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SITE AMPLIFICATION FACTORS ON SEISMIC INTENSITY SCALE BASED ON AMPLIFICATION SPECTRA

Masato TSURUGI[1], Sumio SAWADA[2], Masakatsu MIYAJIMA[3], and Masaru KITAURA[4]

SUMMARY

In order to estimate seismic intensity on JMA (Japan Metrological Agency) scale taking into account the local site effects, we propose a method to estimate site amplification factors of seismic intensity on JMA scale based on the amplification spectra which are obtained from soil profile or seismic observation records at the site. We assume that the amplification factor of seismic intensities is obtained by averaging the amplification spectra for the specific frequency range, which is investigated by three approaches comparing amplification factors of seismic intensity and amplification spectra at the site. Seismic intensities for Approach-1 are obtained from the calculated ground motions with respect to given incident waves using various ground structure models. The other approaches are based on the amplification spectra obtained from the observed records statistically in the Osaka region near Kobe city, Japan. The seismic intensities for Approach-2 are calculated from the observed waveforms. Approach-3 uses the seismic intensities obtained by a questionnaire survey for the 1995 Kobe earthquake. The most appropriate frequency range for each approach is obtained as from 0.4Hz to 7.0Hz for Approach-1, from 0.4Hz to 7.5Hz for Approach-2, and from 0.4Hz to 9.0Hz for Approach-3. Through detailed discussions for the reason of the differences between approaches, it is concluded that the amplification factor of seismic intensity can be estimated by averaging the amplification spectra of the site for the frequency range from 0.4Hz to 7.5Hz.

INTRODUCTION

Prediction of seismic intensity is very important for estimating earthquake damages and planning a regional program for disaster prevention. The seismic intensity on JMA scale, I_{JMA}, is defined as $I_{JMA}=2\log(Max_{0.3}[a(t)])+0.94$, based on Kawasumi's idea [1], where $Max_{0.3}[a(t)]$ gives the threshold level which the absolute values of the waveform $a(t)$ exceed for 0.3 seconds. $a(t)$ is obtained as a vector

[1] Senior Researcher, Geo-Research Institute, Osaka, Japan. Email:turugi@geor.or.jp
[2] Associate Professor, Kyoto University, Kyoto, Japan, Email:sawada@catfish.dpri.kyoto-u.ac.jp
[3] Professor, Kanazawa University, Kanazawa, Japan. Email:miyajima@t.kanazawa-u.ac.jp
[4] Professor, Kanazawa University, Kanazawa, Japan. Email:kitaura@t.kanazawa-u.ac.jp

summation of three components calculated from accelerograms through a specific filter in frequency domain. Because of the complex process mentioned above, the direct relationship between the seismic intensity and the Fourier amplitude spectra of accelerograms cannot easily told. In order to estimate seismic intensity on JMA scale taking into account the local site effects, we propose a method to estimate site amplification factors of seismic intensity on JMA scale based on the amplification spectra which are obtained from soil profile or seismic observation records at the site.

METHOD

Basic idea

The increment of seismic intensity due to site amplification factor, dI, is described by Eqs.1, 2, and 3.

$$dI = I_1 - I_0 \quad (1)$$

where, I_0 is a seismic intensity of input wave, I_1 is that on ground surface.

$$I_0 = 2\log\left(Max_{0.3}\left[\frac{1}{2\pi}\int_{-\infty}^{\infty} H(f)S(f)e^{2\pi ift}df \right]\right) + 0.94 \quad (2)$$

$$I_1 = 2\log\left(Max_{0.3}\left[\frac{1}{2\pi}\int_{-\infty}^{\infty} H(f)G(f)S(f)e^{2\pi ift}df \right]\right) + 0.94 \quad (3)$$

where, $S(f)$ is a complex Fourier spectra of input wave, $G(f)$ a complex site amplification spectra, $H(f)$ a specific band-pass filter for calculating seismic intensity on JMA scale, and i the imaginary unit. $Max_{0.3}$[.] represents a threshold level which the absolute values of the waveform exceed for 0.3 seconds. The basic idea of the study is that a seismic intensity on ground surface, I_1, can be approximated using scalar value G_A, which is calculated from $G(f)$, shown below.

$$I_1 \approx 2\log\left(Max_{0.3}\left[G_A \frac{1}{2\pi}\int_{-\infty}^{\infty} H(f)S(f)e^{2\pi ift}df \right]\right) + 0.94 \quad (4)$$

From Eqs.1, 2, and 4, the increment of seismic intensity, dI, is described by Eq.5.

$$dI = I_1 - I_0 \approx 2\log G_A \quad (5)$$

In this study, an average value of site amplification spectra for the specific frequency range ($f_1<f<f_2$) is used as the scalar value, G_A.

$$G_A = \frac{1}{f_2 - f_1}\int_{f_1}^{f_2} |G(f)|df \quad (6)$$

The most appropriate frequency range is examined by three approaches which compare various amplification factors of seismic intensities and amplification spectra at the site. Seismic intensities for Approach-1 are obtained from the calculated ground motions with respect to given incident waves using various ground structure models. The other approaches are based on the amplification spectra obtained from the observed records statistically in the Osaka region near Kobe city, Japan. The seismic intensities for Approach-2 are calculated from the observed waveforms. Approach-3 uses the seismic intensities obtained by a questionnaire survey for the 1995 Kobe earthquake.

