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DURATION OF STRONG MOTION ACCELERATION RECORDS

By Kazuhiko KAWASHIMA, Koh AIZAWA** and Kazuyuki TAKAHASHI***

Multiple regression analyses of duration of earthquake ground acceleration are presented. Duration is defind as the time interval between the time when accleration amplitude firstly exceeds α times $(0<\alpha<1)$ of peak ground acceleration and the time when acceleration amplitude becomes less than α times of peak ground acceleration in the last. Employed were 394 components of horizontal strong motion acceleration records obtained at 67 free field sites in Japan. Empirical formulae of the durations in terms of earthquake magnitude and epicentral distance are propose for three subsoil conditions.

1. INTRODUCTION

For determining appropirate seismic effects to be considered in design of structures, it is essential to assess characteristics of earthquake ground motions. One of the characteristics of earthquake ground motion of considerable interest in design is the duration of ground accelerations. This is particularly true for assessing nonlinear response of structures and/or seismic stability of soils, for which duration of ground acceleration is one of the most controlling factors.

Because of its interests to engineers, many studies have been made for characteristics of duration of eathquake ground motions. Housner proposed duration of strong phase of shaking in terms of earthquake magnitude (1). Bolt defined a branketed duration for acceleration greater than 0.05 G and 0.1 G (2). Trifunac et al. and Dobry et al. defined the duration as the time required to reach from 5 percent to 95 percent on the Husid plot (3, 4). Vanmarche et al proposed duration S_0 in terms of Arias Intensity I_0 and mean square acceleration σ_0^2 as $S_0=I_0/\sigma_0^2$, which implies that total ground motion intensity is distributed uniformly at constant average power σ_0^2 over the duration (5). Although the branketed duration is the most attractive from practical design point of view, analysis on the duration associated with high acceleration, whith is of particular importance for practice, cannot be achieved at this moment because of shortage of number of strong motion records with high accelertion.

In this paper, new definitions of duration of ground acceleration are proposed. Durations is defined as the time interval between the time when acceleration amplitude firstly exceeds α times $(0<\alpha<1)$ of peak ground acceleration and the time when acceleration amplitude becomes less than α times of peak guound

* Member of JSCE, Dr. Engr., Head of Earthquake Engineering Division, Earthquake Disaster Prevention Department, Public Works Research Institute, Ministry of Construction (Tsukuba Science City, Ibaraki-ken, Japan)
** Member of JSCE, Assistant Research Engineer, Ground Vibration Division, ditto.

acceleration in the last. Because the duration is defined for the specific value of α, analysis can be made with regardless of peak acceleration. It should be noted here that once empirical formulae representing the duration defined herein are developed, the blanketed duraion can be estimated by combining empirical formulae for the duration and those for peak ground acceleration.

2. STRONG MOTION DATA ANALYZED

A total of 197 sete of two orthogonal horizontal components of strong motion acceleration records were used in the analysis. They were recorded between march 1963 and June 1980 at 67 free field sites in Japan (6, 7), and any records on structures including the first floor and basement were excluded. Only earthquakes with magnitude greater than or equal to 5.0 and with focal depth less than 60 km were considered. Fig. 1 shows the classification of the records in terms of earthquake magnitude and epicentral distance. It is apparent from Fig. 1 that near field data caused by large magnitude earthquakes are quite few. Only nine earthquakes with magnitude of 7.0 or greater, which include the Niigata Earthquake of 1964 (M=7.5), the Tokachi-oki Earthquake of 1978 (M=7.4), were analyzed. It is also observed from Fig. 1 that approximately three quarters of the total records were derived from earthquakes with magnitude less than 7.0. Fig. 2 shows the distribution of peak ground acceleration for three ground conditions.

The ground conditions at recording site were classified into three groups. This classification essentially depends on the Japanese practice adopted in the Earthquake Resistant Design Specifications of Highway Bridges (ERDSHB) with a slight modification. The original classification of ERDSHB has four categories for soil condition (8), whereas three soil conditions were considered in this analysis by putting group 2 and 3 of ERDSHB classifications into the same group (9).

