Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Foundation effect in accelerograms of small earthquakes

S. Aoyama
Tokyo University of Agriculture & Technology, Japan

ABSTRACT: Over 240 accelerograms of small earthquakes were recorded near a foundation footing of a 3-storey RC building built on a thin soft layer covering the firm ground of TOKYO area. These records were relatively small size in magnitude. Using the records, the response spectral characteristics are compared with the prediction formula suggested in ERDSHB code. The regression analysis was carried out for the measured records and their characteristics discussed. Also Fourier spectra of the measured records were computed and compared with prediction formula presented by *Trifunac*, and further on, the soil-structure interaction effects were investigated.

1. INTRODUCTION

Due to the increasing interest in earthquake hazard prevention the number of seismorecorder is also increasing. Many of these recorders are set at the building base or at the foundation for the sake of building maintenance. It is easily supposed that the accelerogram recorded with such a recorder reflects the soil-structure interactive motion, so it is an important subject to clarify the nature of the characteristics of the accelerogram.

The difference between an accelerograms in a building and in the free ground near the building was first discussed by *Housner*(1959), and a diminution of building record in response velocity spectrum in shorter period range was pointed out. *Lee, Trifunac*(1982) analyzed horizontal component of accelerograms recorded in 57 buildings during 1930 ~1971 events. They detected that the common logarithm of the normalized Fourier spectra of accelerogram has a common nature, and deduced that the effect of building size is considerably small. *Moslem, Trifunac*(1987) used the same accelerogram and investigated the common logarithm of the Fourier spectral ratio of measured record to that predicted by the formula. A third order polynomial regression formula representing the common logarithm of normalized Fourier spectrum in a building record was also proposed.

In this paper the author has discussed the nature and foundation effects in the accelerograms through the analysis of more than 240 accelerograms recorded in the accelerometer installed in the base mat near the foundation footing of a 3-storey RC building.

2. METHOD OF ANALYSIS

2.1 ABSOLUTE RESPONSE ACCELERATION SPECTRUM

Absolute response acceleration spectrum of the measured records were computed using a standard method. In Japan, ERDSHB{Earthquake Resistant Design Specification of Highway Bridges[2](1990) } recommends the prediction formula of absolute acceleration as follows.

$$\left.\begin{array}{l} S_A^H(T_k, M, \Delta, GC) = a(T_k, GC) \\ \times 10^{b(T_k,GC)M} \times (\Delta + 30)^{c(T_k,GC)} \\ S_A^V(T_k, M, \Delta, GC) = a^V(T_k, GC) \\ \times 10^{b^V(T_k,GC)M} \times (\Delta + 30)^{c^V(T_k,GC)} \end{array}\right\} \quad (1)$$

where, $S_A^H(\cdots)$, $S_A^V(\cdots)$ are the horizontal and vertical absolute response spectrum at damping ratio of 5% respectively, T_k is the vibration period in *sec.* of 1-DOF system, Δ is the epicentral distance in *km*, M is the magnitude in JMA scale, GC denotes the types of 3 kinds of ground conditions shown in Table.1. The 6 coefficients $a(T_k, GC), \cdots$ are given at 10 specified vibration period with 3 types of GC. The measured spectra and those predicted by the eq.(1) are compared.

Table.1 Classification of GC in eq.(1).

group	types of foundation
group-1	Tertiary or older rock, or diluvium with $H < 10m$
group-2	Diluvium with $H > 10m$, or alluvium with $H < 25m$, including soft layer with thickness less than $5m$
group-3	Other than the above, usually soft alluvium or reclaimed land

2.2 FOURIER SPECTRUM ANALYSIS OF THE ACCELEROGRAM

Lee, et al(1982) showed that the normalized Fourier spectrum of the building accelerogram can be expressed in the following form.

$$\log_{10}\{\text{normalized Fourier spectrum}\}$$

$$= A_0(T) + A_1(T)S \qquad (2)$$

where, T is the period, S is the dimension of the building, $A_0(T), A_1(T)$ are the coefficients. The normalization was carried out in such way that the spectrum had a unit amplitude in the period ranging between 0.5 to 2.0 *sec.* The general prediction formula of Fourier spectrum of the accelerogram of free-field ground is presented by *Trifunac*(1976a) as follows.

