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Analysis of Earthquake Response Data Recorded from the Hualien LSST

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ABSTRACT

This paper deals with the analysis of earthquake response data recorded from the Hualien large-scale seismic test (LSST). The recorded data were analyzed to provide information on the response characteristics of the Hualien soil-structure system, the SSI effects and the ground motion characteristics. In between September 1993 and March 2002, more than seventy earthquakes with Richter magnitudes ranging from 3.0 to 7.3 were recorded at the site. The recorded data, were analyzed to provide information on the response characteristics of the Hualien soil-structure system, the SSI effects and the ground motion characteristics. The ground response data were statistically analyzed for their variations with depth, with distance from the model structure, and at the same depths along downhole arrays. The site soil property, i.e., soil stiffness, was derived based on correlation analysis of the recorded data also. In addition, variations of soil stiffness and soil-structure system frequencies were evaluated against various ground motion intensity parameters.

KEY WORDS: SSI(soil-structure interaction), Hualien, LSST (large-scale seismic test), earthquake response data, ground motion, soil stiffness.

1. INTRODUCTION

The analysis of soil-structure interaction (SSI) effects has long been a topic of research. Over the past 20 years, a variety of SSI analysis techniques and associated computer codes have been evolved. However, in spite of significant advances achieved, different techniques often result in different response predictions. Because of the lack of earthquake data from controlled field measurements, there has been no adequate technical basis to benchmark different methodologies quantifying their uncertainties and limitations.

Recognizing the need, a large-scale seismic test (LSST) program in Lotung, a seismically active area in Taiwan has been conducted[1], and a second experiment like the one in Lotung was initiated by an international consortium in Hualien, another seismically active region in Taiwan[2]. The Hualien site contains competent, gravelly soils which are similar to some of the prototypical nuclear power plant foundation soils.

This paper extends the previous studies[3][4] on earthquake response data recorded from the Hualien large-scale seismic test (LSST). To obtain earthquake data for quantifying SSI effects and providing a basis to benchmark analysis methods, a 1/4-th scale cylindrical concrete containment model similar in shape to that of a nuclear power plant containment was constructed in the field where the containment model and its surrounding soil, surface and sub-surface, are extensively instrumented to record earthquake data. The Hualien array started operations in 1993. In between September 1993 and March 2002, more than seventy earthquakes with Richter magnitudes ranging from 3.0 to 7.3 were recorded at the site. The recorded data from these earthquakes provide very valuable informations to study several important issues regarding seismic responses of a soil-structure system.

This paper focuses on analyzing the recorded data to provide information on the response characteristics of the Hualien soil-structure system, the SSI effects and the ground motion characteristics. The ground response data were statistically analyzed for their variations with depth, with distance from the model structure, and at the same depths along downhole arrays. The site soil property, i.e., soil stiffness, was derived based on correlation analysis of the recorded data also. In addition, variations of soil stiffness and soil-structure system frequencies were evaluated against various ground motion intensity parameters

2. HUALIEN LARGE-SCALE SEISMIC TEST

The Hualien site is located along the east coast of Taiwan, south of Lotung. The general geology in Hualien consists of massive unconsolidated, poorly bedded conglomerate composed of pebbles varying in diameters from 10 cm to 20 cm. Geophysical and boring tests conducted in 1989 by the Taiwan Power Company (Taipower) show that the shear wave velocity for the top 100m layer of soil is around 400 m/sec and for the layer below (up to about 7 km depth) is 1500 m/sec to 1850 m/sec. The 50 m boring revealed that the top 5 m is of silty sand and the layer below consists of gravels varying in diameters from 3 cm to 7 cm[2]. More detailed geophysical and geotechnical investigations were subsequently carried out by the Central Research Institute of Electric Power Industries (CRIEPI)[5].

The Hualien test model dimensions are 10.52m in diameter and 16.13m in overall height. The model is roughly 1/4-th scale of a typical nuclear reactor cylindrical concrete containment. Similar to actual construction, about 1/3 of the model is embedded. The test model and its surrounding areas were extensively instrumented[6]. On the test model, accelerometers were installed on the roof, the base and mid sections of the wall. Pressure gages were installed between the model and the soil on the side and at the bottom to monitor interfacial contact pressures. Inside the test model, tilt gages were installed on the basemat to monitor model settlement. The ground surface had accelerometers on three arms radiating from the test model to a radius of 5.5 times the model diameter (Fig. 2(a)). The three downholes were deployed with accelerometers at depths of 5.3 m, 15.8 m, 26.3 m, and 52.6 m (Fig. 2(b)). The Hualien LSST array was designed to provide data to characterize the entire soil-structure system when responding to earthquakes.

