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Site Effect Analysis in the Taipei Basin: Results from TSMIP Network Data

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ABSTRACT

The Taipei basin is a triangle-shaped formation. The ground surface of the basin is almost flat, but tilting gently to the northwest. The geological structure inside the basin consists of Quaternary layers above the Tertiary base rock. A dense strong motion observation network has operated in the Taipei area since 1991, as part of the Taiwan Strong Motion Instrumentation Program (TSMIP). Characteristics of site effects in the Taipei basin are studied using the data recorded by this observation network. In this study, the method of amplitude spectrum ratio is used to analyze site effects in the Taipei basin. This analysis clearly shows that the spectral ratio contours at low frequency bands (0.2 - 1 Hz) correlate with the structures of the Tertiary basement shape and the top soft soil layer. For the higher frequency band (1 - 3 Hz), the main amplification effects occur near the north, east, and south basin edges. This shows that the edge effect found in the Kobe earthquake could possibly occur in this area. Dominant frequencies in the Taipei basin area are also given in this study. This will benefit the microzonation work for future earthquake hazard mitigation in the Taipei basin.

(Key words: Taipei basin, TSMIP, Spectral ratio, Site effects, Dominant frequency)

1. INTRODUCTION

Taiwan is located on the Circum-Pacific seismic belt. The seismicity in the Taiwan area is very high (Hsu, 1961). Therefore, protection of lives and property from disastrous earthquakes are a major concern of the people in the region. The damaging effects of earthquakes are primarily caused by strong ground shaking. To reduce the loss of life and property from strong ground shaking, there needs to be conscientious application of construction codes and earthquake resistant designs, enforcement of effective land-use policies as well as implementation of appropriate retrofit measures. The implementation of such mitigation measurements must be based in large part on the recordings from large earthquakes at distances from 0 to 100 km.

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Such data are crucial for designing earthquake resistant structures and understanding the source mechanisms of earthquakes and the propagation of seismic waves from source to site, including the local site effects.

Amplification of strong ground motion by alluvial deposits during an earthquake has been documented on a lot of occasions and shown to cause damage in recent large earthquakes, for example, 1985 Michoacan earthquake, 1989 Loma Prieta earthquake, 1994 Northridge earthquake, and 1995 Kobe earthquake. Many studies (Boore *et al.*, 1993, 1994; Anderson *et al.*, 1996) have shown that the top alluvium layer will play an important role for site amplification effects. Therefore, site effects studies are very important for mitigating damage during an earthquake. Many methods have been used to characterize site amplification. The best approach is through direct observation of seismic ground motion, although such observations are limited to high seismicity areas and by high cost. A dense strong motion observation network provides an opportunity to understand the basin effects in the Taipei basin. The preliminary results of the site responses in the Taipei basin have been given by Kuo *et al.* (1995) and Wen *et al.* (1995a). In this study, we collect more data and systematically analyze the TSMIP earthquake records for understanding the basin responses by using the spectral ratio method. The average spectral ratio contours at some specific frequencies are selected to compare with the geological and velocity structures under the Taipei basin. For the engineering concern, the dominant frequency pattern in the Taipei basin area is also discussed in this study.

2. GEOLOGICAL STRUCTURE OF THE TAIPEI BASIN

The Taipei basin is a triangle-shaped alluvium structure, with Shanchia, Kuantu, and Nankang at the southwestern, northwestern, and eastern corners (Figure 1). The ground surface of the Taipei basin is almost flat and tilting gently to the northwest. The total area of the Taipei basin is about 240 square kilometers with an altitude of less than 20 meters. The Keelung River flows through it in an east-west direction, the Dahang Creek from the south through the basin center and then northwest to the ocean, and the Chingmei Creek from the southeast merges with the Dahang Creek at around the basin center. Because the Taipei basin is filled with the unconsolidated sediments, its subsurface geology can only be established by information obtained from boring, electrical, and seismic prospecting (Wang *et al.*, 1978; Wang and Lin, 1987). Recently, the basement structure of the Taipei basin area has been explored by deep boring work undertaken by the Central Geological Survey (Fei and Lai, 1994) and a dense reflection seismic survey conducted by the National Central University (Wang *et al.*, 1994a, 1994b; Hsieh *et al.*, 1994). The dotted contour lines in Figure 1 indicate the depth to the basement rock in the Taipei Basin, from inner to outer each line shows the depth from 400 to 100 m, respectively.