$$\left.\begin{array}{l} \log_{10}[FS(T)_{,p}] = M + \log_{10} A_0(R) \\ \quad - \log_{10}\{FS_0(T,M,p,s,v,R)\} \\ \quad \log_{10}\{FS_0(T,M,p,s,v,R)\} \\ = a(t)p + b(T)M + c(T) + d(T)s \\ \quad + e(T)v + f(T)M^2 + g(T)R \end{array}\right\} \qquad (3)$$

where $FS(T)_{,p}$ is the Fourier spectrum of accelerogram in *in/sec.* with confidence level $100p\%$, T is the period of vibration, M is the earthquake magnitude, $\log_{10} A_0(R)$ is the empirical function describing the amplitude attenuation with distance determined by the analysis(*Trifunac*,1976b), $\log_{10}\{FS_0(\cdots)\}$ is the empirical scaling function, and $a(T), b(T), \cdots, g(T)$ are the coefficient functions of T and are determined by the regression analysis. The variable s represent the type of foundation($s = 0$ for alluvium, $s = 1$ for intermediate rocks, and $s = 2$ for basement rocks) , v designate the record component($v = 0$ for horizontal component, $v = 1$ for vertical component), and R is the epicentral distance in *km*.

The ratios of the measured acceleration Fourier spectra of a building to the predicted values given by eq.(3) were computed and normalized to give the maximum ratio in the period range of $0.5 \sim 2.0 sec.$ as unity. The common logarithm of the ratios were examined by the same relationship carried out by *Moslem et al*(1987), *i.e.*

$$\log_{10}\{\text{normalized Fourier spectral ratio}\}$$

$$= B_0(T) + B_1(T)S. \qquad (4)$$

Then the normalized Fourier spectrum was fitted by the third order polynomial with $\log_{10} T$ as follows.

$$\log_{10}\{\text{normalized Fourier spectrum}\}$$

$$= a_0 + a_1 x + a_2 x^2 + a_3 x^3 \qquad (5)$$

where $x = \log_{10} T$. *Moslem et al* treated these four coefficients to reflect the building size using the expression,

$$a_i = \alpha_i + \beta_i S \ (i = 0 \sim 3) \qquad (6)$$

where S is the size of building. But in this case since all the records belong to the same building, the second term in eq.(4) and (6) were ignored.

3. DATA

The accelerograms were obtained by the accelerometer on the foundation mat near the spread footing of the 3-storey building with width= 8.5m, and length=68m. The N-S direction is parallel to the width, and E-W direction is parallel to the length of the building. The accelerometer has direct digital recording facility with 200 Hz sampling.

The foundation of the building is covered by 3~5m soft soil layer over the firm sand and thick gravel layer. So the foundation was determined to belong to the group-2 in Table.1 and to correspond to $s = 1$ case in eq.(3).

From Feb. 1989 to Mar. 1991, 85 events were measured at the site. These events were classified as shown in Table.2 in terms of magnitude and distance range.

Table.2 Classification of the events.

M	Δkm 0~20	21~60	61~120	121~200	201~400	401~	Σ
~3.9	6	4	4				14
4.0~4.4		8	11				19
4.5~4.9		2	13	4	1		20
5.0~5.4			7	5	1		13
5.5~5.9		2	3	3	5		13
6.0~6.9			1	1		3	5
7.0~						1	1
Σ	6	16	39	13	7	4	85

62% of the events are small earthquake with $M < 5.0$ as shown in the Table.2. The recorded accelerograms were handled with cut-off frequency of 25 Hz.

4. RESULTS OF ANALYSIS

4.1 ABSOLUTE ACCELERATION RESPONSE SPECTRUM

Fig.1a,b represent the typical absolute response acceleration spectrum as predicted by the formula in eq.(1). It has been reported(*Kawashima*,1984a,b) that the horizontal component of the prediction value given by the ERDSHB code represent the resultant in horizontal two perpendicular component of acceleration, and in average is 17% larger than the larger of the two maximum values of both components. In this study both N-S and E-W components are separately treated to distinguish the two perpendicular movements parallel to the building.