All the data analyzed were provided by SMAC accelerographs. Because sensitivity at high frequency is substantially low in SMAC accelerographs, instrumental correction was performed considering accuracy of digitization of strong motion records (10).

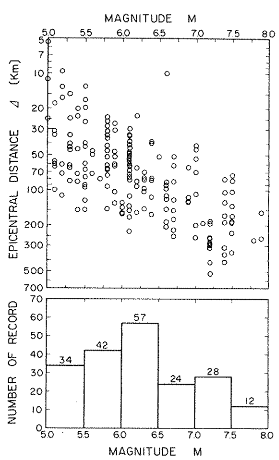


Fig. 1 Classification of Data in terms of Earthquake Magnitude and Epicentral Distance.

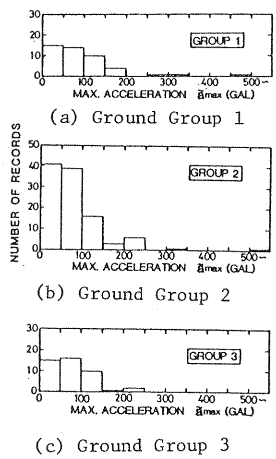


Fig. 2 Distribution of Peak Ground Acceleration.

3. DEFINITION OF DURATION OF GROUND ACCELERATION

Time history of ground acceleration may be characterized by Fig. 3, i.e., acceleration time history starts to vibrate, tend to increase gradually to have a peak value of a_{max}[gal] at time t_{max}[s], and then gradually decrease to final decease. Acceleration amplitude does, of course, not necessarily increase or decrease monotonously with respect to time. Duration of ground acceleration of significant importance in design is the time interal during which acceleration exceeds a certain value specified for design purpose. Therfore taking the peak acceleration a_{max} as a reference value, durations of ground acceleration were defind as

$$T_{\alpha 1}=t_{max}-t_{\alpha 1} \quad \cdots (1)$$

$$T_{\alpha 2}=t_{\alpha 2}-t_{max} \quad \cdots (2)$$

in which $t_{\alpha 1}$ and $t_{\alpha 2}$ represent the time [s] when acceleration amplitued firstly exceeds α times of a_{max} $(0<\alpha<1)$ and the time [s] when acceleration amplitude lastly becomes less than α times of a_{max}, respectively (refer to **Fig. 3**). It should be noted that, for some records, alternative increase and decrease of envelope of acceleration amplitude from αa_{max} are developed between $t_{\alpha 1}$ and $t_{\alpha 2}$. Then total duration T_α [s] is defined as

$$T_\alpha=T_{\alpha 1}+T_{\alpha 2}=t_{\alpha 2}-t_{\alpha 1} \quad \cdots (3)$$

Ten different values were assigned for α in Eqs. (1), (2) and (3), i.e., 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9. It should be noted here that acceleration records analyzed in this study do not cover the whole ground acceleration from start to end because they were recorded by SMAC accelerographs in which delay memory is not provided with. In addition, records at beginning and last parts with acceleration less than about 20 gals are generally neglected for digitization because such parts are not generally important for input ground motion for structures. Therefore durations $T_{\alpha 1}$, $T_{\alpha 2}$ and T_α associated with α smaller than approximately 0.2 are most likely to be accounted shorter than the actual duration, especially for records with small acceleration in amplitude.

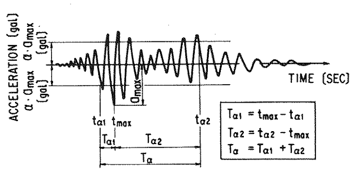


Fig. 3 Definition of Durations $T_{\alpha 1}$, $T_{\alpha 2}$ and T_α.