3. ANALYSIS OF RECORDED EARTHQUAKE RESPONSES

In between September 1993 and March 2002, more than seventy earthquakes with Richter magnitudes ranging from 3.0 to 7.3 have been recorded at the Hualien site (see Table 1 and Fig. 1). Among the earthquakes, EQ 47 (July 14, 2000 earthquake) has the largest peak ground acceleration. Although the magnitude of this earthquake is relatively low (M_L=5.7), its epicenter is very close to the site (11.6km). The earthquake data have revealed that the fundamental frequency of the soil-structure system varied from earthquake to earthquake in the range of 4-6 Hz. In the following sections, ground motion and structural response behaviors based on the recorded data are described in detail.

3.1 Ground Motion

Where applicable, statistical studies were performed. Plotted in Fig. 3(a) are the median (50th percentile) values of normalized peak accelerations of the three downhole (A15, A25, A21) records for all events. The figure shows that the downhole peak ground motion profiles under stations A15 and A25 (both free field) are very similar to each other. The one under station A21 (close to the test model structure) is somewhat different. Since A21 is on the ground surface adjacent to the test model, it qualitatively shows that the presence of the structure, i.e., SSI effect, may have affected the ground motions. It can also be seen in Fig. 3(a) that the peak acceleration reduces as it deconvolves from the ground surface to depth and that the largest reduction occurs near the ground surface.

Fig. 3(b) presents the median values of five percent damped response spectra ratios (depth/ground surface) for the downhole records under stations A15 and A25. The figure shows that the frequency range of the response reduction tends to become broader for deeper stations. In the frequency range of 3-8 Hz, it is noted that the majority of response reduction takes place down to a depth of 5.3 m. However, in the low frequency range (smaller than 2 Hz), response reductions are observed down to a depth of 52.6 m. It is further noted that at the frequency range of the soil-structure system (4-6 Hz), the majority of response reduction takes place down to a depth of 15.8 m.

The statistical distributions of the surface array recordings are given in Fig. 4. These results show that the peak acceleration ratios (Fig. 4(a)) and the response spectra ratios(Fig. 4(b)) in the frequency range larger than 4 Hz approach 1.0 beyond the distance of 36.4m from the center of the structure. Taking into account the uncertainty of the free field motions (see Fig. 5), the distance at which the soil responses were affected by the structure (i.e. influence zone radius) is estimated to be 11.6 m - 21.5 m from the center. This corresponds to a distance of about 0.6 - 1.5 times the structure base dimension from the edge of the base which implies Standard Review Guidelines(SRG) [7] requirements on the influence zone on finite element soil model for SSI analysis are appropriate. This zone of influence is important in assessing structure-soil-structure interaction (SSSI) effects also. In the low frequency range, the influence of the structure on ground motions seems to be insignificant. In other words, the SSI effects on the low frequency range response are minimal.

Fig. 6 presents the ratios of horizontal ground motions with distance from model center for peak ground accelerations groups. The figures indicate that the horizontal distance from the edge of the base where horizontal ground motions are affected by SSI decreases as the earthquake magnitude increases. It was also found that the horizontal ground motions are less affected by SSI for the peak ground accelerations larger about 50 gals, even though these results are not enough to make definitive conclusions.

In Fig. 7-Fig. 9, the estimated average shear wave velocities are plotted against ground motion intensity parameters such as peak ground accelerations, Arias intensity and averaged spectral acceleration. The average shear wave velocities were estimated based on time lags between the two locations obtained from cross-correlation functions [8] between the ground surface records and the records at depths of GL-15.8 m and GL-52.6 m. The figures indicate that the velocities in the EW direction are lower than those in the NS direction, significantly lower for deeper soil. This is evidence of soil anisotropy in the two horizontal directions. It is also observed in Fig. 7 that the estimated average shear wave velocity becomes lower as ground motion intensity parameters increase, characterizing the degradation of soil stiffness under strong ground motions, which seems to match the soil property degradation trend predicted by geotechnical tests[9] [10].

3.2 Structural Response

The variations of the the soil-structure system frequencies of five percent damped response spectra at roof for each earthquake and each horizontal component plotted against various ground motion intensity parameters are given in Fig. 10. The figure shows the general trend that the system frequencies become smaller as ground motion intensity parameters become larger. The system frequency shift is asymptotic with drastic decrease for small increase of the various ground motion intensity parameters and then gradual decrease for larger intensity parameters.

4. CONCLUSIONS

In this study, the earthquake response data recorded at the Hualien large-scale seismic test site and the model structure have been analyzed. Based on the results of the study, the following observations are made :

(1) The peak ground accelerations and the response spectra of soil in the frequency range larger than 3 Hz reduced remarkably at shallow depth. At a depth of GL-52.6m, the responses in the low frequency range (less than 2 Hz) also experienced significant reduction.

