EFFECTS OF SEISMIC AND GEOTECHNICAL CONDITIONS ON MAXIMUM GROUND ACCELERATIONS AND RESPONSE SPECTRA

by

Toshio Iwasaki[I], Kazuhiko Kawashima[II] and Mitsuaki Saeki[III]

SUMMARY

This paper presents the results of multiple regression analysis of 301 strong-motion acceleration records, and also shows the results of a quantification analysis of average response accelerations obtained from 277-component horizontal acceleration records. From the analysis done, empirical formulas which can statistically estimate maximum horizontal acceleration, duration of major motion, and number of zero-crossing in terms of earthquake magnitude, epicentral distance, and subsoil condition, are proposed. Frequency characteristics of horizontal motions and ratios of vertical to horizontal accelerations are averagedly evaluated depending on subsoil conditions. Furthermore, various average response spectrum curves for a linear single-degree-of-freedom (SDOF) system are proposed in terms of earthquake magnitude, epicentral distance, and subsoil condition.

INTRODUCTION

In establishing reasonable criteria for earthquake resistant design of structures, it seems essential to properly evaluate characteristics of ground motions and structural behavior during strong earthquakes. A number of strong motion accelerographs are installed at various engineering structures and on neighboring grounds in Japan to grasp dynamic properties of ground motions and structural responses.

Although there will be a number of factors which affect characteristics of ground motions, it seems probable that three principal factors might be earthquake magnitude, geographical situation of the focal area of an concerned earthquake related to the structural site, and subsoil condition at the site. In this study characteristic variables of ground accelerations are statistically analyzed in terms of these three factors.

The results are utilized as basic materials in standard design seismic forces and seismic loads of "New Criteria of Earthquake Resistant Design (Draft)", (1, 2) proposed by the Ministry of Construction in March, 1977.

ANALYSIS OF ACCELERATION RECORDS

A statistical analysis of measured acceleration records was attempted to quantitatively express characteristic variables of ground motions as functions of seismic conditions and subsoil properties at the observation

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I) Head, Ground Vibration Division, Public Works Research Institute, Ministry of Construction, Tsukuba Science City, Ibaraki-ken, Japan

II) Senior Research Engineer, Ground Vibration Division, Public Works Research Institute, Ministry of Construction

III) Consulting Engineer, Japan Engineering Consultants Co., Ltd. Shinjuku-ku, Tokyo, Japan

point. In the present analysis were employed those records which were obtained during earthquakes with the Richter magnitude of 5.0 or higher and the hypocentral depth of 60 km or shallower, and which include at least one record with the maximum acceleration of 50 gals or higher for an earthquake. Records with the maximum acceleration less than 10 gals were excluded. The total number of the records used is 301 (the number of components treated is 3 × 301 = 903) for 51 earthquakes.

Factors considered in this analysis are Richter Magnitude M, epicentral distance Δ(Km) and subsoil condition which are shown in Table 5. Characteristic variables of acceleration records are illustrated in Fig. 1. In addition to these variables, ratio of vertical to horizontal maximum acceleration, $v = V_{max}/H_{max}$ was also examined.

Table 1 indicates the distribution of 301 records used in the analysis. Table 2 shows formulated regression equations and correlation coefficients, which are obtained from the analysis based on the multiple regression analysis. In the table are shown the results of three characteristic values H_{max}, T_d and N_z in which multiple correlation coefficients are greater than 0.5. Fig. 2 illustrates H_{max} as functions of M and Δ, for the case of the whole type of subsoils.

As for the other three characteristic values T_1, v and T_m, the multiple correlation coefficients are found to be less than 0.5. This means that there is no distinct relation among those values and M and Δ. For these variables the mean values and the standard deviations are evaluated depending on subsoil conditions, and are listed in Table 3.