4. CHARACTERISTICS OF DURATION OF GROUND ACCELERATION

Duration of ground acceleration as defined by Eqs. (1), (2) and (3) were calculated for 394 components of horizontal strong motion acceleration records. **Fig. 4** shows how the durations $T_{\alpha 1}$, $T_{\alpha 2}$ and T_α vary in terms of earthquake magnitude and epicentral distance for $\alpha=0.3$, 0.5 and 0.7 (Ground Group 2). In this figure also presented are the predicted durations by means of multiple regression analysis, which will be described later. **Fig. 4** shows that although there is a general trend that the duration $T_{\alpha 1}$, $T_{\alpha 2}$ and T_α increase with increasing epicentral distance and earthquake magnitude, the durations for the specific combination of earthquake magnitude and epicentral distance have a considerable scatter. Such a scatter is especially significant for duration with α larger than about 0.7. For example, in ease of $\alpha=0.7$, duration $T_{\alpha 2}$ corresponding to epicentral distance of 100 km and earthquake magnitude greater than or equal to 7.0 vary from 0.01 s. to 7 s. (refer to **Fig. 4**(3)), implying that there is a difference between the minimum and the maximum duration of $T_{\alpha 2}$ by a factor of 700. Such a significant scatter of durations corresponding to α larger than about 0.7 depends on the difference of wave shape at high acceleration range, which may be very sensitive on various factors.

Although the observed durations have considerable scatters, multiple regression avalyses were made to study the general characteristics of the durations. To analyze such characteristics, durations were assumed to be represented in terms of earthquake magnitude M and epicentral distance Δ[km] for three subsoil conditions $GC_i(i=1,$ 2 and 3) as

$$\left.\begin{matrix} T_{\alpha 1} \\ T_{\alpha 2} \\ T_\alpha \end{matrix}\right\} = \tilde{a}(GC_i)\times 10^{\tilde{b}(GC_i)M}\times(\Delta+30)^{\tilde{c}(GC_i)} \quad \cdots (4)$$

in which coefficients $\tilde{a}(GC_i)$, $\tilde{b}(GC_i)$ and $\tilde{c}(GC_i)$ are the constants to be determined by multiple regression analysis for each subsoil condition. Eq. (4) is often adopted for attenuation of peak ground