The geological structure inside the basin has the Quaternary layers above the Tertiary base rock. The stratigraphic formations of the Quaternary layers are, in descending order, surface soil, the Sungshan Formation, the Chingmei Formation, and the Hsinchuang Formation. The Sungshan Formation is composed mainly of alternating beds of silty clay and silty sand, and covers almost the whole Taipei basin. The Chingmei Formation is a fan-shaped body of conglomerate deposits. The Hsinchuang Formation consists of bluish grey, clayey

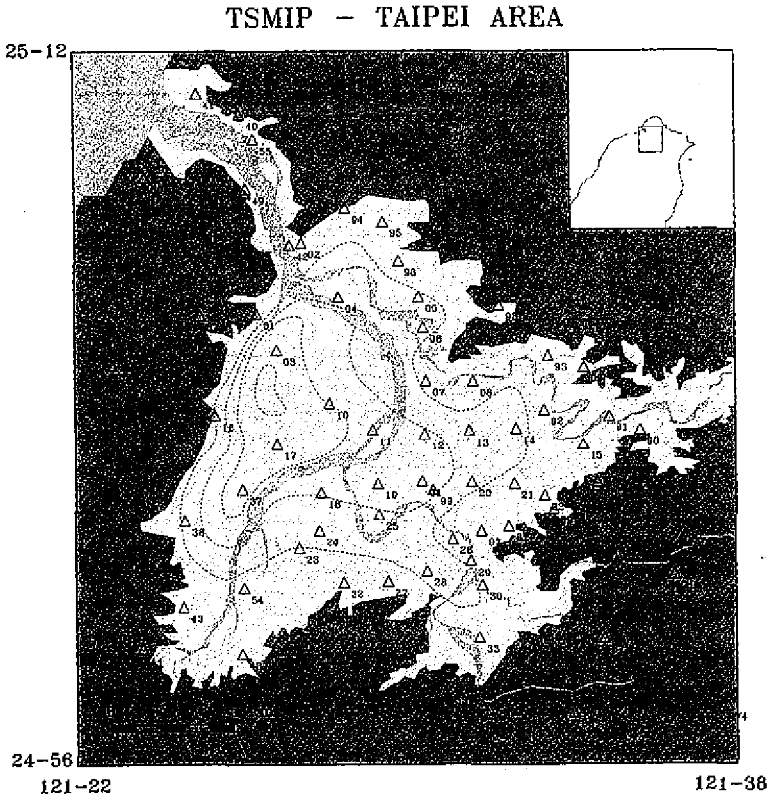


Fig. 1. Locations of the TSMIP network stations in Taipei area. Numbers indicate the station codes. The dotted contours indicate the depth in meters to the base rock surface in the Taipei basin, from inner to outer each line shows the depth from 400 to 100 m, respectively.

sand with some conglomerate beds (Wang and Lin, 1987). Recently, Teng *et al.* (1994) separated the Hsinchuang Formation into Wuku and Panchiao Formations. Wen *et al.* (1995b) calculated the V_p and V_s from surface to the depth of 350 meters through the travel time analysis of seismic waves by using the Wuku downhole records in the western part of Taipei basin. The average P- and S-wave velocity structures of the Taipei basin are shown in Table 1 which were results from the reflection seismic survey in the whole Taipei basin area done by Wang *et al.* (1996).

3. TSMIP NETWORK AND EARTHQUAKE DATA

The Taiwan Strong Motion Instrumentation Program (TSMIP, Shin, 1993; Kuo *et al.*, 1995) is conducted by the Seismological Observation Center of the Central Weather Bureau, Taiwan, ROC. The main purpose of this program is to study the characteristics of ground motion in different geological conditions, and the responses of various types of man-made

Table 1. Velocity structure of Taipei Basin (Wang *et al.*, 1996).

Formation	Depth (m)		Vp	Vs
	Northwest	Southeast	(m/sec)	(m/sec)
Sungshan	0-25	0-15	450	170
	20-50	15-35	1500	230
	50-100	35-50	1600	340
Chingmei	100-160	50-100	1800	450
Wuku	160-320	100-200	2000	600
Panchiao	320-400	200-250	2200	650
Basement			3000	1200

structures. All results can be used to improve the design spectrum and building codes in current use. The program installed up to 600 digital free field strong motion instruments and 400*3 digital channels of strong motion monitoring systems in nine metropolitan areas. About 100 free field stations are already in operation in Taipei area, and 43 stations are within the Taipei basin. The station interval is about 2 km, on average. The distribution of stations is shown in Figure 1 in triangle symbols and the number near each station gives the station code. Each station includes one strong motion instrument and a recording room. A strong motion instrument is a force-balance accelerometer. The recorder has 16 bits' resolution, can record the ground motion within ±2g, and has pre-event and post-event memory. Each strong ground motion station has the same design. A small fiberglass house covered on a concrete plate as a recording room. All stations have AC power. In the event of a power system shutdown by earthquake or other causes, the recording system can still operate for about 4 days on DC power.