(2) The peak ground accelerations and the response spectra of soil in the frequency range larger than 4 Hz were affected by soil and structure interaction up to a horizontal distance of about 1.65 times the base dimension of the structure, measured from the edge of the base, and down to a depth of approximately 1.5-2.5 times the base dimension. It implies that Standard Review Guidelines(SRG)[7] requirements on the influence zone of finite element soil model for SSI analysis are appropriate.

(3) The horizontal distance from the edge of the base where horizontal ground motions are affected by SSI decreases as the earthquake magnitude increases and for the peak ground accelerations larger than about 50 gals.

(4) The shear wave velocity in soil layer and the frequency of the soil-structure system becomes lower as earthquake intensity parameters increase characterizing the degradation of soil under strong ground motions

(5) The soil responses show anisotropy of soil at the site in two horizontal directions. The anisotropy appears to be larger for deeper soil.

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Table 1 Earthquakes recorded at the LSST array in Hualien site

EVENT EQ No.	ORIGIN TIME (UT)	DEPTH	MAG.	Max. Ground Acclerations (gal)		
		(km)	ML	L(N-S)	T(E-W)	V
1	1993 09 16 12:18:45.36	21.1	4.2	16.9	13.4	8.2
2	1994 01 20 05:50:15.57	49.5	5.6	39.4	48.8	24.5
6	1995 02 23 05:19:02.78	21.7	5.8	51.4	45.8	23.9
7	1995 05 01 14:50:45.67	2.2	4.9	135.8	73.7	115.5
8	1995 05 02 06:17:21.60	8.9	4.6	87.5	64.9	118.2
15	1996 05 28 21:53:22.35	25.0	5.1	82.5	51.5	86.3
25	1998 07 17 18:44:39.93	1.8	4.8	96.3	68.8	37.6
36 1)	1999 09 20 17:47:15.85	8.0	7.3	87.1	118.9	32.7
37	1999 11 01 17:53:02.25	31.3	6.9	59.3	106.1	29.0
38	1999 11 05 05:50:32.34	4.6	4.1	63.5	50.2	89.2
40	2000 05 06 13:41:52.84	27.0	5.1	72.0	47.9	106.0
41	2000 06 10 18:23:29.45	16.2	6.7	51.8	46.9	21.0
47 2)	2000 07 14 00:07:32.64	7.2	5.7	82.3	142.0	21.0
55	2000 09 10 08:54:46.53	17.7	6.2	114.5	61.9	99.8
64	2000 10 24 07:11:57.66	18.4	4.8	57.9	49.9	35.6
70	2002 03 31 06:52:49.95	13.8	6.8	44.5	59.4	17.4