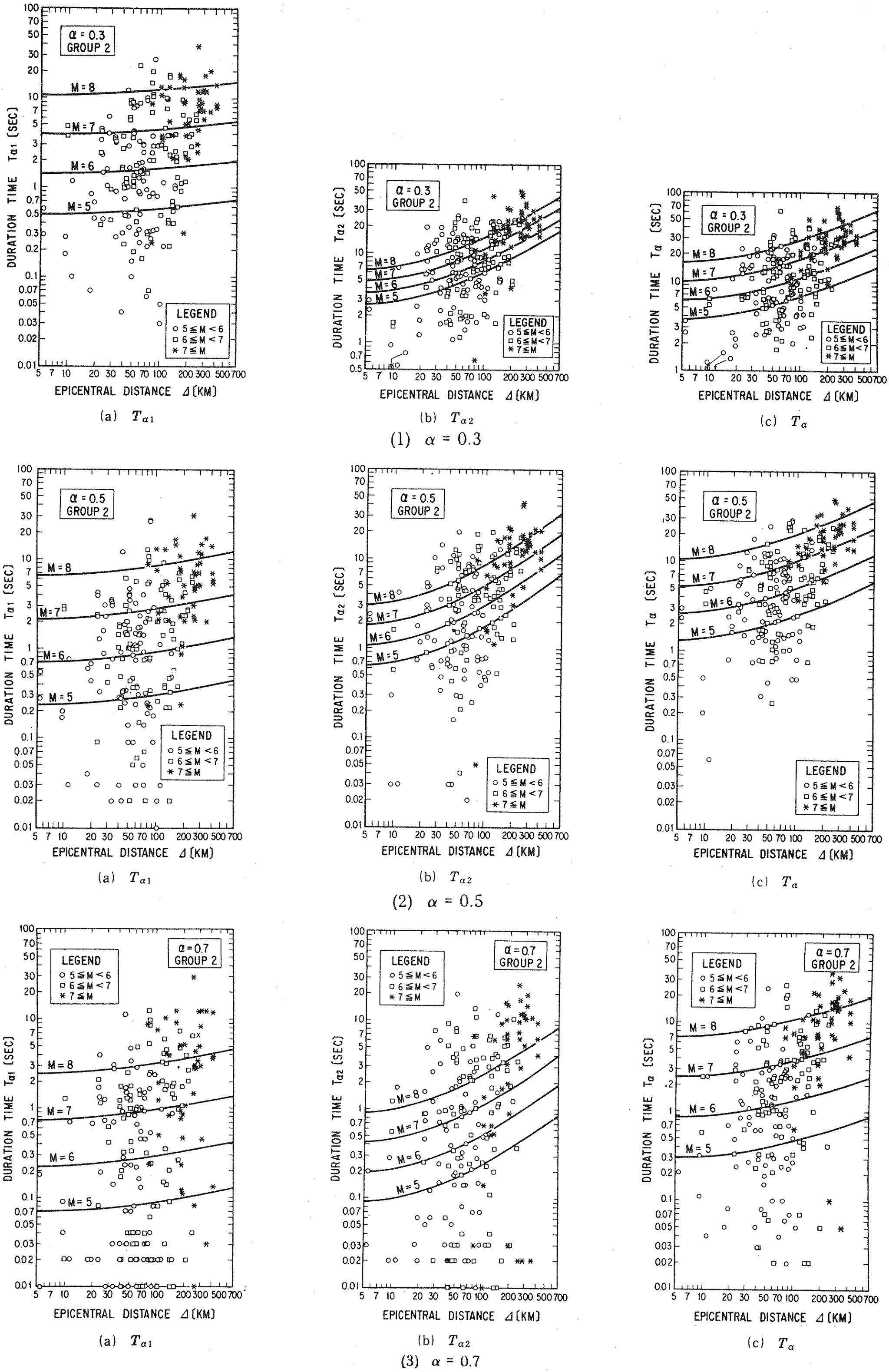


Fig. 4 Variation of Durations $T_{\alpha 1}$, $T_{\alpha 2}$ and T_{α} with respect to Earthquake Magnitude and Epicentral Distance (Ground Group 2).

accelerations. Because the durations defined by Eqs. (1), (2) and (3) are closely associated with acceleration amplitude, Eq. (4) was considered suitable to represent variation of duration in terms of earthquake magnitude and epicentral distance. It should be noted here that although it is often claimed that the epicentral distance is not necessarily a suitable parameter to represent the distance from source of energy released by earthquake, this was used here because the epicentral distance is the only parameter which can be definitely determined for all earthquakes analyzed in this study.

Multiple regression analysis was performed with use of 394 components of horizontal acceleration records, and the coefficients $\tilde{a}$, $\tilde{b}$ and $\tilde{c}$ as well as the correlation coefficient R were determined as shown in Table 1. Figs. 5, 6 and 7 show the variations of these coefficients with respect to α for $T_{\alpha 1}$, $T_{\alpha 2}$ and T_{α}, respectively. The results show that the correlation coefficient R takes a value of 0.5 to 0.8 for the durations associated with α less than about 0.7. However, as is anticipated from significant scatter of the observed durations the correlation coefficient R for the durations associated with α larger than about 0.7 is significantly small. Therefore although the durations for α greater than 0.7 are presented, their accuracy should be considered poor.

It is seen from Figs. 5, 6 and 7 that the general trend of variation of coefficients $\tilde{a}$, $\tilde{b}$ and $\tilde{c}$ in terms of α is almost the same between $T_{\alpha 1}$, $T_{\alpha 2}$ and T_{α}. The coefficient $\tilde{a}$ decreases with increasing α with the exception for α greater than about 0.7. Such characteristics are independent of subsoil conditions. The coefficient $\tilde{b}$ slightly increases with increasing α in a range of α less than about 0.7. Difference of the coefficient $\tilde{b}$ in accordance with subsoil condition is significant for α larger than about 0.7. It is noteworthy that the coefficient $\tilde{b}$, which represents the effect of earthquake magnitude on durations, takes positive values with a few exception. This implies that an increase of earthquake magnitude develops an

Table 1 Coefficient $\tilde{a}$, $\tilde{b}$ and $\tilde{c}$, and Correlation Coefficient R.

