

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

by

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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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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  $3 \times 301 = 903$ ) for 51 earthquakes.

Factors considered in this analysis are Richter Magnitude  $M$ , epicentral distance  $\Delta$ (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  $\Delta$ , 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  $\Delta$ . 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:

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

where

$\overline{SA}(T,h)$  = Predicted absolute acceleration response spectral amplitude for given  $T$  and  $h$ ,  
 $T$  = Natural period of a SDOF system (sec),  
 $h$  = 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  $T = 0.5$ s 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:

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

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  $\alpha$ :

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

There are 277  $\alpha$ -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  $\alpha$  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  $\Delta$ . 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.