By the end of 1995, many earthquakes had been recorded by this network since its installation. The events that triggered more than ten stations are listed in Table 2. All events were at least 30 km away from the Taipei basin. Source parameters in Table 2 are determined by the local seismic network of the Central Weather Bureau, Taiwan. The magnitude range is from 4.6 to 6.6 on the local magnitude scale, hypocentral depths cover from 3 to 116 km, and most of the peak ground accelerations (PGA) within the basin are all lower than 50 gal, except in four events. In this study, the characteristics of the ground motions are analyzed in the frequency domain by the spectral ratio method to understand site effects in the Taipei basin area. Earthquakes marked by symbol * in Table 2 are used for the spectral ratio analysis. Figure 2 shows a typical waveform recorded at station TAP001, which is located at the Central Weather Bureau, near the basin center. Although the PGA is lower than 10 gal, but the resolution is good enough to use for our analysis.

Table 2. Earthquakes used in this study.

Event	Origin Time	Epicenter	Depth (km)	M_L	No.	PGA (gal)
1*	1992-09-28 14:06:02.85	122.67°E 23.87°N	18	5.8	12	16(08)
2*	1993-01-23 08:59:26.31	121.74°E 24.08°N	29	5.6	18	17(22)
3	1994-01-20 05:50:15.57	121.85°E 24.06°N	49	5.6	32	22(22)
4	1994-02-01 22:44:27.66	122.69°E 24.75°N	116	6.1	24	23(22)
5	1994-03-06 19:37:20.98	122.02°E 24.82°N	98	5.5	12	19(22)
6	1994-04-18 10:36:41.69	122.03°E 24.80°N	95	5.1	11	16(22)
7	1994-04-30 09:14:17.12	122.07°E 24.35°N	4	5.0	17	29(22)
8	1994-05-19 06:03:40.99	121.71°E 24.72°N	87	4.6	12	12(22)
9*	1994-05-23 15:16:58.75	122.64°E 23.86°N	6	6.0	34	19(22)
10*	1994-05-24 04:00:40.49	122.60°E 23.83°N	4	6.6	43	39(22)
11*	1994-06-05 01:09:30.09	121.84°E 24.46°N	5	6.2	51	97(22)
12	1994-06-06 08:57:24.49	121.95°E 24.43°N	3	5.1	14	24(22)
13	1995-02-23 05:19:02.78	121.69°E 24.20°N	22	5.8	41	45(38)
14	1995-03-24 04:13:51.09	121.86°E 24.64°N	76	5.6	61	69(21)
15	1995-04-03 11:54:40.08	122.43°E 23.94°N	15	5.9	27	12(32)
16	1995-04-24 10:04:00.96	121.62°E 24.65°N	63	5.3	43	24(53)
17	1995-05-31 14:09:30.47	121.88°E 24.44°N	37	4.8	11	17(22)
18*	1995-06-25 06:59:07.09	121.67°E 24.61°N	40	6.1	70	180(38)
19	1995-07-05 17:33:48.64	122.12°E 24.83°N	9	4.6	13	7(32)
20	1995-07-14 16:52:46.48	121.85°E 24.32°N	9	5.8	63	22(22)
21	1995-08-20 09:25:03.00	121.58°E 24.69°N	57	4.9	60	42(22)
22*	1995-12-01 03:17:04.62	121.64°E 24.61°N	45	5.7	69	66(38)
23	1995-12-18 16:17:54.53	121.69°E 24.02°N	22	5.8	24	8(21)

* : Events, TAP016 referent site recorded, used for spectral ratio analysis.

No. : Number of triggered stations in the Taipei area.

PGA : Peak ground acceleration recorded within Taipei basin. Numbers inside the parentheses are the station code, which PGA occurred.