(a) Coefficients for $T_{\alpha 1}$

a	Ground Group 1				Ground Group 2				Ground Group 3			
	ã	b̃	c̃	R	ã	b̃	c̃	R	ã	b̃	c̃	R
0.9	0.00215	0.188	0.0445	0.183	3.50×10^{-4}	0.325	0.0991	0.267	7.05×10^{-5}	0.225	0.825	0.322
0.8	2.15×10^{-4}	0.233	0.619	0.279	1.07×10^{-4}	0.418	0.305	0.368	2.45×10^{-4}	0.213	0.802	0.301
0.7	1.81×10^{-5}	0.264	1.254	0.444	8.32×10^{-5}	0.519	0.203	0.442	5.06×10^{-4}	0.395	0.236	0.316
0.6	6.88×10^{-6}	0.397	1.202	0.588	2.71×10^{-4}	0.447	0.321	0.466	0.00108	0.417	0.179	0.399
0.5	2.10×10^{-5}	0.360	1.167	0.622	4.41×10^{-4}	0.479	0.214	0.537	0.00214	0.480	−0.0666	0.467
0.4	5.21×10^{-5}	0.378	1.013	0.695	0.00131	0.432	0.196	0.544	0.00448	0.418	0.0170	0.471
0.3	1.19×10^{-4}	0.338	1.009	0.679	0.00205	0.443	0.114	0.548	0.00513	0.418	0.0262	0.493
0.2	2.74×10^{-4}	0.365	0.819	0.699	0.00419	0.407	0.142	0.531	0.0193	0.264	0.309	0.446
0.1	0.00312	0.313	0.548	0.653	0.0104	0.378	0.119	0.506	0.113	0.177	0.300	0.431

(b) Coefficients for $T_{\alpha 2}$

a	Ground Group 1				Groud Group 2				Ground Group 3			
	ã	b̃	c̃	R	ã	b̃	c̃	R	ã	b̃	c̃	R
0.9	2.76×10^{-4}	−0.255	1.928	0.413	0.00198	0.169	0.167	0.168	0.00199	−0.293	1.667	0.254
0.8	8.34×10^{-4}	−0.240	1.779	0.358	7.46×10^{-5}	0.294	0.777	0.368	6.96×10^{-5}	0.326	0.801	0.363
0.7	6.81×10^{-5}	0.0283	1.758	0.440	1.39×10^{-4}	0.334	0.741	0.413	0.00129	0.258	0.604	0.317
0.6	3.74×10^{-4}	−0.055	1.846	0.534	0.00123	0.184	0.936	0.440	0.00293	0.183	0.832	0.364
0.5	3.92×10^{-4}	0.194	1.229	0.560	0.00284	0.227	0.785	0.538	0.0190	0.102	0.841	0.395
0.5	0.00282	0.169	1.038	0.670	0.00118	0.191	0.694	0.522	0.0793	0.108	0.642	0.457
0.3	0.00553	0.176	0.947	0.657	0.0609	0.131	0.635	0.566	0.511	0.129	0.277	0.465
0.2	0.0707	0.138	0.606	0.612	0.3213	0.142	0.341	0.531	1.488	0.132	0.111	0.433
01	0.570	0.119	0.290	0.507	2.355	0.138	0.0201	0.454	2.328	0.179	−0.0881	0.385