NUMERICAL APPROACH (APPROACH-1)

Outline of analysis

From Eq.5, the increment of seismic intensity due to site amplification factor, dI_N, is described in Eq.7.

$$\log G_A = \frac{1}{2} dI_N + b_N \quad (7)$$

Here, b_N should be zero originally, but it is introduced as the unknown parameter to examine a precision of approximation. The increment of seismic intensity, dI_N, is difference between seismic intensity of

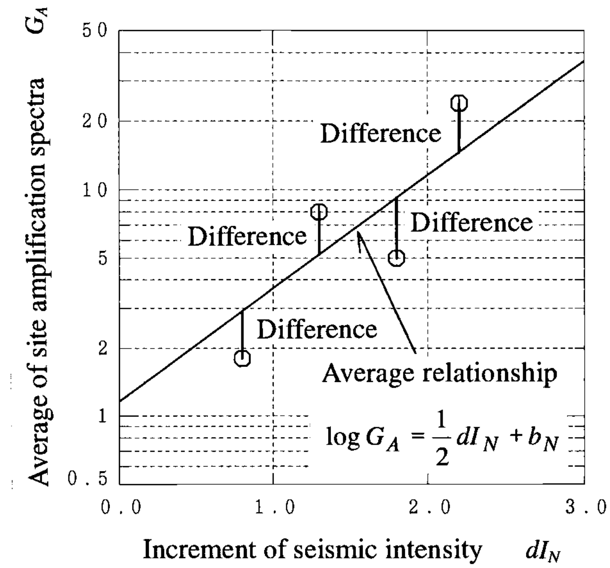

Fig.1 Example of the relationship between the average of site amplification spectra, G_A, and the increment of seismic intensity, dI_N.

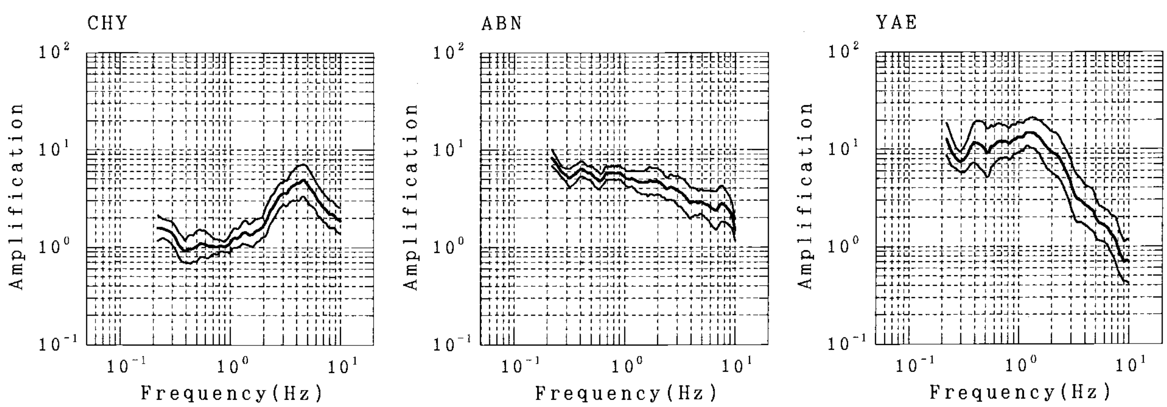

Fig.2 Examples of the site amplification spectra at the sites. Thick lines show the mean values and thin lines show the mean +/- standard deviations. (Left: Weathered rock site, Center: Diluvium site, Right: Alluvium site)

earthquake motion on ground surface, I_1, and that on seismic bedrock, I_0. I_0 and I_1 can be calculated by Eqs.2 and 3. If the frequency limits f_1 and f_2 in Eq.6 are given, an average of site amplification spectra in that frequency range at site k, $G_A(k)$, and an increment of seismic intensity at site k, $dI_N(k)$, are obtained. Then, b_N is decided by the least mean square method and the variance of estimated seismic intensity, D_N, is calculated by Eq.8 (Fig.1).

$$D_N = \sum_{k=1}^{n} \left[\log G_A(k) - \left\{ \frac{1}{2} \times dI_N(k) + b_N \right\} \right]^2 \tag{8}$$

where, n is number of the sites used. 19 seismic observation sites in the Osaka region, Japan, are analyzed. The site amplification spectra at the sites have been evaluated by Tsurugi *et al*. [2, 3]. Examples of site amplification spectra at the sites are shown in Fig.2. Thick lines show the mean values

Table 1 The order of the frequency range in Approach-1.