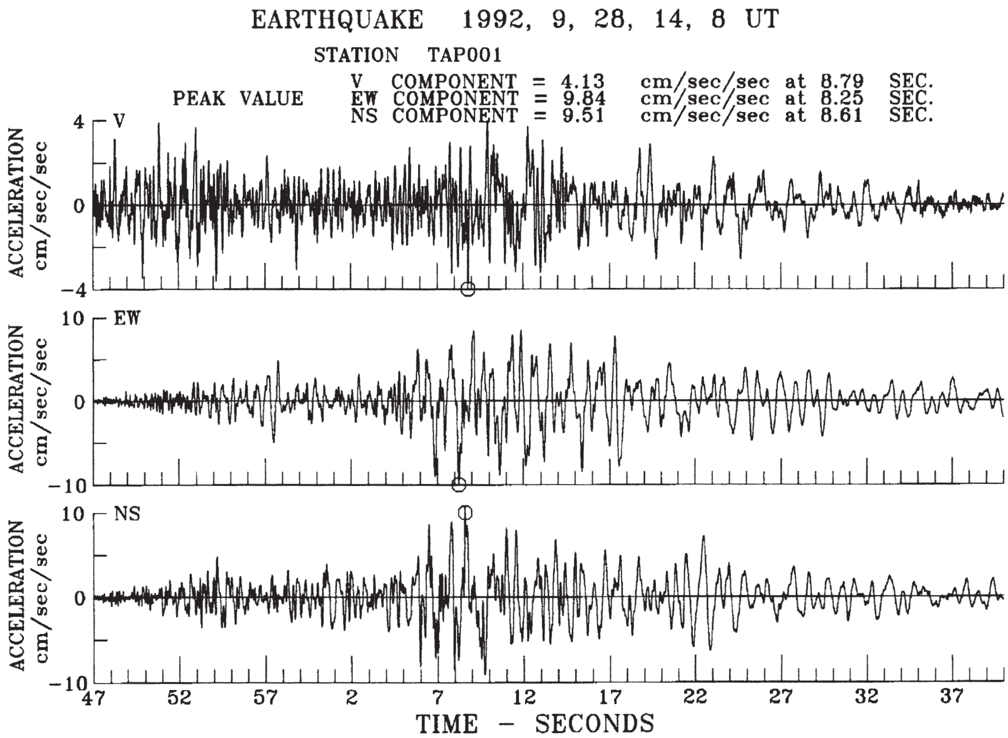


Fig. 2. Accelerograms of the September 28, 1992 earthquake recorded at station TAP001.

4. SPECTRAL RATIO ANALYSIS

To understand the soil amplification effects in the frequency domain, the spectral ratios of the soft soil stations were calculated with respect to the TAP016 site, which is near the edge of the basin. Most earthquakes recorded are 50 km away from Taipei basin to the east and south-east. The variation of azimuth and incident angle is not so large. Therefore, selection of TAP016 as the reference site will not affect the pattern of average spectral ratio very much. Another reason for selecting this station was that it was among the first installed in the TSMIP network, so it has more records that can be used. The spectral ratios are calculated as follows (Beresnev and Wen, 1996a): (1) a window containing the shear wave is identified; (2) the window is tapered at both ends (at 5% of the length) using a cosine function; (3) the Fourier amplitude spectrum is calculated; (4) the spectrum is smoothed 1 times using a 3-point running Hanning average; (5) two smoothed spectra are divided; (6) the root-mean-square (RMS) spectral ratio is then calculated from the two horizontal ratios of EW and NS components. Figure 3 shows an example of the spectral ratio of the TAP001 and TAP016 station pair. The shaded bands represent ±1 standard deviation areas.

For the purpose of the earthquake resistant design, earthquake engineers must consider the site response at a specific period. For example, the structure period of a ten-flour building is at about 1 second. If the input ground motion is dominate at 1 Hz, then the building will has a resonant effect, which means an earthquake may easily cause big damage to this building. Therefore, in this study, we select 7 periods (4, 3, 2, 1.5, 1, 0.5, and 0.3 sec) to plot out the contour map for understanding the frequency responses in the Taipei basin. Figures 4a to 4g represent the mean spectral ratio contours for these periods, respectively. From these figures, it is obvious that the waves at different frequencies have different amplification patterns in the Taipei basin. Figures 4a – 4d represent the low frequency responses (period from 4 to 1.5 seconds) in the Taipei basin. The contours show that main amplification effects occurred in the western part of the Taipei basin and the Sungshan area. Nevertheless, the response at the higher frequency band of larger than 1 Hz (Figures 4e - 4g) shows different amplification effects. The high contour areas occur near the basin edges at the north, east, and south basin boundaries. The responses in the western part of the Taipei basin and the Sungshan area do not show strong amplification effects anymore. The basement structure (The dotted contours in