ANALYSIS OF EARTHQUAKE RESPONSE SPECTRA

The Port and Harbour Research Institute, the Ministry of Transport and the Public Works Research Institute, the Ministry of Construction have been conducting response spectrum analysis for major ground motions obtained at various grounds during moderate to strong earthquakes (3, 4, 5). In the present analysis, the response spectra computed at the two Institutes for 277 horizontal components of ground motions, which were triggered during 68 earthquakes with the Richter magnitude between 4.5 and 7.9 and the hypocentral depth of 60 km or shallower, are employed.

Table 4 shows the distribution of the number of data points in each of the combinations of items and categories. As may be seen from this table, the data used in this study are far from sufficient in number nor uniform in distribution. The quality of data set may be improved only when more records become available. The results of the present analysis should be carefully treated and interpreted by taking into account the inherent characteristics of the data set.

Statistical analysis was made for 277 acceleration response spectral amplitudes at each of the 18 natural periods of a SDOF system in terms of earthquake magnitude, epicentral distance, and the recording-site ground condition. The method and results of this analysis are reported elsewhere in detail (6, 7).

As shown in Table 5, each of the three above-mentioned items was classified into several discrete categories, and the following form of prediction formula was assumed:

$$\overline{SA}(T,h) = f_M(T,h) \times f_\Delta(T,h) \times f_{GC}(T,h) \qquad (1)$$

where

$\overline{SA}(T,h)$ = Predicted absolute acceleration response spectral amplitude for given T and h,
T = Natural period of a SDOF system (sec),
h = 0.05 = Damping factor of a SDOF system,
$f_M(T,h)$ = Weighing factor for each magnitude category in Table 5,
$f_\Delta(T,h)$ = Weighing factor for each distance category in Table 5,
$f_{GC}(T,h)$ = Weighing factor for each ground conditions category in Table

The values of the weighing factors were so determined that the predicted spectral amplitudes best agree with the measured spectral amplitudes. The results obtained for each of the 18 natural periods investigated are summarized in Table 6. For example, the absolute acceleration response spectral amplitude for T = 0.5s and h = 0.05 that would be obtained from the ground motion recorded on Type III ground and caused by an earthquake with $M = 6.1 \sim 6.7$ and $\Delta = 20 \sim 59$ km is predicted by Eq. (1) and Table 6 as follows:

$$\overline{SA}(0.5,\ 0.05) = 0.309 \times 2.91 \times 140 = 126\ (\mathrm{cm/s^2})$$

Several predicted response spectra are shown in Fig. 3.

Fig. 4 shows the influence of earthquake magnitude on the absolute acceleration spectral amplitude for a fixed combination of distance and site condition categories. The effect is illustrated in terms of the ratio of the weighing factor of a certain magnitude category to that of the magnitude category between M = 4.5 and M = 5.3. It is seen that the effect of magnitude is different for different period ranges of a SDOF system. As far as Fig. 4 is concerned, the effect of magnitude is most noticeable in the range of natural period between about 0.7 and 1.5 sec.

The effect of epicentral distance on the acceleration response spectrum is illustrated in Fig. 5, in which are shown the ratios of weighing factors for different distance categories to that for $\Delta = 200 \sim 405$ km category. Generally speaking, the increase in response acceleration due to the decrease in epicentral distance is seen to be more pronounced for SDOF systems having natural periods shorter than about 0.8 sec.

Fig. 6 shows the effect of recording-site ground conditions on the response spectra in terms of the ratios of weighing factors for different ground condition categories to that for Type I ground. The effect is most noticeable in the period range of SDOF systems between 0.5 and 2.0 sec., in which the absolute acceleration response spectral amplitude increases as the soils become softer.

The uncertainty of the attenuation law was examined through the empirical distribution of the ratio between the observed and the predicted amplitude at each of the 18 natural periods. Denote this ratio by α:

$$\alpha = SA/\overline{SA} \qquad (2)$$

There are 277 α-values available at each natural period. Their distributions were found to be independent of the natural period T of the SDOF system, and the probability density function of α was found to be expressed by the log-normal model as shown in Fig. 7.

CONCLUSIONS

Based on these statistical analyses, the following conclusions were deduced.