It is apparent that the predicted values given by eq.(1) are about 3 or 5 times larger than the measured values. The reason for these differences may be due to (1)the coefficients suggested by the code being

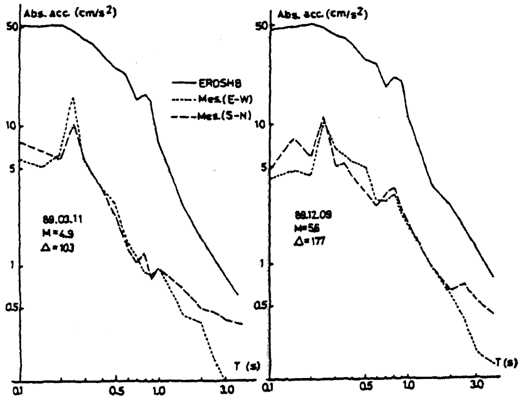

Fig.1a Absolute acceleration spectrum, measured and predicted by the ERDSHB code (horizontal).

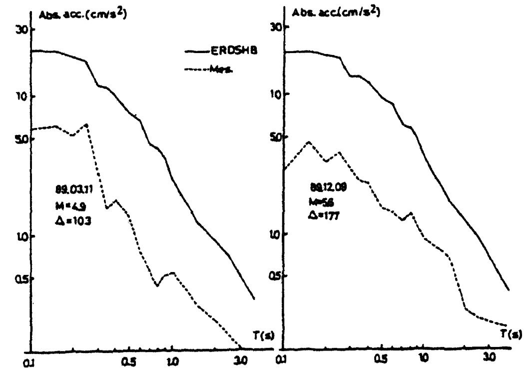

Fig.1b Absolute acceleration spectrum, measured and predicted by the ERDSHB code (vertical).

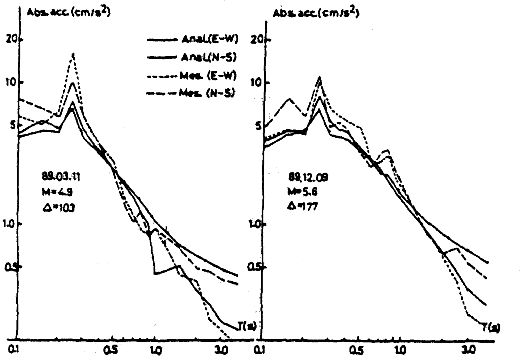

Fig.2a Absolute acceleration spectrum, measured and predicted by the analysis (horizontal).

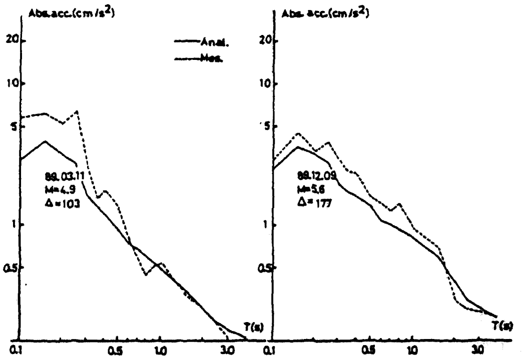

Fig.2b Absolute acceleration spectrum, measured and predicted by the analysis (vertical).

obtained from relatively large earthquake of $M > 5$, and (2)the suggested formula is obtained by the records not affected by the soil-structure interaction. The local peak in the measured response spectrum is observed around the period $T = 0.25sec.$, which is not shown by the prediction formula.

Then using the measured record, the regression-analysis based on the attenuation rule expressed by the eq.(1), was carried out. The computed regression coefficients were denoted as $\hat{a}(T_k, GC)$, $\hat{a}^V(T_k, GC)$, $\hat{b}(T_k, GC), \cdots, \hat{c}^V(T_k, GC)$ corresponding to the eq.(1).

Using the obtained coefficients, the response spectrum of the same events shown in Fig.1 were predicted as shown in Fig.2a,b. From the figure, good approximation of the analyzed coefficients is observed. It can also be seen that the local peak at the period $T = 0.25sec.$ is reproduced. The ratios of the measured coefficients to those given by the code *i.e.* $\hat{a}/a, \hat{a}^V/a^V, \cdots$ are shown in Fig.3.