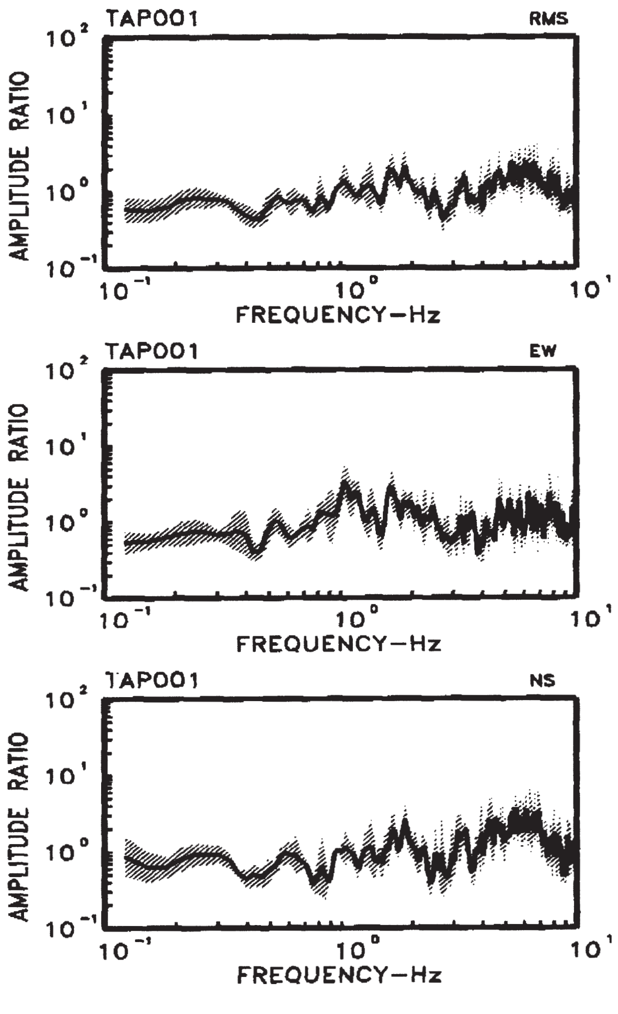


Fig. 3. Spectral ratio between TAP001 and TAP016 station pair. Figures include the results of two horizontal components and their RMS value. The shaded bands represent ±1 standard deviation areas.