(1) The absolute maximum horizontal acceleration, the duration of major motions, and the number of zero-crossings can be approximately evaluated as functions of the earthquake magnitude, the epicentral distance, and subsoil condition.

(2) The period of vibration (T_1) at the time of H_{max}, the ratio of vertical to horizontal accelerations (v), and the mean period of vibration (T_m) during the major motion are not clearly related with M and Δ. The following two points, however, can be seen.

  (a) The mean values of T_1 and T_d get longer as subsoils become softer. This tendency is obvious for soft alluvial grounds. The ratio of T_1 to T_m is 1.20 to 1.26, and the ratio is almost constant, irrespectively of subsoil conditions.

  (b) The mean value of v being 0.32 to 0.34 is not strongly affected by subsoil conditions. Since the standard deviation is 0.15 to 0.21, the vertical acceleration can be assumed to be the half of the horizontal acceleration for the designing purpose.

(3) An empirical formula was obtained for predicting the spectral amplitude of absolute response acceleration of a SDOF system ($h = 0.05$) for a given period and a given set of earthquake magnitude, epicentral distance and site condition as a simple product of three weighing factors.

(4) The effect of earthquake magnitude was found most noticeable in the period range longer than about 0.7 sec., in which the increase in spectral amplitude due to the increase in magnitude is more notable than in shorter-period range. The increase in spectral amplitude due to the decrease in epicentral distance is most pronouncedly found in the shorter-period range less than about 0.8 sec. The effect of site ground conditions is well demonstrated in the period range between 0.5 and 2.0 sec., in which the spectral amplitude generally increases as the soils become softer.

(5) By using the fact that the ratio of observed and predicted amplitude, $\alpha = SA/\overline{SA}$, was found to be lognormally distributed, basic information was supplied that can be used to obtain the acceleration response spectrum for a given probability of being exceeded.

(6) In applying the results obtained from this study to predict response spectra, it is necessary to make engineering judgement especially by noting the following:

1. The data used for analysis are far from sufficient in number nor uniform in distribution. There is a serious shortage of accelerograms of large earthquakes, especially recorded at short epicentral distances.

2. Magnitude and distance categories have relatively wide ranges and the classifications of ground conditions involve considerable ambiguity.

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Table 1 Classification of 301 Strong-Motion Records Analyzed

Magnitude M	Ground Condition	Epicentral Distance Δ (km)					Total	
		20>	20~59	60~119	120~199	200<		
5.0 ~ 5.9	Type I	2	3				5	67
	Type II	3	12	3			18	
	Type III	4	16	5	2	2	29	
	Type IV	2	5	7	1		15	
6.0 ~ 6.4	Type I		3	6	3	1	13	81
	Type II		7	8	2	1	18	
	Type III		12	13	8	1	34	
	Type IV		3	6	6	1	16	
6.5 ~ 6.9	Type I		1	2	1		4	62
	Type II		1	6	6		13	
	Type III	1	5	10	10	1	27	
	Type IV		1	4	9	4	18	
7.0 ~ 7.4	Type I			1		3	4	41
	Type II				2	12	14	
	Type III				2	14	16	
	Type IV			1	1	5	7	
7.5 ~ 7.9	Type I				1	2	3	50
	Type II				3	8	11	
	Type III			2	6	16	24	
	Type IV				1	11	12	
Total		12	69	74	64	82	301	

Note: Numbers of records for four ground conditions are 29 for Type I, 74 for Type II, 130 for Type III, and 68 for Type IV.