The order	Percentage*	Frequency range (Hz)		$\overline{D_N}$	$\overline{b_N}$
		Lower f_1	Upper f_2		
1	0.02	0.4	7.2	0.1159	-0.045
4	0.09	0.4	7.0	0.1163	-0.042
7	0.15	0.4	7.5	0.1175	-0.048
14	0.30	0.5	7.0	0.1197	-0.043
19	0.41	0.4	6.5	0.1207	-0.033
22	0.47	0.5	7.5	0.1217	-0.049
27	0.58	0.6	7.0	0.1227	-0.043
33	0.71	0.5	6.5	0.1234	-0.034
42	0.90	0.6	6.5	0.1256	-0.035
44	0.95	0.6	7.5	0.1257	-0.050
47	1.01	0.7	7.0	0.1268	-0.044
49	1.05	0.4	8.0	0.1269	-0.056
55	1.18	0.4	6.0	0.1273	-0.027
63	1.35	0.7	6.5	0.1287	-0.036
68	1.46	0.5	6.0	0.1294	-0.027

Percentage*:The percentage of the order obtained by Eq.11.

and thin lines the mean +/- standard deviations. The mean value of site amplification spectra is used as $|G(f)|$.

The lower frequency limit, f_1, is varied from 0.4Hz to 9.9Hz with 0.1Hz interval, and the upper frequency limit, f_2, from 0.5Hz to 10Hz with 0.1Hz interval. The value of 0.4Hz and 10Hz are corresponding with lower and upper frequencies of effective range on the site amplification spectra, which are judged from S/N ratio. The total number of frequency ranges calculated is 4,656. To decide the most appropriate frequency range, average value of D_N, $\overline{D_N}$, is calculated by Eq.9 for each frequency range. The frequency range which minimizes $\overline{D_N}$ is considered as the most appropriate frequency range.

$$\overline{D_N} = \frac{1}{N_1}\sum_{j=1}^{N_1} D_N(j) \qquad (9)$$

where, N_1 is number of the input waves (12 waves), $D_N(j)$ means D_N for j-th wave. The observed and simulated seismic waves at rock site are used for the input waves. The simulated waves are obtained by the stochastic Green's function method. The average value of b_N, $\overline{b_N}$, is also calculated by Eq.10 for each frequency range.

$$\overline{b_N} = \frac{1}{N_1}\sum_{j=1}^{N_1} b_N(j) \qquad (10)$$

where, $b_N(j)$ means b_N for j-th wave.

Result

Table 1 shows the obtained $\overline{D_N}$ in order. The order from the smallest $\overline{D_N}$ among 4,656 cases, the percentage of the order obtained by Eq.11, the frequency ranges, and $\overline{b_N}$ are also shown in the table.

Table 2 The order for the frequency range from 0.4Hz to 7.0Hz with respect to each input wave.

Input Wave No.	The order	Percentage*	D_N	b_N
1	404	8.68	0.2708	-0.010
2	593	12.74	0.2729	-0.015
3	378	8.12	0.1496	-0.065
4	5	0.11	0.0969	-0.056
5	270	5.80	0.0526	-0.049
6	7	0.15	0.0777	-0.043
7	141	3.03	0.0816	-0.051
8	173	3.72	0.0833	-0.048
9	5	0.11	0.0782	-0.055
10	5	0.11	0.0982	-0.041
11	15	0.32	0.0456	-0.029
12	237	5.09	0.0884	-0.039

Percentage*:The percentage of the order obtained by Eq.11.

$$Percentage = \frac{O}{4656} \times 100 \tag{11}$$

where, O is the order of the frequency range and 4,656 is total number of frequency ranges for the analysis. Though the lower and upper frequency limit, f_1 and f_2 are given in the 0.1Hz interval in this analysis, cases with 0.1Hz interval for equal to or less than 1 Hz, and 0.5Hz interval for more than 1Hz are selected for listing in the table for simplicity, except the 1st order.

From the table, $\overline{D_N}$ for the frequency range from 0.4Hz to 7.0Hz, which is 4th in the ranking, is almost same with that for the best frequency range from 0.4Hz to 7.2Hz. Table 2 shows the order for the frequency range from 0.4Hz to 7.0Hz with respect to each input wave. We discuss whether the significant difference is recognized in the relationship between G_A and dI_N for two frequency ranges, i.e. the best frequency range of each input wave and that from 0.4Hz to 7.0Hz. Fig.3 shows an example of relationship between G_A and dI_N with respect to the input wave No.2 for two frequency ranges as shown below.

(a) From 0.9Hz to 8.8Hz

(b) From 0.4Hz to 7.0Hz

The frequency range from 0.9Hz to 8.8Hz is the best frequency range for the input wave. However, the relationship between G_A and dI_N for the frequency range from 0.4Hz to 7.0Hz is almost same with that for the best frequency range except a site. Similar results can be obtained with respect to other input waves. Therefore we concluded that the increment of seismic intensity due to site amplification factor correlates sufficiently with the average of site amplification spectra between 0.4Hz to 7.0Hz in this approach.