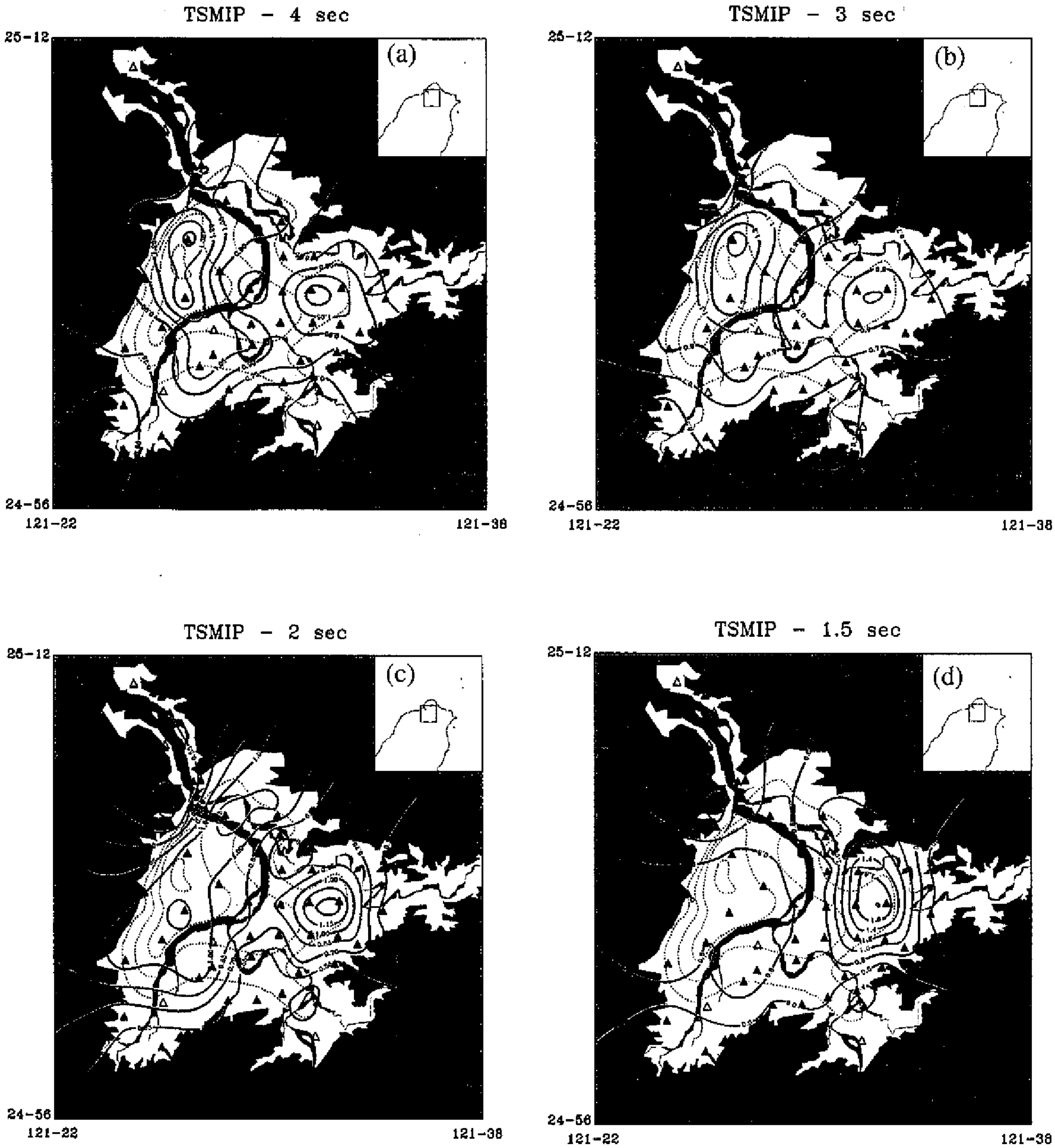
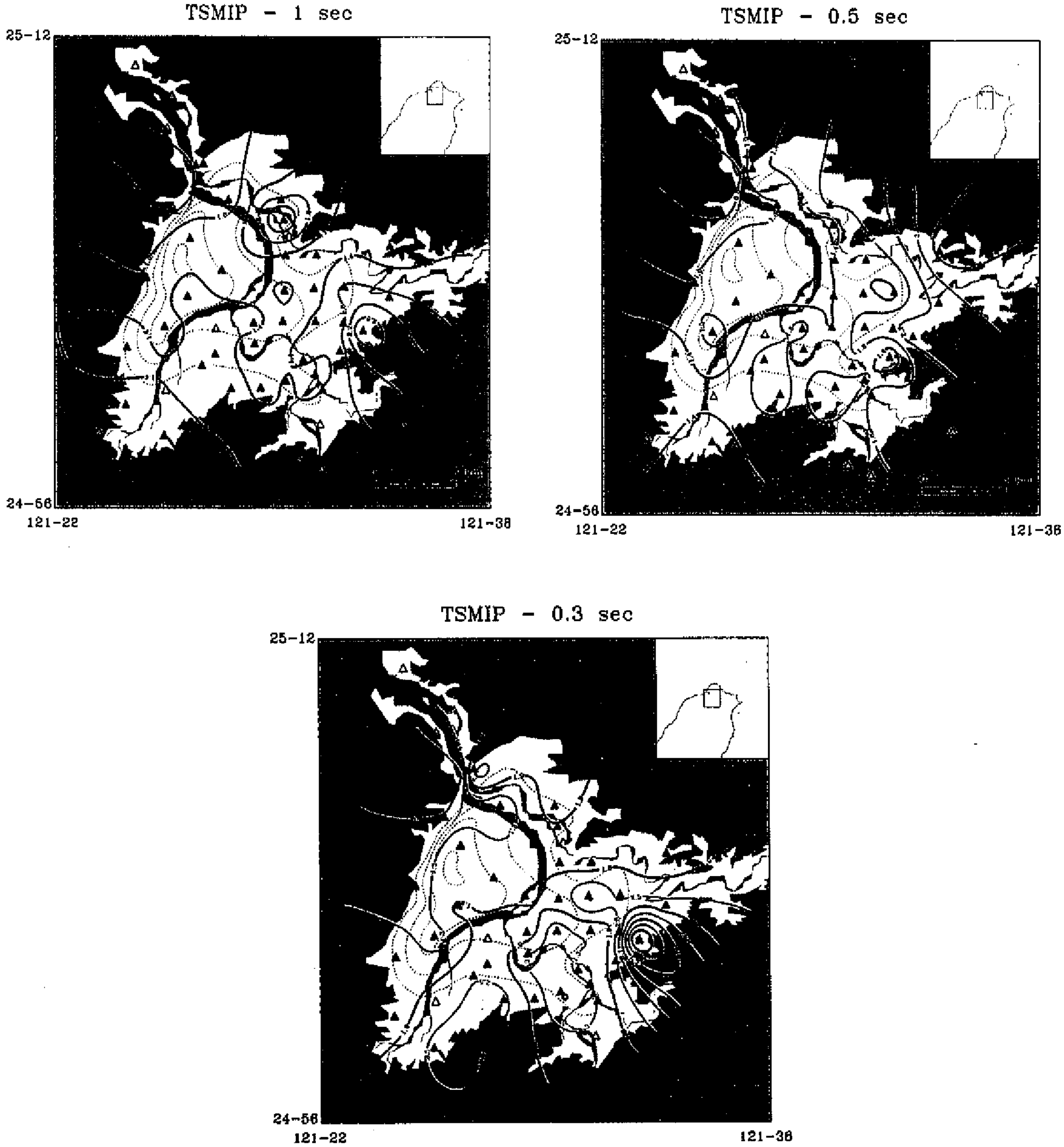


Fig. 4. Contours of the mean spectral ratio in the Taipei basin: (a) 4 sec, (b) 3 sec, (c) 2 sec, (d) 1.5 sec, (e) 1 sec, (f) 0.5 sec, and (g) 0.3 sec. The solid contours indicate the mean spectral ratio. The triangles and dotted contours are the same as those in Figure 1. The black triangles are stations that were used in this analysis.