Table 2 Regression Equations for Hmax., Td and Nz

Characteristic Value	Ground Condition f	Emprical Equations	Multiple Correlation Coefficient r
Hmax (gals)	Type 1	$46.0 \times 10^{0.208M} \times (\Delta+10)^{-0.686}$	0.48
	Type 2	$24.5 \times 10^{0.333M} \times (\Delta+10)^{-0.924}$	0.59
	Type 3	$59.0 \times 10^{0.261M} \times (\Delta+10)^{-0.886}$	0.62
	Type 4	$12.8 \times 10^{0.432M} \times (\Delta+10)^{-1.125}$	0.68
	Whole	$34.1 \times 10^{0.308M} \times (\Delta+10)^{-0.925}$	0.61
Td (sec)	Type 1	$3.89 \times 10^{-4} \times 10^{0.466M} \times \Delta^{0.589}$	0.89
	Type 2	$1.37 \times 10^{-2} \times 10^{0.262M} \times \Delta^{0.485}$	0.71
	Type 3	$2.75 \times 10^{-2} \times 10^{0.291M} \times \Delta^{0.265}$	0.61
	Type 4	$2.28 \times 10^{-1} \times 10^{0.199M} \times \Delta^{0.233}$	0.52
	Whole	$2.08 \times 10^{-2} \times 10^{0.274M} \times \Delta^{0.394}$	0.65
Nz	Type 1	$1.43 \times 10^{-2} \times 10^{0.410M} \times \Delta^{0.444}$	0.75
	Type 2	$4.23 \times 10^{-1} \times 10^{0.0974M} \times \Delta^{0.681}$	0.66
	Type 3	$6.28 \times 10^{-1} \times 10^{0.272M} \times \Delta^{0.0313}$	0.54
	Type 4	$4.05 \times 10^{0.190M} \times \Delta^{-0.0646}$	0.29
	Whole	$4.68 \times 10^{-1} \times 10^{0.243M} \times \Delta^{0.195}$	0.54

Table 3 Average and Standard Deviations of T_1, v and T_m

		Ground Condition			
		Type I	Type II	Type III	Type IV
T_1 (sec.)	Average	0.36	0.43	0.49	0.75
	S. D.	0.52	0.39	0.30	0.42
v	Average	0.34	0.33	0.34	0.32
	S. D.	0.15	0.18	0.18	0.21
T_m (sec.)	Average	0.30	0.34	0.39	0.61
	S. D.	0.36	0.22	0.22	0.35
T_1/T_m		1.20	1.26	1.26	1.23

Table 4. Distribution of Data Set

MAGNITUDE M	GROUND CONDITION	EPICENTRAL DISTANCE Δ (km)					TOTAL	
		6 ~ 19	20 ~ 59	60~119	120~199	200~405		
4.5 ~ 5.3	TYPE I	6	4				10	60
	TYPE II	4	10				14	
	TYPE III	12	8	8	2		30	
	TYPE IV	6					6	
5.4 ~ 6.0	TYPE I		4	2			6	48
	TYPE II	4	4	4			12	
	TYPE III	2	12	6			20	
	TYPE IV	4	2	4			10	
6.1 ~ 6.7	TYPE I		4	6			10	102
	TYPE II		4	4	2		10	
	TYPE III	4	32	22	8	2	68	
	TYPE IV		6	4	2	2	14	
6.8 ~ 7.4	TYPE I			4	3	2	9	29
	TYPE II			2	4	2	8	
	TYPE III				4	4	8	
	TYPE IV					4	4	
7.5 ~ 7.9	TYPE I				2	2	4	38
	TYPE II				6	2	8	
	TYPE III		2	6	4	2	14	
	TYPE IV				2	10	12	
TOTAL		42	92	72	39	32	277	

Table 5. Items and Categories Used for Quantification Analysis

ITEM	CATEGORY	MEAN FOR THE DATA IN EACH CATEGORY
EARTHQUAKE MAGNITUDE (M)	M = 4.5 ∿ 5.3	4.96
	M = 5.4 ∿ 6.0	5.75
	M = 6.1 ∿ 6.7	6.30
	M = 6.8 ∿ 7.4	7.06
	M = 7.5 ∿ 7.9	7.65
EPICENTRAL DISTANCE (Δ: km)	Δ = 6 ∿ 19	11.7
	Δ = 20 ∿ 59	38.2
	Δ = 60 ∿ 119	82.9
	Δ = 120 ∿ 199	158.7
	Δ = 200 ∿ 405	271.3
GROUND CONDITION AT RECORDING SITE	TYPE I : TERTIARY OR OLDER ROCK (DEFINED AS BEDROCK), OR DILUVIUM WITH H* < 10 m.	
	TYPE II: DILUVIUM WITH H ≧ 10 m, OR ALLUVIUM WITH H < 10 m.	
	TYPE III: ALLUVIUM WITH H < 25 m INCLUDING SOFT LAYER** WITH THICKNESS LESS THAN 5 m.	
	TYPE IV: OTHER THAN THE ABOVE, USUALLY SOFT ALLUVIUM OR RECLAIMED LAND.	