The coefficient a or $\hat{a}$ define the shape of the response spectrum, b and c are related to effects of the distance attenuation. It is clear that the ratios of the coefficient related to $\hat{b}$ and $\hat{c}$ are not far from unity. This means that the distance attenuation rule is almost the same for the measured small events as suggested for those in the code.

On the other hand, the ratio of the coefficient $\hat{a}$ largely varies, and the depression of horizontal coefficients of 2~5% is notable in the period range of 0.5 ~ 0.7$sec.$. Coefficients of two perpendicular horizontal component(N-S and E-W) show nearly the same behavior, but E-W component is slightly smaller when compared with N-S component.

The essential difference between a, b, c and $\hat{a}, \hat{b}, \hat{c}$, (that is the difference between large and small earthquakes) represents the coefficient $a(T_k, GC)$ in eq.(1).

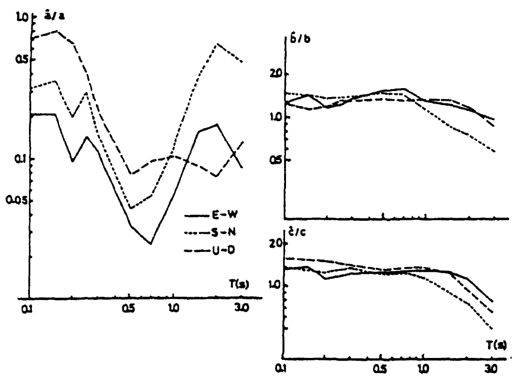

Fig.3 The ratios of the regression coefficients.

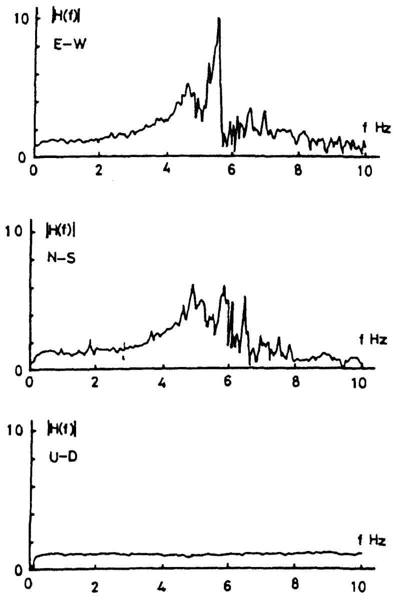

Fig.4 Frequency response functions of the building.

4.2 BUILDING NATURAL VIBRATION

The vibration characteristics of the building was determined by measuring micro-tremors of the building. The synchronous velocity records at the first floor and the roof top were obtained using the velocity meters. The amplitude of frequency response function $|H(f)|$ was determined by assuming the input (first floor) - output (roof top) system. Theoretically $|H(f)|$ is defined as follows.

$$S_{xy}(f) = |H(f)| S_{xx}(f) \qquad (7)$$

where, $S_{xx}(f)$ is the power spectrum of the first floor vibration, $S_{xy}(f)$ is the amplitude of the cross spectrum of first floor and roof top, and f is the frequency. $|H(f)|$ gives the gain in the roof top vibration. $|H(f)|$ is computed from the relationship in the eq.(7), and is shown in Fig.4 in three orthogonal direction components.

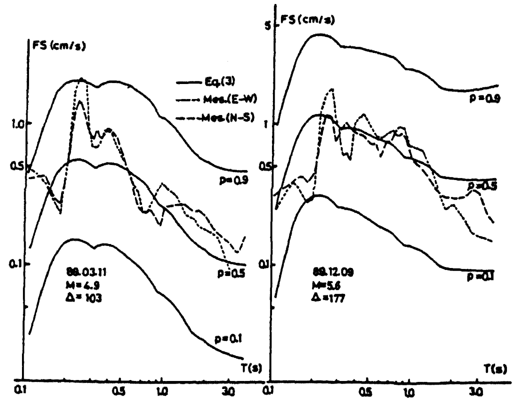

Fig.5a Measured and predicted Fourier spectra (horizontal).