(*Fig. 4*. continued)

Figure 1) may explain the high spectral ratio area that occurred in the western part of the Taipei basin, which is the deepest area of the Taipei area. But, it can not explain the low frequency responses of the high contour area in the Sungshan area. The bottom depth contours map of the Sungshan Formation is given in Figure 5 (Wang *et al*., 1996). This top alluvium

TAIPEI BASIN SUNGSHAN FORMATION BOTTOM

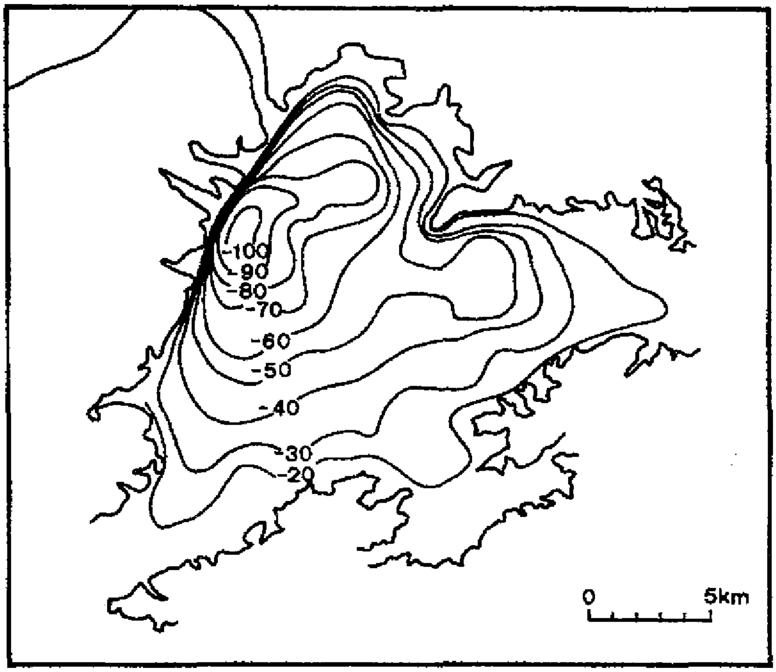


Fig. 5. Contour map indicates the depth in meters to the bottom of Sungshan Formation in the Taipei basin (Wang *et al.*, 1996).

layer in the Taipei basin seems play an important role for site amplifications as mentioned by Anderson *et al.* (1996). The two deepest areas of the soft Sungshan Formation can correlate with the two high spectral ratio areas at the lower frequency bands (Figures 4a - 4d). More studies are needed to clarify the role of this top alluvium layer in the Sungshan Formation.

The results in Figure 4 represent the mean spectral ratios at each station from several earthquakes. For studying the variability of these mean ratios, we calculate the ratio of standard deviation with reference to the corresponding mean values at each frequency to check the variability of the mean spectral ratios over the Taipei basin. If the ratio between the standard deviation with reference to the corresponding mean value is high, then the variability of the mean value at that station is high. In this study, we do not try to analyze quantitatively the site amplification factor. So, we plot the standard deviations with reference to the corresponding mean values in contours as that in Figure 4. Figure 6 shows an example of the result at 4 seconds. Comparing Figure 6 and Figure 4a, we find that the high contour areas in the western part of the Taipei basin and the Sungshan area in Figure 4a changed to contour low in Figure 6. This means that the high contour areas in Figure 4a can really demonstrate the site responses in the Taipei basin. Other frequency bands show the same results.

5. DOMINANT FREQUENCY ANALYSIS

Dominant frequency at a specific soft soil site will receive the most attention by the earthquake engineer for earthquake resistant designs. This can determined from the transfer function at that site, which is calculated from the spectral ratio between the records at surface and those at basement rock. In previous paragraph, the spectral ratios are calculated with respect to the TAP016 site, which is near the edge of the basin, but not in the basement rock. Also, the number of events is not many, so the dominant frequencies found from these ratios may be biased. An earthquake record should include source, path, and site effects. One of the most useful methods of improving the resolution of any data is stacking. For more detailed treatments, see an applied geophysics text, *e.g.*, Telford *et al.* (1976), or, for seismological applications, Aki and Richards (1980). Therefore, in this step this simple method is applied. All spectra recorded at each station are stacked together to eliminate the source and path effects. Thus, the stacking process will joint out the site response. Many studies (Lermo and Chavez-Garcia, 1993; Field and Jacob, 1995; Theodulidis and Bard, 1995; Chavez-Garcia *et al.*, 1996; Theodulidis *et al.*, 1996; Bonilla *et al.*, 1997; Yamazaki and Anstry, 1997; Dimitriu *et al.*, 1998) show that horizontal-to-vertical (H/V) ratio can be used to find out the dominant frequency. Mean H/V ratio at each station was also calculated in this study and together used with the stacking spectrum to find out the dominant frequency at that station.