EMPIRICAL APPROACH (APPROACH -2)

Outline of analysis

The increment of seismic intensity due to site amplification factor, dI_E, is defined as difference between a seismic intensity at the site used (I_{tar}) and that of a reference rock site (I_{ref}) in this approach. Because the hypocentral distances at the sites are different from that at the reference rock site, the seismic intensities at

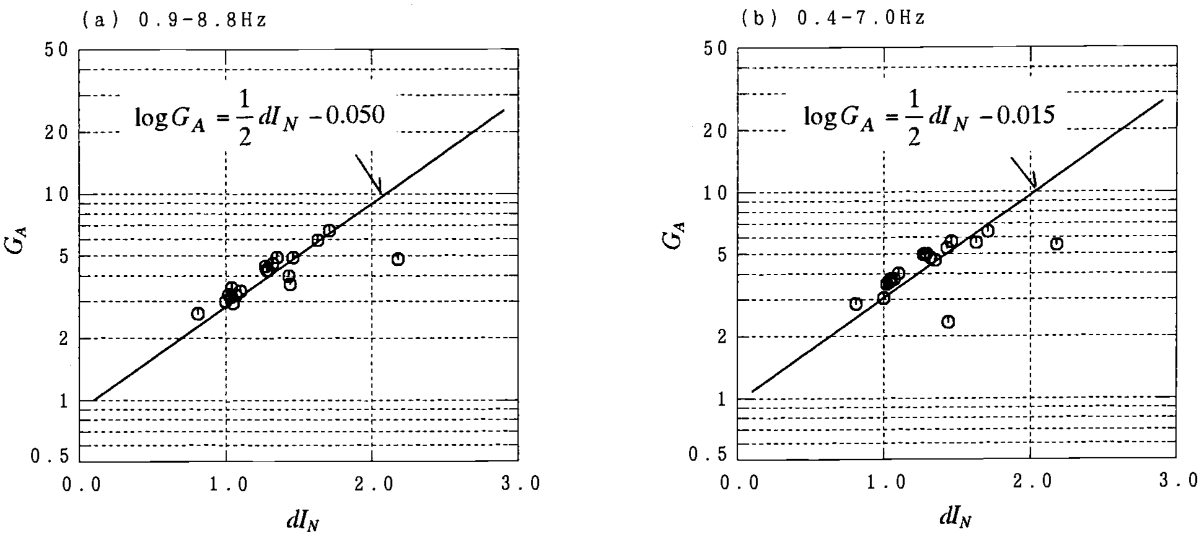

Fig.3 The relationship between the average of site amplification spectra, G_A, and the increment of seismic intensity, dI_N, with respect to the input Wave No.2.

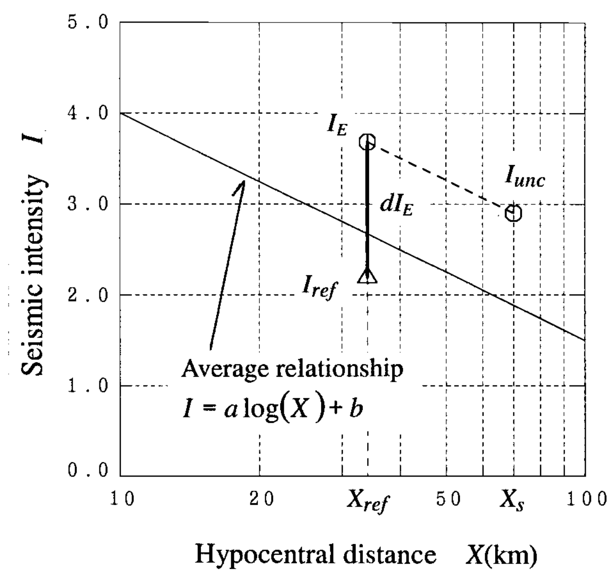

Fig.4 Schematic illustration for correcting path effects in Approach-2.

the sites are necessary to be corrected considering path effects. The method for correcting path effects is shown in Fig.4 and below.

1. The coefficients of attenuation characteristics on seismic intensity described in Eq.12, a and b, are obtained by the least mean square method for each earthquake using all available data in addition to the site used in this approach.

   $$I = a\log(X) + b \quad (12)$$

   where, X is hypocentral distance (km).
2. The corrected seismic intensities at the sites, I_E, are obtained by Eq.13.

   $$I_E = I_{unc} + a\log(X_s - X_{ref}) \quad (13)$$

where, I_{unc} is the seismic intensity at the site, X_s and X_{ref} are the hypocentral distances at the site and the reference rock site, respectively.

3. The increments of seismic intensity due to site amplification factor, dI_E, are described in Eq.14.

$$dI_E = I_E - I_{ref} \tag{14}$$

The relationship between the average of site amplification spectra, G_A, and the increment of seismic intensity, dI_E, is described in Eq.15, which is the same with equations in Approach-1. b_E is obtained by the least mean square method and the variance of estimated seismic intensity, D_E, is calculated by Eq.16.

$$\log G_A = \frac{1}{2} dI_E + b_E \tag{15}$$

$$D_E = \sum_{k=1}^{n} \left[\log G_A(k) - \left\{ \frac{1}{2} \times dI_E(k) + b_E \right\} \right]^2 \tag{16}$$

where, n is number of the sites (19 in this approach). To obtain the most appropriate frequency range, average value of D_E, $\overline{D_E}$, is calculated for each frequency range by Eq.17.

$$\overline{D_E} = \frac{1}{N_2} \sum_{j=1}^{N_2} D_E(j) \tag{17}$$

where, N_2 is the number of the earthquakes (6 earthquakes), $D_E(j)$ means D_E for j-th earthquake. The earthquakes of No.1, 3, and 6 are crustal earthquakes with short hypocentral distance, No.2 and 4 intraplate earthquakes, No.5 a crustal earthquake with long hypocentral distance, about 200km. The average value of b_E, $\overline{b_E}$, is also calculated for each frequency range by Eq.18.

$$\overline{b_E} = \frac{1}{N_2} \sum_{j=1}^{N_2} b_E(j) \tag{18}$$

where, $b_E(j)$ means b_E for j-th wave.