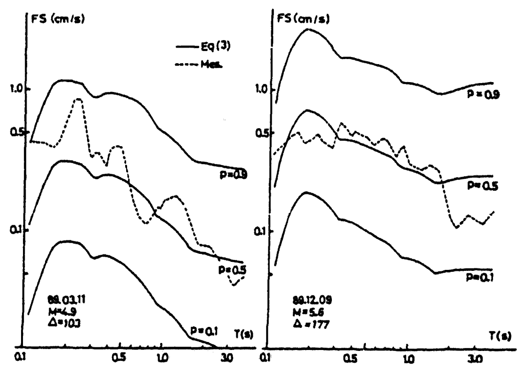

Fig.5b Measured and predicted Fourier spectra (vertical).

From the figure, it is clear that the dominant gain of vibration amplitude in two horizontal direction is about 4.5 ~ 5.5Hz frequency in S-N component, 5.5Hz in E-W component, and the corresponding gain is about 6 and 10 respectively. But in the vertical vibration, there is no significant magnification observed. Therefore it is deduced that the natural period of the building in horizontal vibration is about 0.2*sec.*, and there are no evident vibrational characteristics in the vertical vibration. These natural periods are nearly the same periods appearing in the absolute acceleration response spectrum shown in the Fig.2.

4.3 FOURIER SPECTRUM

The characteristics of the accelerograms of the build-

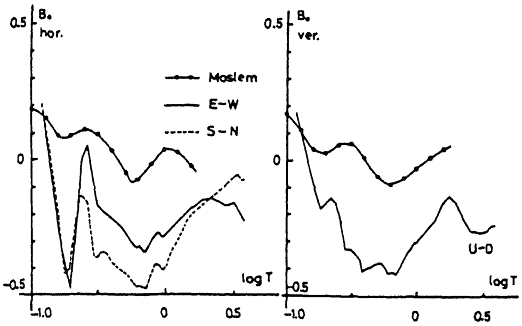

Fig.6 Normalized Fourier spectral ratio

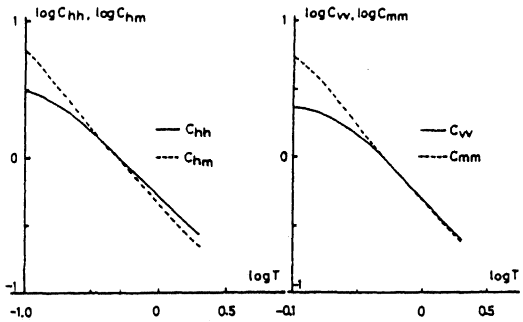

Fig.8 Velocity functions of circular footing.

ings have been discussed in relation to the prediction formula given by eq.(3)(*Moslem*, 1987). Fig.5a,b represent the typical comparison of the measured and predicted curves of the Fourier spectrum. In the estimation using the eq.(3), the confidence level of 50% is used throughout the analysis. From the figure, it is also observed that the measured Fourier spectrum has a large value compared to the prediction value near the period $T = 0.25sec.$. Then the mean log ratio of the spectra $B_0(T)$, defined by the eq.(4) is computed using recorded 34 events which have the maximum response acceleration spectrum larger than $10cm/sec^2$.. Fig.6 shows the obtained $B_0(T)$ along with the curve obtained by *Moslem et al*(1987).

The analyzed variation range is larger than the average of many of the building obtained by *Moslem et al*, but the fundamental decrease or increase along the abscissa is the same. The peak in the horizontal component curve at the $\log_{10} T = -0.6$ is not clear in the vertical component. It is interesting to note that the variation of the coefficient $B_0(T)$ essentially resembles that of the ratio of the regression coefficient $\hat{a}/a, \cdots$ shown in Fig.3. Next, the third order polynomial regression coefficients in eq.(5) were obtained. The obtained coefficients are shown in Table.3. The approximation curve of normalized Fourier spectrum

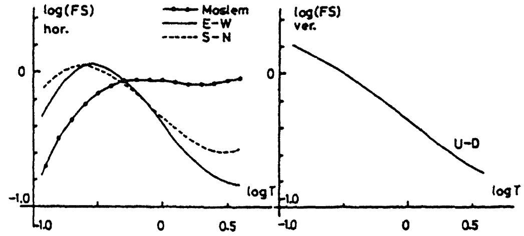

Fig.7 Normalized Fourier spectrum of eq.(5).