Remark : 1) Chi-Chi Earthquake, 2) EQ47 has largest peak ground acceleration

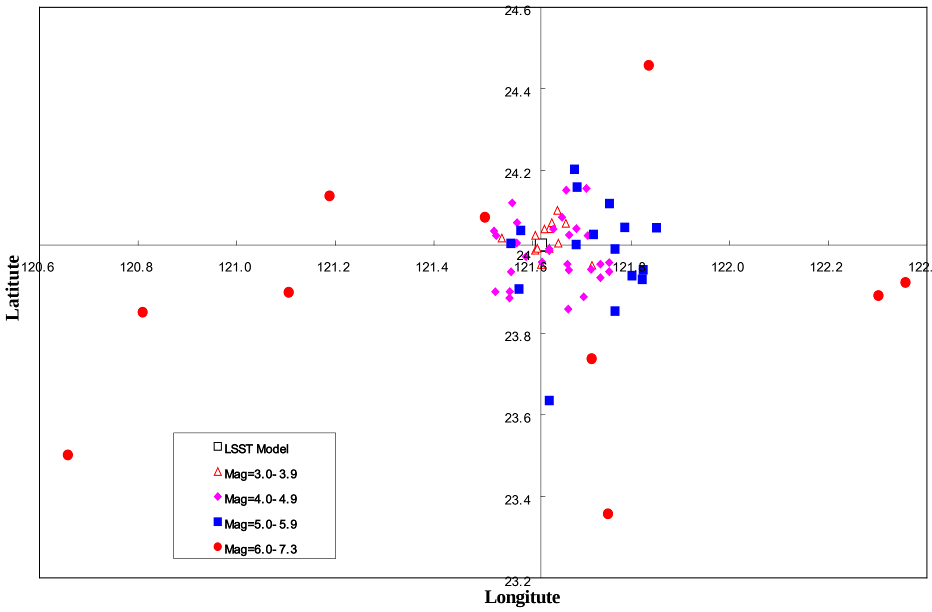
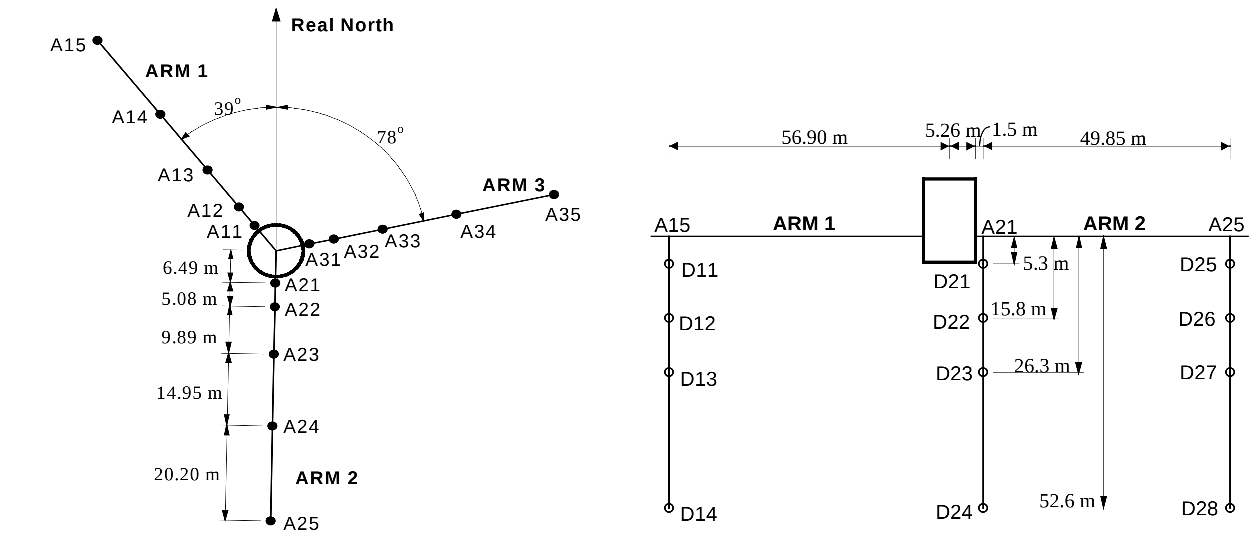
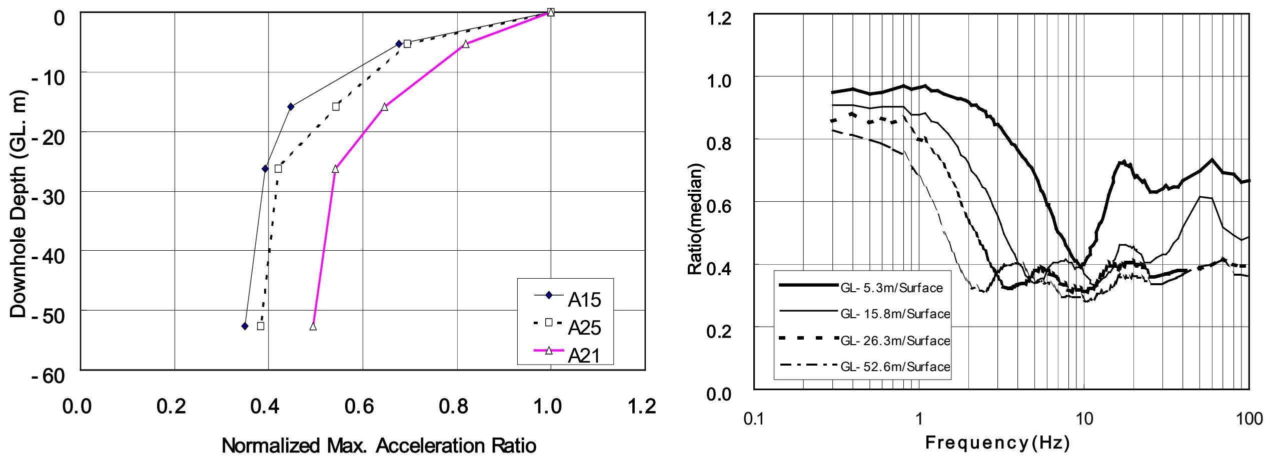


