change occurs where the depth to bedrock changes abruptly as shown in Fig. 8. Moreover, the spatial change of the anomaly around the 0 mGal level is steeper along the line A (up to 3.8 mGal/km) than along the line B (up to 2.7 mGal/km). This difference is well explained by the difference in the spatial change of depth to bedrock between the lines A and B.

DISCUSSION

From the analysis of microseisms, the bedrock appears to subside from 0 m near the foot of the mountains to 1,000 m or more below the reclaimed land, with abrupt change in the northern part of the lines (Fig. 8). This is supported by the distribution of the bandpass-filtered Bouguer gravity anomaly (Fig.9). Because both the wave length of microseisms, more than 1.5km at 0.4 Hz, and the grid interval of mesh data of the gravity, 500m, are longer than or comparable to the lateral scale of the abrupt changes, it can not be

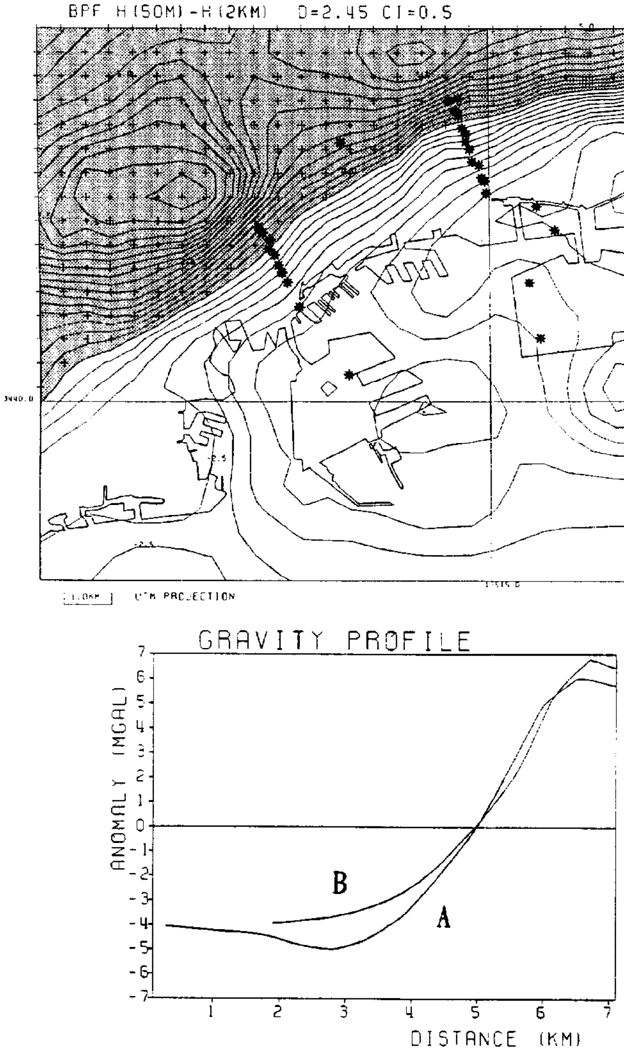

Fig. 9. Bandpass-filtered Bouguer gravity anomaly (a) and its profiles along microseism observation lines A and B (b). White and dotted areas denote negative and positive anomaly. Contour interval is 0.5mGal. Bold lines in the profile correspond to the observation lines of microseisms.

determined whether the change is stepwise or not. Recently, seismic reflection experiments carried out along north-south lines in the Kobe-Hanshin area revealed some step-like structures of soil sediments near the foot of mountains (Endo *et al.*, 1995). Therefore, it is highly probable that the bedrock subsides stepwise between the belt-like zone and the foot of the mountains.

The belt-like zone of damage is located on the deeper side of the step (Fig. 8), from which to the coastal region both the horizontal and vertical soil-induced amplifications become very large. The large amplification of vertical components comparable to the horizontal one (Fig. 6), is attributable to both the thick soil sediments and steep configuration of bedrock, because in the case of sedimentary region where the bedrock is not so deep and steep, the horizontal amplification is usually much larger than vertical one (Akamatsu *et al.*, 1991, 1992, 1996). A question arises, however, why the seriously damaged area was concentrated in a narrow belt-like zone within the wide area with large amplification of microseisms. At this point, it should be noticed that the frequency of the amplifications inferred from microseisms is much lower than the natural frequency of wooden houses, typically 2 - 10 Hz. The step-like configuration of bedrock may cause focusing of high-frequency seismic-waves, which results in a concentration of seismic energy in a narrow region on the deeper side of the step (Nakagawa and OCU Team, 1995). Such phenomenon was observed during the 1963 Skopje Earthquake (Poceski, 1963). It is also supposed that interference between the surface waves secondarily generated at the edge of the basin and the incident S-waves under the belt-like zone brings large amplitude in that zone. The amplitudes of aftershocks in this high-frequency range observed in the belt-like zone were much larger than those in the neighboring regions, and are explained by the interference (Pitarka *et al.*, 1996). Therefore, the phenomena of focusing and interference due to the irregular configuration of bedrock are considered to be responsible for the appearance of the belt-like zone.