(c) Coefficients for T_{α}

a	Ground Group 1				Ground Group 2				Ground Group 3			
	ã	b̃	c̃	R	ã	b̃	c̃	R	ã	b̃	c̃	R
0.9	0.00224	−0.0106	0.800	0.206	3.57×10^{-4}	0.317	0.337	0.309	8.34×10^{-5}	0.155	1.210	0.359
0.8	3.80×10^{-5}	0.167	1.502	0.481	4.44×10^{-4}	0.374	0.430	0.414	1.00×10^{-4}	0.440	0.619	0.454
0.7	5.00×10^{-5}	0.207	1.546	0.731	4.54×10^{-4}	0.453	0.353	0.518	0.00307	0.288	0.539	0.432
0.6	2.15×10^{-4}	0.229	1.293	0.714	0.00226	0.304	0.624	0.605	0.00244	0.270	0.779	0.587
0.5	4.43×10^{-4}	0.292	1.041	0.732	0.00691	0.301	0.498	0.641	0.0149	0.207	0.691	0.607
0.4	0.00234	0.251	0.919	0.772	0.0223	0.256	0.471	0.642	0.0617	0.172	0.583	0.614
0.3	0.00468	0.241	0.863	0.746	0.0642	0.212	0.453	0.631	0.254	0.157	0.406	0.651
0.2	0.0421	0.204	0.586	0.710	0.259	0.184	0.325	0.598	0.764	0.126	0.338	0,672
0.1	0.341	0.176	0.298	0.657	1.446	0.169	0.090	0.560	1.539	0.148	0.167	0.602

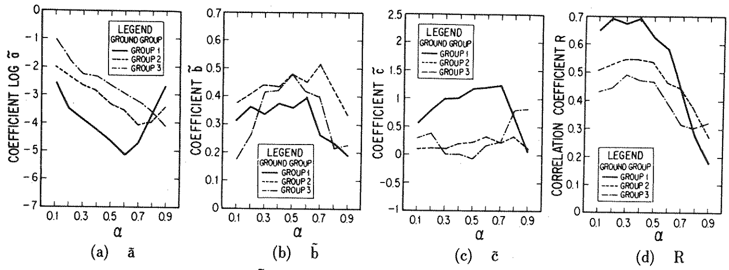


Fig. 5 Coefficients $\tilde{a}$, $\tilde{b}$ and $\tilde{c}$, and Correlation Coefficient R for $T_{\alpha 1}$.

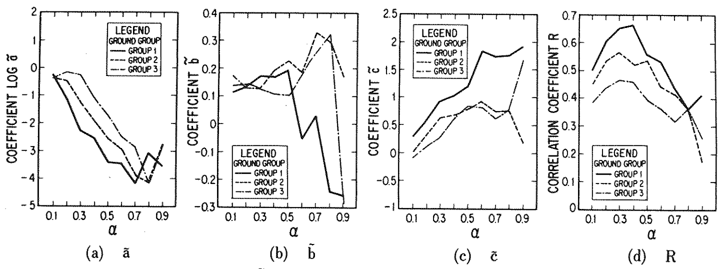


Fig. 6 Coefficients $\tilde{a}$, $\tilde{b}$ and $\tilde{c}$, and Correlation Coefficient R for $T_{\alpha 2}$.

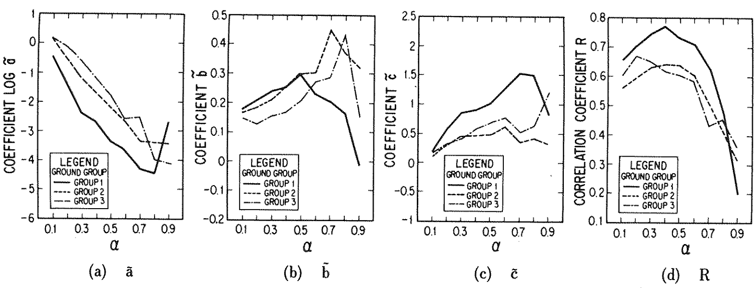


Fig. 7 Coefficients $\tilde{a}$, $\tilde{b}$ and $\tilde{c}$, and Correlation Coefficient R for T_{α}.

increase of the durations.

The coefficient $\tilde{c}$ increases with increasing α. This inclination is significant in the case for $T_{\alpha 2}$. It is also seen that the coefficient c, which represents increasing rate of duration with respect to epicentral distance, take positive values. It is therfore apparent that the longer the epicentral distance is, the longer the durations are.

Predicted durations for α=0.3, 0.5 and 0.7 are shown in Fig. 4 for earthquake magnitudes of 5, 6, 7 and 8. Only the results for ground group 2 are presented because the other results show the same characteristics.