Fig. 1 Epicenters of recorded earthquakes



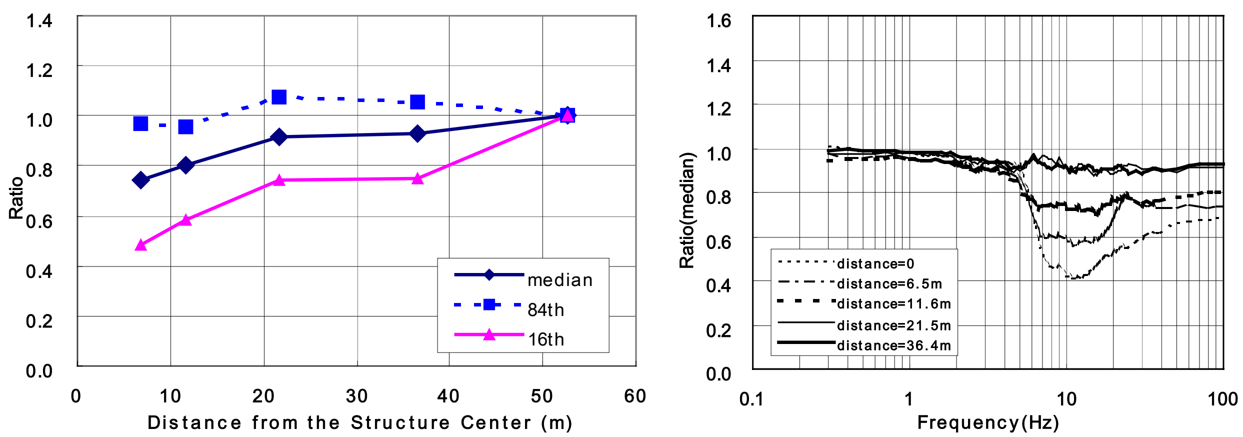
(a) Ground surface accelerometer (Plan View) (b) Downhole accelerometer (Elevation View)

Fig. 2 Ground accelerometers



(a) Normalized max. acceleration (b) Ratio of response spectra

Fig. 3 Median values of normalized max. ground accelerations and response spectra ratios along downhole array



(a) Ratio of max. ground acceleration (b) Ratio of response spectra

Fig. 4 Ratios of soil responses with distance from the center of model structure

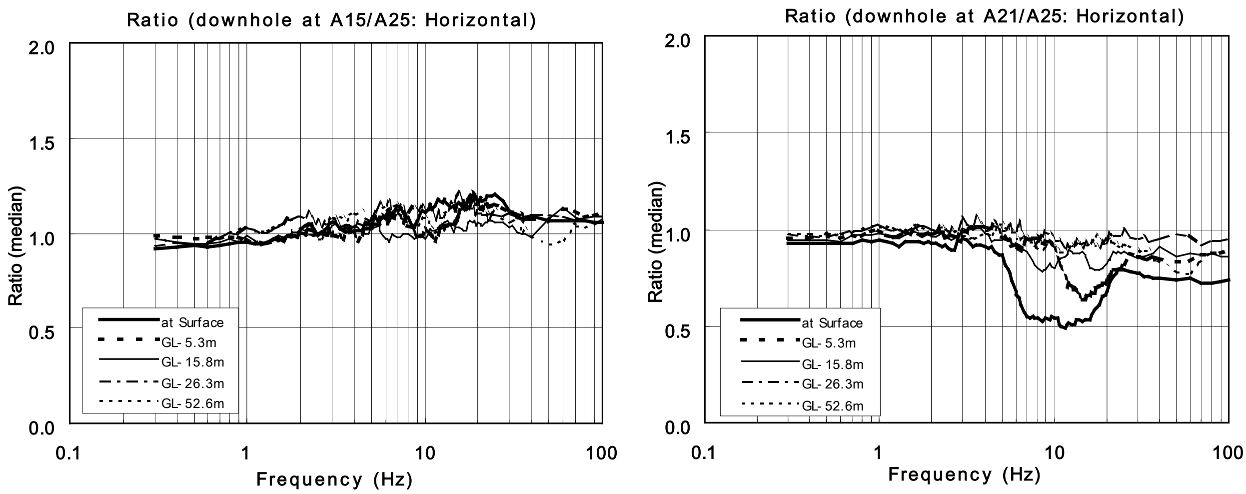


Fig. 5 Ratio of soil responses with same depth of downhole (horizontal)