Figure 7 represents the contour of the dominant frequencies in the Taipei basin area. The distribution of the dominant frequencies shows that the areas near the basin edge have a higher dominant frequency. It is about 2.5 - 2.8 Hz near the basin edge in the north, and it can reach to about 2.8 Hz near the southern edge of the basin. Another high dominant frequency area is in the eastern edge (Hsinyi area), which is also about 2.9 Hz. That is why this area always shows a high PGA value during most earthquakes (Table 2, where station no. 22 is at the Hsinyi Elementary School). This result also indicates that the edge effect that occurred during the 1995 Kobe earthquake might possibly happen in the Taipei basin area. More detail analysis is needed to study this effect. The western part of the Taipei basin and Sungshan area show a low dominant frequency in the contour map. The dominant frequencies are about 0.6 - 0.8 Hz.

6. DISCUSSIONS AND CONCLUSIONS

The dense TSMIP network provides an opportunity for us to understand the site effects in the Taipei basin. In this study, we use the spectral ratio method to calculate the frequency response at each station with respect to a referent site TAP016, which is located at the western edge of the basin. The mean spectral ratio contours at some specific periods are selected to compare with the geological structure under the Taipei basin.

From the analysis of earthquake records of the dense TSMIP network, it is noted that different areas have different local site effects in the Taipei basin. By comparison of the results with the geological structure, we can understand that the low frequency responses on the western part of the Taipei basin and Sungshan area are correlated with the basin structure and the top soft soil layer (Sungshan formation). The high frequency responses mainly occur near the

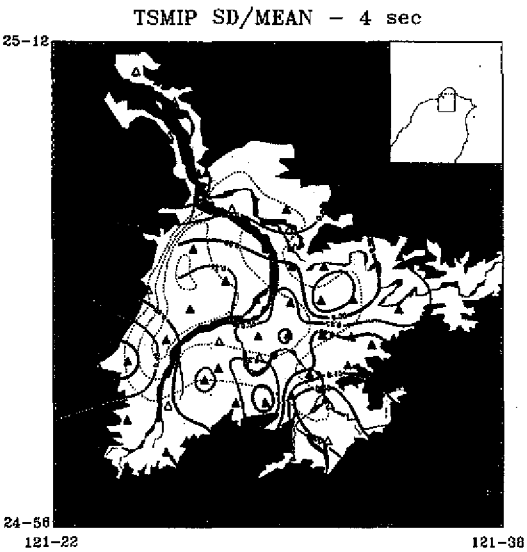


Fig. 6. Ratio distribution of the standard deviation with reference to the corresponding mean value. The triangles and dotted contours are the same as those in Figure 1. The black triangles are stations that used in this analysis.

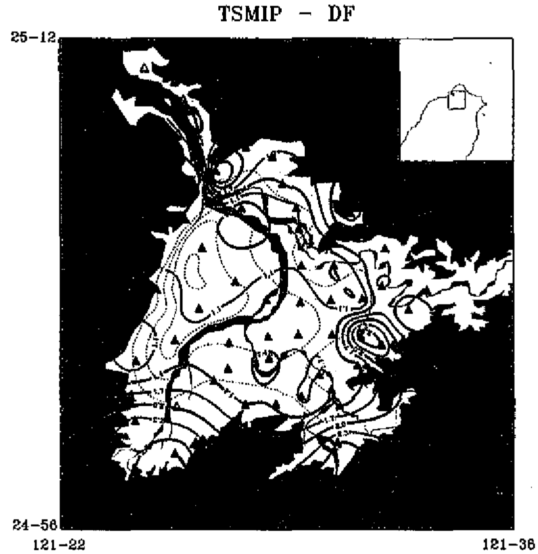


Fig. 7. Dominant frequency contour in Taipei basin. Contour interval is 0.3 Hz. The triangles and dotted contours are the same as those in Figure 1. The black triangles are stations that were used in this analysis.

edge of the Taipei basin, except for a steep structure at the western boundary. The soft soil layer of the Sungshan formation may dominate the site response in the Taipei basin generally, but more study is needed to confirm this point of view. The characteristics of the site responses in the Taipei basin during earthquakes can be understood through this study.

Distribution of dominant frequencies in the Taipei basin (Figure 7) shows a very good correlation that compares with the previous spectral ratio distributions (Figure 4). So, a simple zonation of the earthquake responses in the Taipei basin can be inferred from these results. Zone A, with a predominantly low frequency band response (0.2 - 1 Hz), is located in the western part of the Taipei basin and Sungshan area; Zone B, with a predominantly slightly higher frequency band response (1 - 3 Hz), is near the basin edge in the north, east, and south edges; and Zone C is located between Zones A and B. Although the Taipei basin is not a large area, it already shows a large variation in the spectral ratio and dominant frequency contours. This implies that microzonation work is needed in the Taipei basin area to carry out earthquake hazard mitigation.

In this study, spectral ratios are calculated with respect to a reference site, but they can not exactly represent a site transfer function. So, the amplification factor is not discussed in this paper. At the same time, the results in this study only indicate weak motion responses in the

Taipei basin. As reviewed by Beresnev and Wen (1996b), nonlinear soil response may also have to be considered when input motion is larger than some thresholds.

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