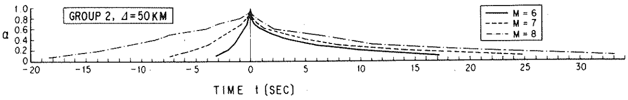
Figs. 8, 9 and 10 show the effects of earthquake magnitude, epicentral distance and subsoil condition, respectively, on the predicted duration $T_{\alpha 1}$, $T_{\alpha 2}$ and T_{α}. It should be noted in these results that t_{max} defined by Eqs. (1) and (2) is taken as an origin of the time axis so that general shape function of acceleration amplitude be realized. It should be also noted here that as was described in the preceding sections accuracy of durations associated with α less than about 0.2 and greater than about 0.7 is poor. Therefore they should be regarded as auxiliary results. It is understood from Figs. 8, 9 and 10 that the effects of earthquake magnitude is the most pronounced both on the durations and on the shape function of ground acceleration. Duration $T_{\alpha 1}$ has the reverse characteristics with $T_{\alpha 2}$, i.e., effect of earthquake magnitude is much more pronounced in $T_{\alpha 1}$ than in $T_{\alpha 2}$ while the reverse is true for epicentral distance. It is seen in Fig. 10 that duration $T_{\alpha 1}$ and $T_{\alpha 2}$ are significantly short in ground group 1. It should be noted that the effects of earthquake magnitude, epicentral distance and ground condition predicted by Eq. (4) appear to be consistent with the observed characteristics described in the preceding section.

5. DEVIATION AROUND PREDICTED DURATION

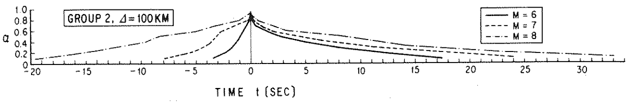
As can be seen from the correlation coefficients in Table 1, the correlations between predicted durations and observed values may be regarded as rather low especially for durations associated with large value of α. This implies that the observed duration exhibits considerable deviations from the predicted durations. The reason for such a large scatter is believed to be caused by insufficiency of the parameters assumed in Eq. (4), i. e., although three principal parameters are selected for factors that may influence the durations, there are many other factors such as properties of path condition, focal mechanism, deeper site conditions, etc. It is therefore necessary to consider the scatter of the predicted durations around the observed ones when Eq. (4) is to be used for practical purpose. For this purpose, the ratio of an observed duration and the predicted duration is defined as

$$U_{T\alpha 1}=\frac{T^{OB}_{\alpha 1}}{T^{P}_{\alpha 1}},\quad U_{T\alpha 2}=\frac{T^{OB}_{\alpha 2}}{T^{P}_{\alpha 2}},\quad U_{T\alpha}=\frac{T^{OB}_{\alpha}}{T^{P}_{\alpha}} \qquad \cdots\cdots (5)$$

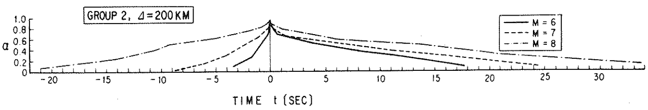
in which superscript OB and P denote the observed and predicted values, respectively. Fig. 11 shows the effect of earthquake magnitude and epicentral distance on the ratio $U_{T\alpha}$. Only the results of $U_{T\alpha}$ for α=0.5 and ground group 2 are presented here because the results for other conditions are of generally the same type. It seems that the ratios are almost independent of earthquake magnitude and epicentral distance. Fig. 12 shows histograms of log $U_{T\alpha}$ for α=0.5 and ground group 2. It is obvious that distribution of log $U_{T\alpha}$ be idealized by normal distribution. The standard deviations of log $U_{T\alpha 1}$, log $U_{T\alpha 2}$ and log $U_{T\alpha}$ are



(a) Δ = 50 KM

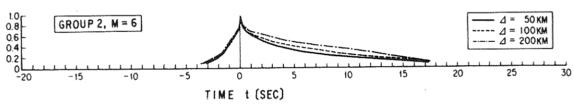


(b) Δ = 100 KM

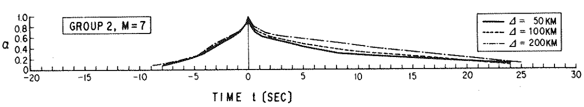


(c) Δ = 200 KM

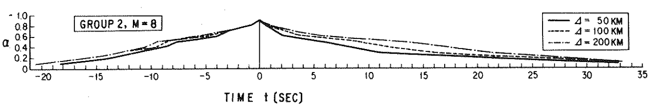
Fig. 8 Effect of Earthquake Magnitude on Duration (Ground Group 2).