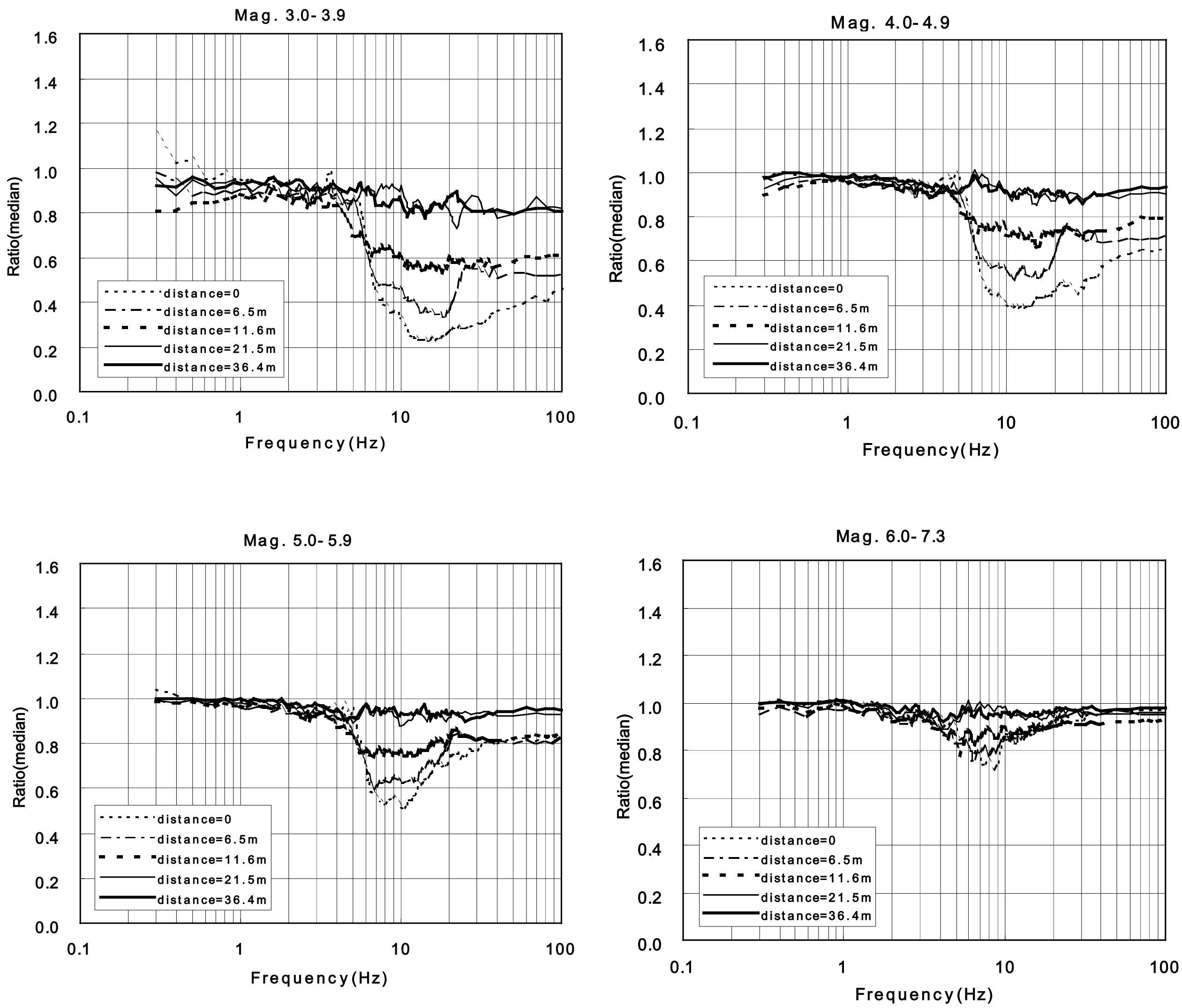
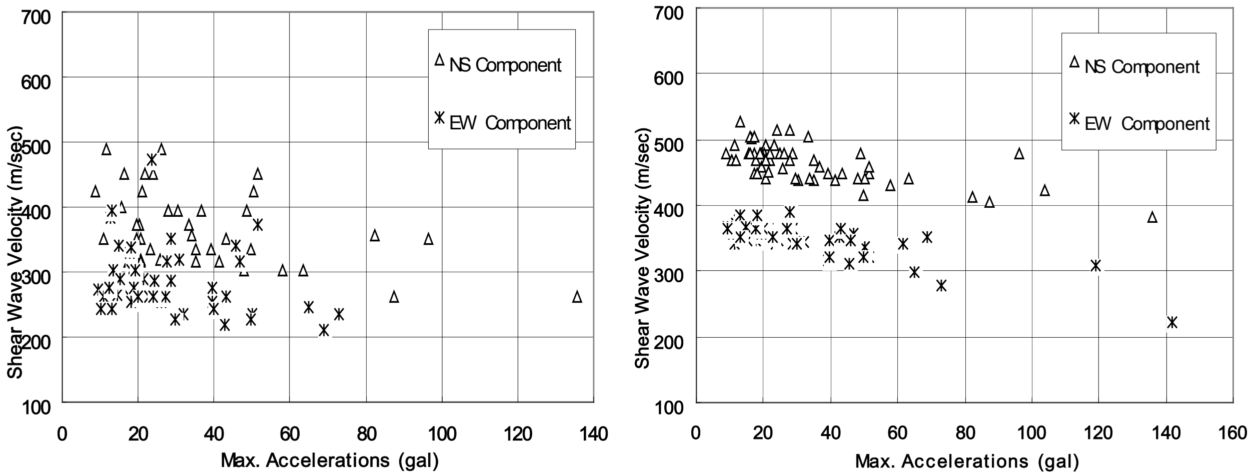
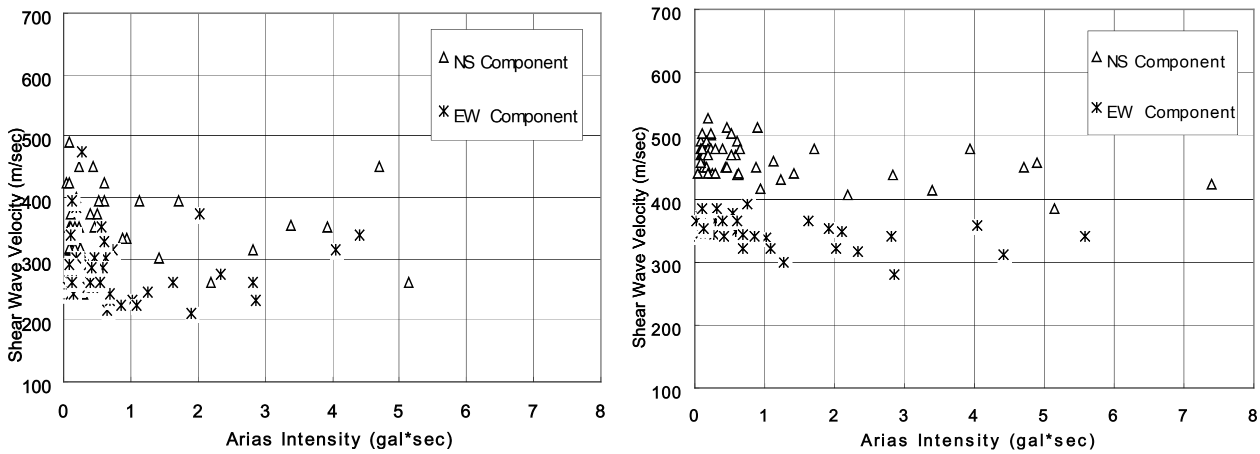