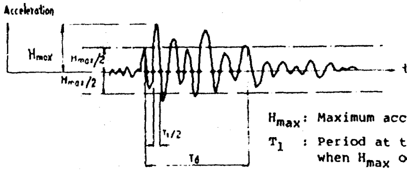
* DEPTH TO BEDROCK.

** SAND LAYER VULNERABLE TO LIQUEFACTION OR EXTREMELY SOFT COHESIVE SOIL LAYER.

Table 6. Weighting Factors Obtained from Quantification Analysis

T*	ρ**	$f_M(T, 0.05)$					$f_\Delta(T, 0.05)$					$f_{GC}(T, 0.05)$			
		MAGNITUDE (M)					EPICENTRAL DISTANCE (Δ: km)					GROUND CONDITION (GC)			
		4.5∿5.3	5.4∿6.0	6.1∿6.7	6.8∿7.4	7.5∿7.9	6 ∿19	20∿59	60∿119	120∿199	200∿405	TYPE I	TYPE II	TYPE III	TYPE IV
0.10	0.56	0.218	0.278	0.296	0.399	1.00	5.10	2.67	2.05	0.994	1.00	126	107	120	106
0.15	0.53	0.225	0.274	0.297	0.448	1.00	4.85	3.01	2.15	1.00	1.00	155	130	141	125
0.20	0.54	0.185	0.280	0.288	0.499	1.00	5.48	3.24	2.07	1.05	1.00	169	149	161	129
0.25	0.55	0.171	0.254	0.283	0.534	1.00	6.86	3.65	2.33	1.21	1.00	135	129	143	129
0.30	0.56	0.164	0.269	0.280	0.548	1.00	6.59	3.51	2.25	1.27	1.00	109	130	147	131
0.35	0.55	0.161	0.274	0.302	0.588	1.00	5.74	3.05	2.13	1.24	1.00	92.8	126	149	142
0.40	0.57	0.152	0.268	0.311	0.557	1.00	5.45	3.01	1.92	1.33	1.00	83.0	122	145	144
0.50	0.63	0.108	0.237	0.309	0.593	1.00	6.35	2.91	1.60	1.36	1.00	76.6	113	140	156
0.60	0.67	0.0889	0.246	0.321	0.618	1.00	5.88	2.79	1.46	1.32	1.00	62.1	101	134	159
0.70	0.70	0.0730	0.222	0.315	0.644	1.00	6.77	2.96	1.56	1.37	1.00	50.0	88.8	118	148
0.80	0.68	0.0683	0.214	0.294	0.595	1.00	5.89	2.73	1.54	1.28	1.00	47.9	91.0	115	145
0.90	0.67	0.0672	0.214	0.285	0.581	1.00	5.13	2.38	1.48	1.20	1.00	46.4	90.5	113	136
1.00	0.67	0.0653	0.204	0.284	0.636	1.00	4.62	2.15	1.40	1.16	1.00	43.3	89.3	107	125
1.50	0.72	0.0503	0.138	0.204	0.534	1.00	4.40	2.20	1.44	1.00	1.00	33.0	56.5	68.5	84.6
2.00	0.71	0.0605	0.148	0.215	0.585	1.00	3.66	1.99	1.29	0.924	1.00	24.7	36.8	44.1	46.2
2.50	0.70	0.0587	0.136	0.183	0.405	1.00	3.50	1.95	1.34	0.947	1.00	21.9	32.7	35.8	33.0
3.00	0.69	0.0660	0.138	0.194	0.391	1.00	3.26	1.79	1.35	0.867	1.00	18.8	26.6	28.5	26.6
4.00	0.68	0.0704	0.144	0.187	0.395	1.00	2.61	1.61	1.27	0.788	1.00	15.7	20.3	24.1	19.1