Result

The order from the smallest $\overline{D_E}$ among 4,656 cases, the percentage of the order, the frequency ranges, $\overline{D_E}$, and $\overline{b_E}$ are shown in Table 3 in the same way with the previous approach. The best frequency range is from 0.4Hz to 7.5Hz in this approach. Table 4 shows the order for the frequency range from 0.4Hz to 7.5Hz with respect to each earthquake. The order for frequency range from 0.4Hz to 7.5Hz is included within 5% for the earthquakes No.1, 2, 4, and 6. We again discuss whether the significant difference is in the relationship between the average of site amplification spectra, G_A, and the increment of seismic intensity, dI_E, in two frequency ranges, i.e. the best frequency range of each earthquake and from 0.4Hz to 7.5Hz. Fig.5 shows an example of relationship between G_A and dI_E with respect to the earthquake No.2 for two frequency ranges as shown below.

(a) From 0.4Hz to 9.2Hz

(b) From 0.4Hz to 7.5Hz

The frequency range from 0.4Hz to 9.2Hz is the best for this earthquake. However, the relationship between G_A and dI_E for the frequency range from 0.4Hz to 7.5Hz is almost same with that for the best frequency range. Similar results can be obtained for the earthquakes of No.1, 4, and 6. Therefore, we concluded in this approach that the increment of seismic intensity due to site amplification factor has a good correlation with the average of site amplification spectra between 0.4Hz to 7.5Hz.

With respect to the earthquakes of No.3 and 5, the increment of seismic intensity doesn’t correlate well with the average of site amplification spectra at the frequency range. The reasons are mentioned later.

Table 3 The order of the frequency range in Approach-2.

The order	Percentage*	Frequency range (Hz)		$\overline{D_E}$	$\overline{b_E}$
		Lower f_1	Upper f_2		
1	0.02	0.4	7.5	0.4753	0.056
7	0.15	0.5	7.5	0.4765	0.055
19	0.41	0.6	7.5	0.4784	0.054
23	0.49	0.4	7.0	0.4793	0.064
26	0.56	0.4	8.0	0.4796	0.048
27	0.58	0.5	7.0	0.4797	0.063
32	0.69	0.7	7.5	0.4802	0.053
34	0.73	0.6	7.0	0.4807	0.062
42	0.90	0.7	7.0	0.4815	0.061
45	0.97	0.5	8.0	0.4816	0.047
47	1.01	0.8	7.5	0.4821	0.052
49	1.05	0.8	7.0	0.4823	0.060
62	1.33	0.9	7.0	0.4835	0.059
67	1.44	0.9	7.5	0.48436	0.051
68	1.46	0.6	8.0	0.48440	0.046

Percentage*:The percentage of the order obtained by Eq.11.

Table 4 The order for the frequency range from 0.4Hz to 7.5Hz with respect to each earthquake.

Earthquake No.	The order	Percentage*	D_E	b_E
1	8	0.17	0.1348	-0.197
2	169	3.63	0.2910	0.204
3	1641	35.24	0.5285	0.218
4	94	2.02	0.4632	0.184
5	864	18.56	1.0608	-0.040
6	152	3.26	0.3737	-0.030

Percentage*:The percentage of the order obtained by Eq.11.