Fig. 6 Ratio of soil responses with distance from model center for magnitude groups (horizontal)



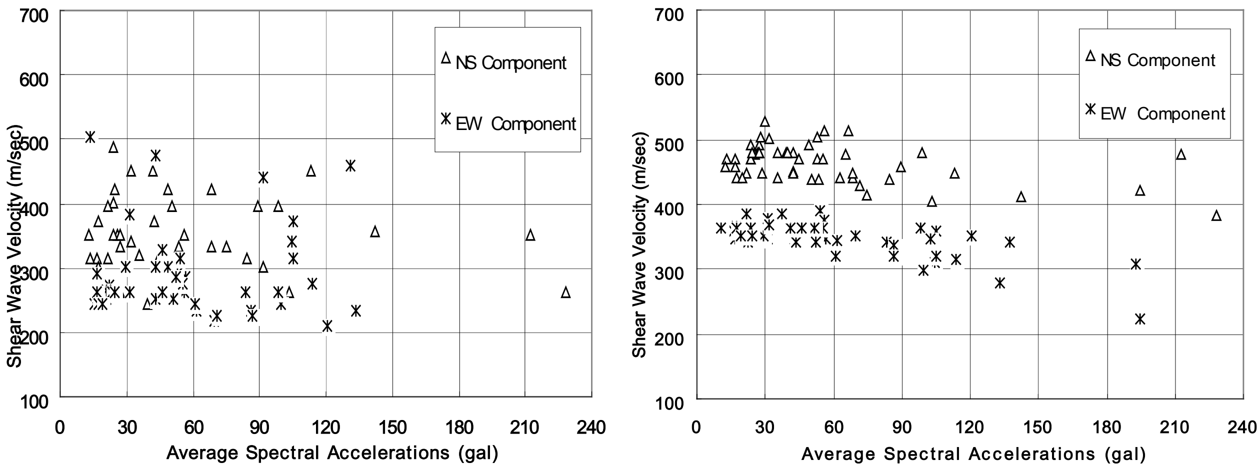
(a) GL -15.8m (b) GL –52.6m

Fig. 7 Maximum ground accelerations vs. estimated average shear wave velocities between gound surface and underground