Table.3 Coefficients in eq.(5).

a_i	E-W	S-N	*Moslem*	U-V
a_0	-0.3677	-0.3428	-0.0572	-0.3482
a_1	-1.2082	-0.8731	-0.0945	-0.7218
a_2	-0.0356	-0.2451	-0.1892	0.0129
a_3	1.3322	1.0092	0.7707	0.1390

in three directions are shown in Fig.7, accompanied by *Moslem*'s curve in horizontal direction.(whereby , $S = 8.5m = 28ft$ for concrete structure case is used as the conditions of building size.) The correlation coefficients of fit are larger than 0.95 in all directions, so the high applicability of the regression expression of eq.(5) was demonstrated.

In the horizontal component, even the deviation of the measured value from the regression curve is large in shorter period range($\log_{10} T < -0.5$), good coincidence of both curve in longer period range is attained. In the *Moslem*'s curve, the spectrum increases up to $\log_{10} T = 0.2$ abscissa, and keep constant value in longer period range. On the other hand, the analyzed curve shows dominant spectral peak at $\log_{10} T = -0.6 \sim -0.5$ ($T = 0.25 \sim 0.32sec.$) and in longer period range than the peak period the curve decreases mountainously. The period which gives the peak value of the spectrum corresponds to the natural period of the building. The spectrum of vertical component shows monotonous decrease. This may be, correspond to the fact that there is no obvious resonance of the building in vertical motion.

4.4 FOOTING VIBRATION CHARACTERISTICS

The analyzed accelerograms are influenced by the soil-structure interaction of the footing. Among the various investigation of the footing vibration, the flexibility function obtained by *Luco et al*(1971) was used. It is supposed that the movement of a footing caused by earthquake is mainly horizontal, vertical and rocking. Consider a rigid circular footing of radius r_0 under the action of harmonic moment $Me^{i\omega t}$, horizontal force $He^{i\omega t}$, and vertical force $Ve^{i\omega t}$. Denote the harmonic radial displacement at the center of footing with $u_r e^{i\omega t}$, vertical displacement with $u_z e^{i\omega t}$, and rotation angle at the center with $\alpha^{i\omega t}$. Where M, H, and V are the amplitude of moment, horizontal and vertical force respectively, ω is the circular frequency of the vibration, and t is time. These displacements are formally expressed in the following form.

$$\left.\begin{array}{rl} u_r = & \frac{H}{k_H}(f_1 + ig_1) + \frac{M}{k_{HM}}(f_4 + ig_4) \\ u_z = & \frac{V}{k_V}(f_2 + ig_2) \\ \alpha = & \frac{M}{k_M}(f_3 + ig_3) + \frac{H}{k_{MH}}(f_5 + ig_5) \end{array}\right\} \quad (8)$$

where, k_H, k_V, k_M, k_{HM}, and k_{MH} are the static stiffness, and coefficients $f_1, \cdots, f_5$, and $g_1, \cdots .g_5$ are real and imaginary part of the complex flexibility respectively and also are complicate function of the nondimensionalized frequency : $\bar{\omega} = r_0\omega/\beta$. Here, β is the shear velocity of the soil. *Luco* gives general shapes of these functions. If we assume the nature of the Fourier spectrum analyzed above is related to the footing motion defined by the eq.(8), the velocity response is necessary because the Fourier spectrum of accelerogram represent velocity. Differentiating the displacement, we obtain the velocity response ($\dot{u}_r$, $\dot{u}_z$, and $\dot{\alpha}$) as follows.