(a) M = 6

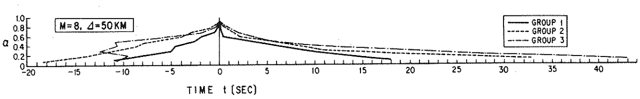


(b) M = 7

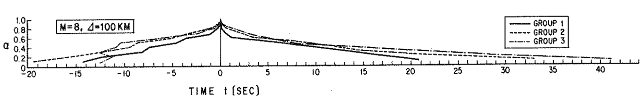


(c) M = 8

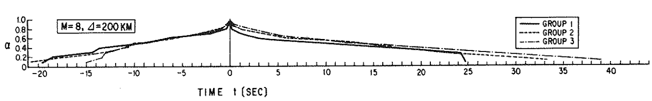
Fig. 9 Effect of Epicentral Distance on Duration (Ground Group 2).



(a) Δ = 50 KM



(b) Δ = 100 KM



(c) Δ = 200 KM

Fig. 10 Effects of Subsoil Condition on Duration (Earthquake Magnitude of 8).

Table 2 Standard Deviation of log $U_{T\alpha 1}$, log $U_{T\alpha 2}$ and log $U_{T\alpha}$.

Duration	Ground Group	Coefficient 0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
$T_{\alpha 1}$	1	0.378	0.423	0.468	0.476	0.604	0.703	0.879	0.973	0.833
	2	0.519	0.527	0.536	0.554	0.624	0.750	0.864	0.940	0.942
	3	0.367	0.464	0.476	0.503	0.551	0.690	0.896	0.979	0.962
$T_{\alpha 2}$	1	0.237	0.281	0.361	0.367	0.575	0.664	0.875	0.961	0.846
	2	0.209	0.283	0.348	0.479	0.531	0.707	0.890	0.970	0.946
	3	0.232	0.221	0.268	0.409	0.588	0.763	0.873	0.974	0.961
T_{α}	1	0.208	0.255	0.301	0.293	0.380	0.414	0.573	0.792	0.888
	2	0.212	0.273	0.310	0.343	0.390	0.468	0.669	0.800	0.935
	3	0.171	0.168	0.217	0.302	0.368	0.466	0.619	0.801	0.957

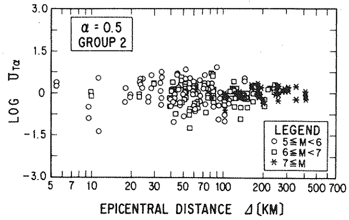


Fig. 11 Effect of Earthquake Magnitude and Epicentral Distance on Log $U_{T\alpha}$ (α=0.5, Ground Group 2).

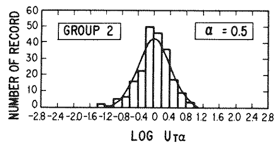


Fig. 12 Histogram of Log $U_{T\alpha}$ (α=0.5, Ground Group 2).

listed in Table 2.

6. CONCLUDING REMARKS

The preceding pages present the results of multiple regression analysis of duration of strong motion acceleration as defined by Eqs. (1), (2) and (3). Empirical formulae to predicte the duration $T_{\alpha 1}$, $T_{\alpha 2}$, T_{α} in terms of earthquake magnitude, epicentral distance and subsoil conditions are proposed by Eq. (4). Because the scatter around the predicted durations is considerable, especially for durations associated with α larger than about 0.7, consideration on deviations of the observed duration as defined by Eq. (5) is indispensable.

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