In a viewpoint of microzoning of an urban area in a sedimentary region, it is very important to clarify the subsurface structure and its seismic effect. For this, the comparative analysis of microseisms and gravity data is very useful, because these data reflect the different physical parameters, that is, the distribution of impedance and that of density. In the case where detailed information of subsurface structure is not available, the Bouguer gravity anomaly, especially when bandpass filtered, provides some image of 3-D bedrock configuration responsible for ground vibration characteristics inferred from microseisms.

CONCLUSION

The belt-like zone of severe damage caused by the 1995 Hyogoken-nambu Earthquake is located on thick soil sediments. Between the belt-like zone and the foot of the mountains, the depth to bedrock increases stepwise. The step-like configuration of bedrock may cause focusing of seismic waves as well as interference of secondary-generated surface waves and incident S-waves, which brings large amplitude of seismic waves responsible for the distribution of earthquake damage. In conclusion, it is very important to clarify the detailed structure of the bedrock and its effects on ground vibration characteristics during strong motion in a sedimentary basin. For this purpose, the microzoning based on the comparative analysis of microseisms and Bouguer gravity anomaly is highly prospective.

REFERENCES

Akamatsu, J., Fujita, M. and Kameda, H. (1991) Long-period (1-10 s) microtremor measurements in the area affected by the 1989 Loma Prieta earthquake, *Proc. 4th Int'l Conf. on Seismic Zonation*, II, 393-400.

Akamatsu, J., M. Fujita, and K. Nishimura (1992). Vibrational characteristics of microseisms and their applicability to microzoning in a sedimentary basin. *J. Phys. Earth*, 40, 137-150.

Akamatsu, J., K. Nishimura, M. Komazawa, K. Onoue, A. Kitahara and H. Morikawa (1994a). Earthquake disaster on thick soil sediments --Case study for the Kushiro plain--. *Proc. Geo-Environments and Geo-Technics, Geo. Soc. Jap.*, 4, 375-380 (in Japanese with English abstract).

Akamatsu, J., W. Li, H. Morikawa, H. Saito, Q. Lu, N. Tao, H. Kameda, Z. Zaiyong and T. Fujiwara (1994b). Vibrational characteristics of soil sediments in the Shanghai plain inferred from microseisms. *Annuals Disas. Prev. Res. Inst., Kyoto Univ.*, 37B-1, 119-126 (in Japanese with English abstract).

Akamatsu, J., K. Nishimura and M. Komazawa (1995a). Microzoning of a sedimentary region based on comparative analysis of microseisms and gravity data. *Proc. 5th Int's Conf. on Seismic Zonation*, II, 933-940.

Akamatsu, J., H. Morikawa, H. Saito and M. Jido (1995b). Relation between the distribution of damage caused by the 1995 Hyogoken-nambu Earthquake and ground vibration characteristics inferred from microseisms. *J. Natural Disas. Sci.*, 16-2, 63-70.

Akamatsu, J., H. Yasui, K. Nishimura and M. Komazawa (1996). Application of microseisms to microzoning of an urban area in a sedimentary basin. *Proc. IASPEI Symp. S2, Earthquake Hazard and Risk, Advance in Natural and Technological Hazard Res., Kluwer Academic Publs* (in press).

Endo, H., S. Watanabe, M. Makino, Y. Murata, K. Watanabe and A. Urabe (1995). Subsurface geology and disaster caused by the 1995 South Hyogo Earthquake. *Proc. of Symp. on The Great Hanshin-Awaji Earthquake and Its Geo-Environments, The Committee of Environmental Geology, Geol. Soc. Jap.*, 219-224.

Gupta, V. K. and Ramani, N. (1980). Some aspects of regional-residual separation of gravity anomalies in a Precambrian terrain, *Geophysics*, 45, 1412-1426.

Komazawa, M. (1984). On the quantitative gravimetric analysis in the Hokuroku district. *Geophy. Explor.*, 37, 123-134 (in Japanese with English abstract).

Nakagawa, K. and OCU. Investigation Team an the Hanshin Great Earthquake disaster (1995). A relation between earthquake ground failure and subsurface structure. *Proc. of Symp. on The Great Hanshin-Awaji Earthquake and Its Geo-Environments, The Committee of Environmental Geology, Geol. Soc. Jap.*, 233-238.

Pitarka, A., K. Irikura, T. Iwata and T. Kagawa (1996). Was the basin edge geometry responsible for the damage concentration in Higashinada-ku during the 1995 Hyogoken-nanbu (Kobe) Earthquake. *J. Phys. Earth* (in press).

Poceski, A. (1963) The ground effects of the Skopje July 26 1963 earthquake. *Bull. Seism. Soc. Am.*, 59, 1-22.