*T = PERIOD (SECONDS), **ρ = CORRELATION COEFFICIENT



H_{max}: Maximum acceleration

T_1 : Period at the time when H_{max} occurs

T_d : Duration of major motion (= Time interval between the initial time and the last time when A is equal to the half of H_{max})

N_z : Number of zero-crossing within the time of T_d (n=12 for the case shown)

T_m = $2T_d/N_z$

Fig. 1 Definitions of T_1, T_d, N_z, and T_m

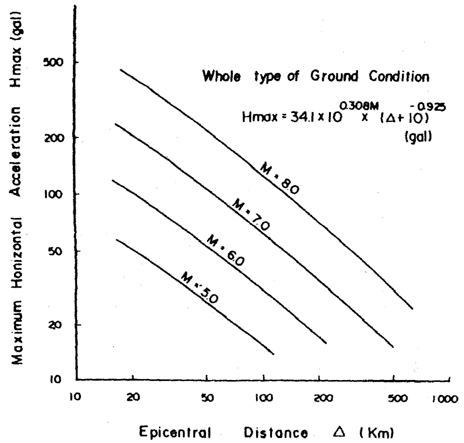


Fig. 2 Epicentral Distance versus Maximum Horizontal Acceleration

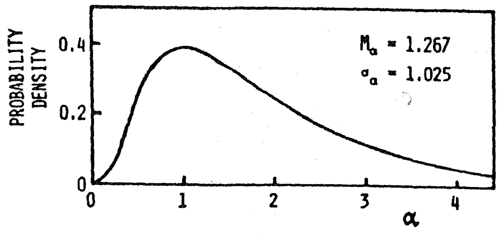


Fig.7. Probability Density of $\alpha = SA/\overline{SA}$.

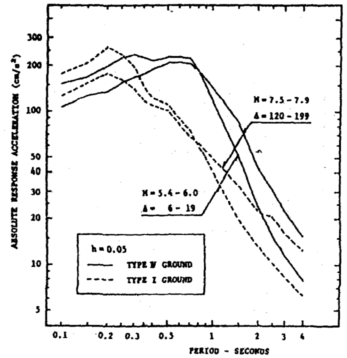


Fig.3. Examples of Predicted Acceleration Spectra

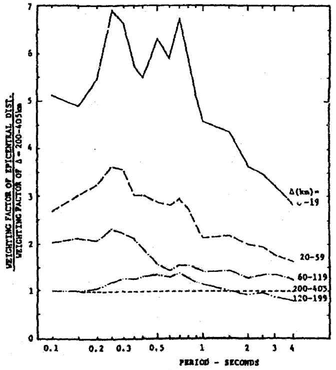


Fig.5. Effect of Epicentral Distance on Acceleration Spectra

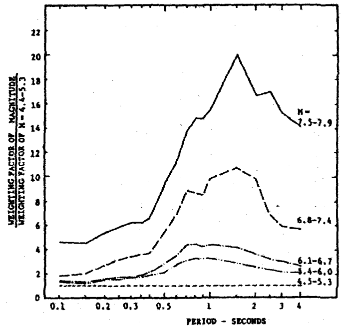


Fig.4. Effect of Magnitude on Acceleration Spectra

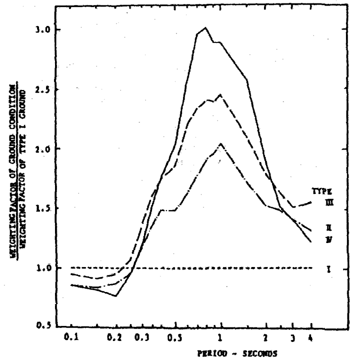


Fig.6. Effect of Ground Condition on Acceleration Spectra