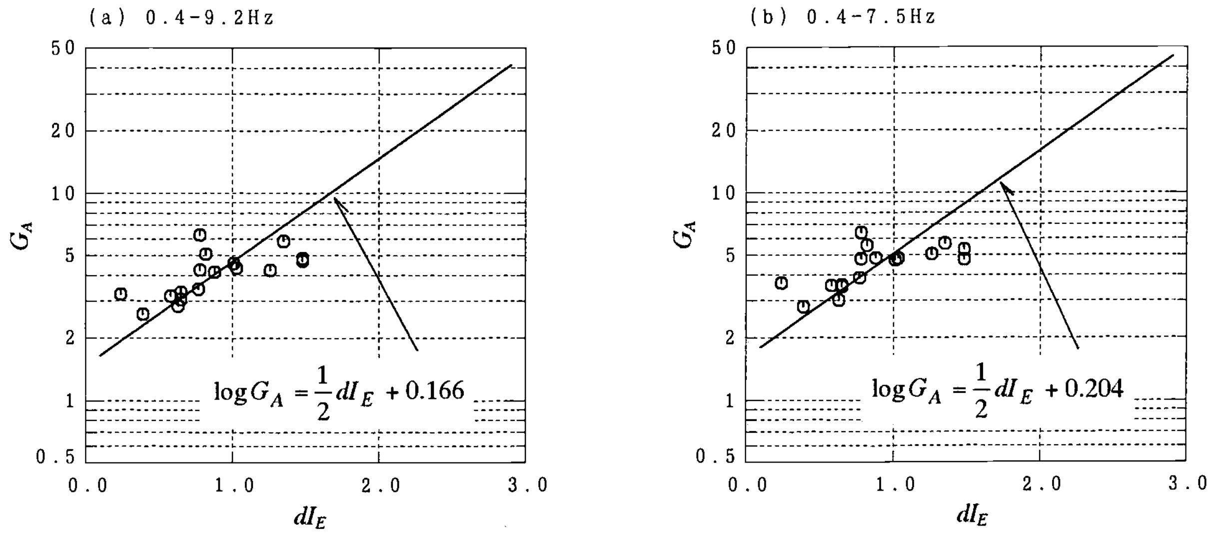

Fig.5 The relationship between the average of site amplification spectra, G_A, and the increment of seismic intensity, dI_E, with respect to the earthquake No.2.

APPROACH BASED ON QUESTIONNAIRE SURVEY OF SEISMIC INTENSITY (APPROACH -3)

Outline of analysis

The site amplification index, ΔI_Q, has been obtained from a questionnaire survey of seismic intensity during the 1995 Kobe earthquake by Tsurugi *et al*. [4]. The relationship between the average of site amplification spectra, G_A, and ΔI_Q is described in Eq.19 which is in the same way with Approach-1 and Approach-2. b_Q is obtained by the least mean square method and the variance of estimated seismic intensity, D_Q, is calculated by Eq.20.

$$\log G_A = \frac{1}{2}\Delta I_Q + b_Q \quad (19)$$

$$D_Q = \sum_{i=1}^{n}\left[\log G_A(i) - \left\{\frac{1}{2}\Delta I_Q(i) + b_Q\right\}\right]^2 \quad (20)$$

where, n is number of the sites used (18 sites), $G_A(k)$ the average value of site amplification spectra in a frequency range at site k, $\Delta I_Q(k)$ the site amplification index from questionnaire survey at site k. The frequency ranges considered are the same with those in Approach-1 and Approach-2.

Result

The order from the smallest D_Q among 4,656 cases, the percentage of the order, the frequency ranges, D_Q, and b_Q are shown in Table 5 in the same way with Approach-1 and Approach-2. Fig.6 shows the relationship between G_A and ΔI_Q for six frequency ranges as shown below.

(a) From 0.4Hz to 9.1Hz (1st of order, correspond with 0.02% of all cases)
(b) From 0.4Hz to 9.0Hz (3rd of order, correspond with 0.06% of all cases)
(c) From 0.6Hz to 8.5Hz (46th of order, correspond with 0.99% of all cases)
(d) From 0.9Hz to 8.0Hz (140th of order, correspond with 3.01% of all cases)

Table 5 The order of the frequency range in Approach-3.

The order	Percentage*	Frequency range (Hz)		D_Q	b_Q
		Lower f_1	Upper f_2		
1	0.02	0.4	9.1	0.1106	0.554
3	0.06	0.4	9.0	0.1107	0.555
8	0.17	0.4	9.5	0.1119	0.547
10	0.21	0.5	9.0	0.1120	0.554
20	0.43	0.5	9.5	0.1139	0.546
23	0.49	0.6	9.0	0.1146	0.552
33	0.71	0.4	8.5	0.1157	0.564
35	0.75	0.4	10.0	0.1160	0.538
36	0.77	0.5	8.5	0.1162	0.562
40	0.86	0.6	9.5	0.1173	0.544
44	0.95	0.7	9.0	0.1178	0.551
46	0.99	0.6	8.5	0.1180	0.561
52	1.12	0.5	10.0	0.1187	0.536
58	1.25	0.7	8.5	0.1202	0.559
64	1.37	0.7	9.5	0.1212	0.542

Percentage*:The percentage of the order obtained by Eq.11.

(e) From 1.0Hz to 7.5Hz (235th of order, correspond with 5.05% of all cases)
(f) From 1.5Hz to 7.0Hz (446th of order, correspond with 9.58% of all cases)
The relationship between G_A and ΔI_Q for frequency range from 0.4Hz to 9.0Hz is almost same with that for the best frequency range from 0.4Hz to 9.1Hz as shown in Fig.6. We concluded in this approach that the increment of seismic intensity due to site amplification factor has good correlation with the average of site amplification spectra between 0.4Hz to 9.0Hz.

PROPOSED METHOD TO ESTIMATE INCREMENT OF SEISMIC INTENSITY BASED ON SITE AMPLIFICATION SECTRA

Equation for estimating increment of the seismic intensity on JMA scale

The most appropriate frequency ranges are obtained as that from 0.4Hz to 7.0Hz in Approach-1, from 0.4Hz to 7.5Hz in Approach-2, and from 0.4Hz to 9.0Hz in Approach-3. The lower frequency limits are 0.4Hz for all approaches, whereas the upper frequency limits are different from each approach. Table 6 shows the order of these frequency ranges in each approach. From the table, the following discussion can be done.