$$\left.\begin{array}{rl} \dot{u}_r = & \frac{H}{k_H}C_{HH}(\bar{\omega}) + \frac{M}{k_{HM}}C_{HM}(\bar{\omega}) \\ \dot{u}_z = & \frac{V}{k_V}C_{VV}(\bar{\omega}) \\ \dot{\alpha} = & \frac{M}{k_M}C_{MM}(\bar{\omega}) + \frac{H}{k_{MH}}C_{MH}(\bar{\omega}) \end{array}\right\} \quad (9)$$

where, the amplitude function of velocities are $|C_{HH}| = \omega\sqrt{f_1^2 + g_1^2}, |C_{VV}| = \omega\sqrt{f_2^2 + g_2^2}, \cdots$ etc. If we assume that the characteristic state of $\bar{\omega} = 1$ correspond to the natural period of buildings, we can develop the nondimensional frequency to the real frequency. Moreover the same normalization used in the Fourier spectrum analysis was applied to the velocity amplitude function, and their common logarithm obtained. Fig.8 shows 4 kinds of those normalized velocity function as a function of common logarithm of the real period.

The velocity functions $|C_{HH}|$ and $|C_{HM}|$ are related to the horizontal movement, and $|C_{VV}|, |C_{MH}|$ and $|C_{MH}|$ are related to the vertical movement. All these functions show a decrease along the period axis, and this state correspond to the vertical component of the Fourier spectrum shown in Fig.7. But the peak in the Fourier spectrum is not realized for horizontal component.

5. CONCLUSIONS

The results obtained from the analyses of the accelerogram at the building footing under relatively small earthquakes are as follows.

1. The absolute acceleration response spectra are smaller than the prediction formula by $1/5 \sim 1/3$ in all period range. Examining the regression coefficients of the measured data, the coefficients related to distance attenuation are almost the same to the prediction formula, and the coefficient $a(T_k, GC)$ in eq.(1) is largely different from the formula.

2. Using the regression coefficients obtained from the data, the local peak at the period $T_k = 0.25sec.$ occurs in acceleration response spectrum, corresponding to the natural period of the building.

3. From the analysis of Fourier spectral ratio of the measured and predicted value, there is the much wider variation when compared to the average of many buildings. Their variation with period is resemble that of the regression coefficient $a(T_k, GC)$ in eq.(1)

4. The normalized Fourier spectrum is well defined by the third order polynomials, and the horizontal component shows eminent peak at the period $T = 0.25sec.$, which is not observed in the average of many buildings.

5. The result mentioned in 3. and 4. above may be caused by the predominant magnification of the vibration at a period near the natural period of the building since the linear nature will mostly appear under small scale vibration.

6. The result of these analyses will be helpful in the usage of the prediction formula of response spectrum or Fourier spectrum in buildings under common scale earthquake.

REFERENCES

[1] Housner G W.,1959. 'Interaction of building and ground during an earthquake',*Bull. Seism. Soc. Am.* 47: 179–186.

[2] Japan Road Association.,1990., 'Specifications for Earthquake Resistant Design of Highway Bridges': 141–147.

[3] Kawashima K.,Aizawa K.,1984a. 'Attenuation of earthquake response spectra based on multiple regression analysis of Japanese strong motion data',*Proc. of JSCE.* 350: 181–186.

[4] Kawashima K.,Aizawa K.,Takahashi K.,1984b. 'Attenuation of peak ground motions and absolute acceleration spectra of vertical earthquake ground motion',*Proc. of JSCE.* 362: 169–176.

[5] Lee V W., Trifunac M D.,Feng C C.,1982. 'Effects of foundation size on fourier spectrum amplitudes of earthquake accelerations record in buildings',*Soil Dyn. & Earth. Eng.* 1: 52–58.

[6] Luco J E.,Westman R A.,1971. 'Dynamic response of circular footings',*J. of Eng. Mech. Div., Proc. of ASCE.* 97, No.EM5: 1381–1395.

[7] Moslem K., Trifunac M D.,1987. 'Spectral amplitudes of strong earthquake accelerations recorded in buildings', *Soil Dyn. & Earth. Eng.* 6: 100–107.

[8] Trifunac M D.,1976a. 'Preliminary empirical model for scaling Fourier amplitude spectra of strong ground acceleration',*Bull. Seism. soc. Am.* 66: 1343–1373.

[9] Trifunac M D.,1976b., 'Preliminary analysis of the peaks of strong earthquake ground motion',*Bull. Seism. Soc. Am.* 66: 189–219.