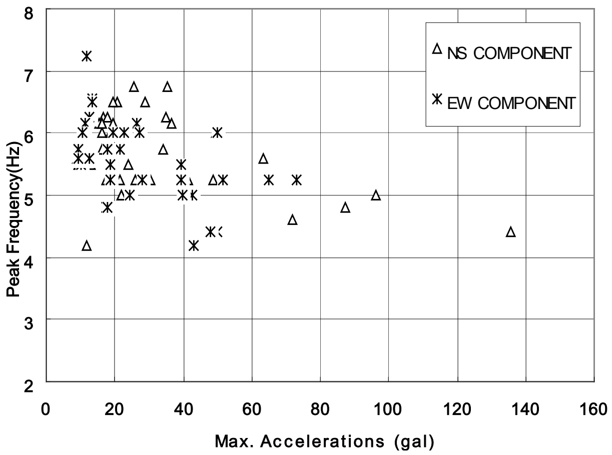
(a) GL -15.8m (b) GL –52.6m

Fig. 8 Arias intensities vs. estimated average shear wave velocities between ground surface and underground

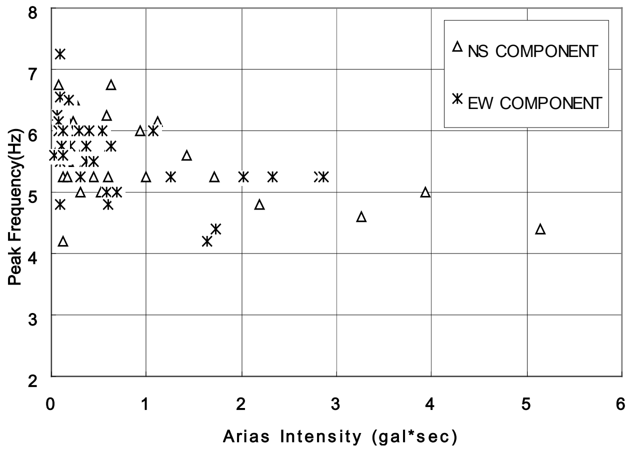


(a) GL -15.8m (b) GL –52.6m

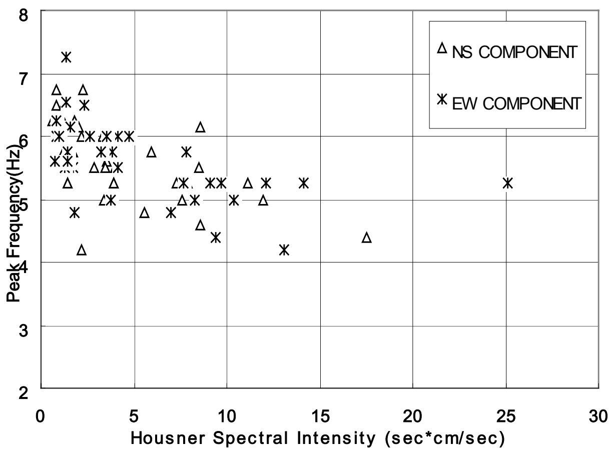
Fig. 9 Average spectral accelerations vs. estimated average shear wve velocities between ground surface and underground



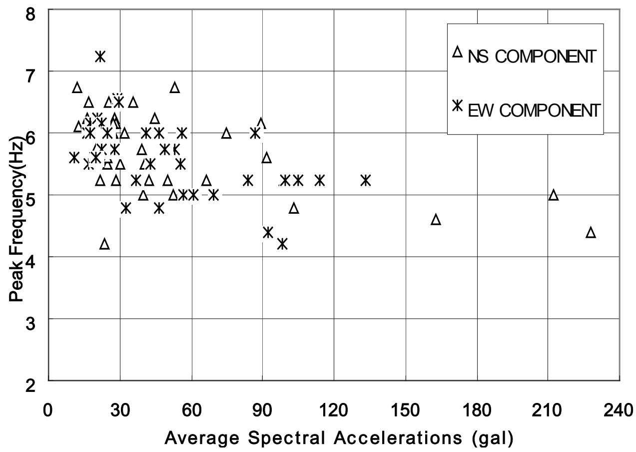
(a) PGA vs. peak frequencies of roof



(b) Arias intensity vs. peak frequencies of roof



(c) HSI vs. peak frequencies of roof



(d) ASA vs. peak frequencies of roof

Fig. 10 Peak frequencies of roof response spectra vs. various ground motion intensity parameters