・The frequency range from 0.4Hz to 7.0Hz is not so good, because the order of this range is beyond 5% of all cases in Approach-3.
・The frequency range from 0.4Hz to 9.0Hz is not so good, because the order of this range is beyond 5% of all cases in Approach-2.
・The frequency range from 0.4Hz to 7.5Hz is good, because the order of this range is within 1% in Approach-1 and Approach-2, and within 5% in Approach-3.

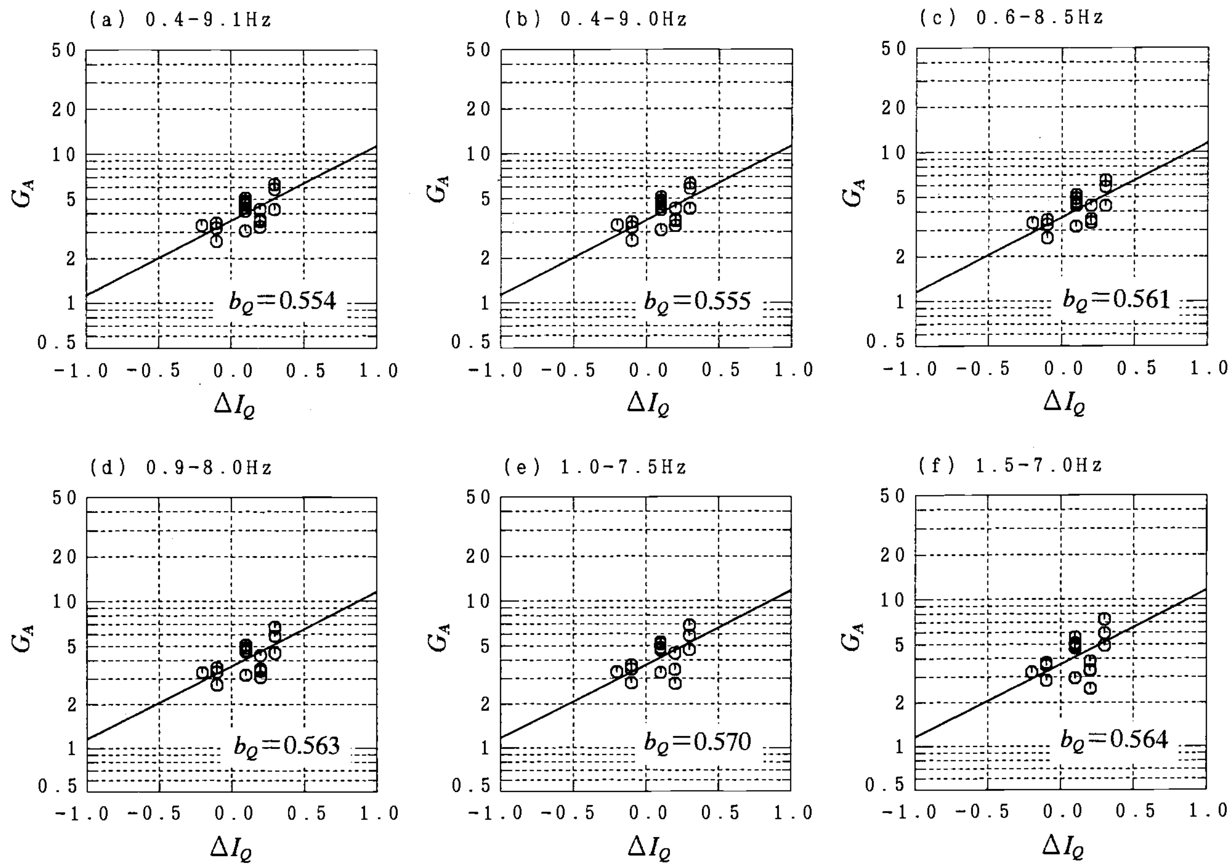

Fig.6 The relationship between the average of site amplification spectra, G_A, and the site amplification index, ΔI_Q. ($\log G_A = \frac{1}{2}\Delta I_Q + b_Q$)

Table 6 The order of most appropriate frequency ranges in each approach.

Frequency range	0.4～7.0Hz			0.4～7.5Hz			0.4～9.0Hz		
	The order	Percent-age*	b^*	The order	Percent-age*	b^*	The order	Percent-age*	b^*
Approach-1	4	0.09	-0.042	7	0.15	-0.048	409	8.78	-0.072
Approach-2	23	0.49	0.064	1	0.02	0.056	236	5.07	0.032
Approach-3	348	7.47	0.585	224	4.81	0.579	3	0.06	0.555

Percentage*:The percentage of the order obtained by Eq.11.
b^{*}: b_N in Eq.7, b_E in Eq.14, or b_O in Eq.18

Therefore, the frequency range from 0.4Hz to 7.5Hz is adopted as the most appropriate frequency range. The relationships between the average of site amplification spectra for the frequency range and the increment of seismic intensity in each approach are shown below.
In Approach-1,

$$\log G_A^{0.4-7.5} = \frac{1}{2} dI_N - 0.048 \tag{21}$$

i.e.

$$dI_N = 2\log G_A^{0.4-7.5} + 0.096 \tag{22}$$

In Approach-2,

$$\log G_A^{0.4-7.5} = \frac{1}{2} dI_E + 0.056 \tag{23}$$

i.e.

$$dI_E = 2\log G_A^{0.4-7.5} - 0.112 \tag{24}$$

In Approach-3,

$$\log G_A^{0.4-7.5} = \frac{1}{2} \Delta I_Q + 0.579 \tag{25}$$

i.e.

$$\Delta I_Q = 2\log G_A^{0.4-7.5} - 1.158 \tag{26}$$

where, $G_A^{0.4-7.5}$ is the average of site amplification spectra for the frequency range from 0.4Hz to 7.5Hz. b_N should be zero, because there is no amplification at the rock site. It is found from Table 4 that the estimated seismic intensity includes the error whose range is about 0.1. We can conclude that the increment of seismic intensity due to site amplification factor have a good correlation with the average of site amplification spectra between 0.4Hz to 7.5Hz, and the equation for estimating increment of seismic intensity can be described in Eq.27.

$$dI_N = 2\log G_A^{0.4-7.5} \tag{27}$$

Limitation of the proposed equation for estimating increment of the seismic intensity

It was found that the increment of seismic intensity doesn't correlate well with the average of site amplification spectra between 0.4Hz to 7.5Hz for the earthquakes of No.3 and 5 in Approach-2. Fig.7 shows acceleration Fourier spectra during the earthquakes of No.3, 5, and 6 at a site. For the earthquake of No.6, the increment of seismic intensity correlate well with the average of site amplification spectra at the frequency ranges. The Fourier spectrum during the earthquake of No.3 is about 0.1 times smaller than that of No.6 in the frequency range from 0.4Hz to 7.5Hz. The seismic motion in low frequency range was not excited, because the magnitude of this earthquake is only 4.0 on JMA scale. The Fourier spectrum in high frequency range during the earthquake of No.5 is smaller than that in low frequency range. The seismic motion in high frequency range was attenuated in the long propagation path about 200km. Similar results are obtained at the other sites.

Through the discussion above, the proposed equation to estimate increment of seismic intensity cannot be applied to the earthquakes with long hypocentral distance and the small earthquakes. However, there is no problem for the purpose of disaster prevention, because the seismic intensity during these earthquakes is not so large.

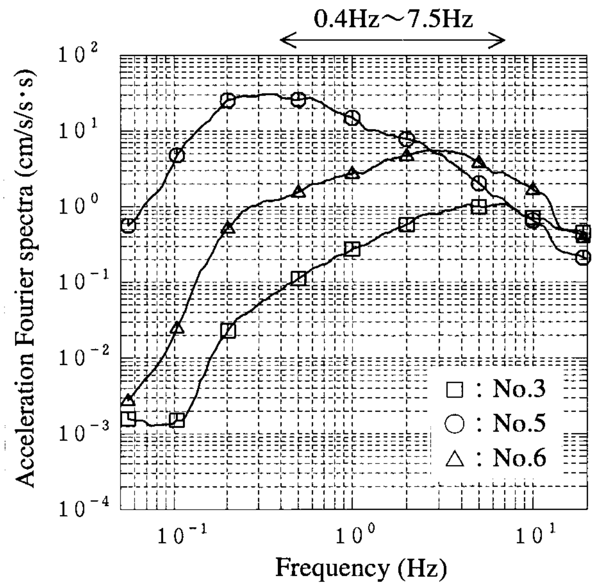

Fig.7 Acceleration Fourier spectra during the earthquakes of No.3, 5, and 6.

CONCLUSION

In order to estimate seismic intensity on JMA (Japan Metrological Agency) scale taking into account the local site effects, we propose a method to estimate site amplification factors of seismic intensity on JMA scale based on the amplification spectra which are obtained from soil profiles or seismic observation records at the site. The increment of seismic intensity is found to have a good correlation with the average of site amplification spectra between 0.4Hz to 7.5Hz, and the equation for estimating increment of seismic intensity is proposed as shown below.

$$dI = 2\log {G_A}^{0.4-7.5}$$

$${G_A}^{0.4-7.5} = \frac{1}{7.5-0.4}\int_{0.4}^{7.5}\left|G(f)\right|df$$

where, *dI* is the increment of seismic intensity on JMA scale due to site amplification factor and *G*(*f*) is the site amplification spectra.

REFERENCES

1. Kawasumi,H. "Intensity and magnitude of shallow earthquakes, Travaux Scientifique", BCSI, Series A, Vol.19, pp.99-114, 1954.
2. Tsurugi M., Tai M., Kowada A., Tatsumi Y., Irikura K., "Estimation of empirical site amplification effects using observed records", 12th World Conference on Earthquake Engineering, No.1243, CD-ROM, 2000.
3. Tsurugi M., Sawada S., Miyajima M, Kitaura M., "Re-estimation of site amplification effects in Kansai region", Journal of Structural Engineering, Vol.48A, pp.577-586, 2002 (In Japanese).
4. Tsurugi M., Sawada S., Irikura K., Toki K., "Distribution of site amplification factors on Osaka plain based on questionnaire survey of The 1995 Hyogo-Ken Nambu Earthquake", 6th International Conference on Seismic Zonation, CD-ROM, 2000.