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A NEW DEFINITION OF STRONG MOTION DURATION AND COMPARISON WITH OTHER DEFINITIONS

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The work described in this paper deals with the assessment of the duration characteristics for horizontal and vertical components of strong ground motion records obtained in Japan, U. S., Mexico and Greece. The accelerograms used correspond to a range of earthquake magnitudes, between 5.1 and 8.1, to distances to the fault between 0.08 and 484 km and to local subsurface conditions ranging from rock to soft clay. A total of 326 horizontal and 116 vertical components were used in the study. The definition of the strong motion duration in this study is closely related to the part that contributes significantly to the seismic energy. The duration characteristics of the above-mentioned strong motion records, using the proposed definition have been estimated and compared with their corresponding values as given by Trifunac-Brady and McCann-Shah. Correlations have been established between strong motion duration obtained by various definitions and magnitude, distance to the fault and local subsurface conditions.

Keywords: duration, magnitude, distance, soil conditions, weighting scheme

1. INTRODUCTION

The strong motion duration is one of the main parameters that control the damaging effects of an earthquake. The other important parameters, such as level of shaking and frequency content, have been studied by many researchers up to now and a number of different parameters have been proposed for quantifying them.

The duration of strong shaking during an earthquake plays a key role in many seismic engineering problems. The full significance of the duration on the response of very lightly damped linear systems and of yielding or strength degrading non-linear systems is already known. Estimates of duration are of utmost importance in problems related to phenomena of low cycle fatigue, soil liquefaction and seismic settlement. The duration determines the number of cycles during vibration and together with the overall amplitudes of induced excitation, plays a major role in governing the results of any response to strong earthquake ground motion.

Moreover, the duration characteristics and generally their dependence on various parameters such as, magnitude, distance to the source and soil conditions are necessary in the case of generation of synthetic earthquake motions.

2. BACKGROUND

Several important studies for the estimation of the duration of strong earthquake ground motions have been made. The definitions of the strong motion duration that will be used in the present study are summarized below;

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Trifunac and Brady (1975) defined the beginning of the strong motion section of an accelerogram, as the time at which 5 % of the Arias intensity is reached and the end as the time that yields 95 % of the total Arias intensity. Arias intensity (Arias, 1969) is given by;

$$I=\frac{\pi}{2g}\int_0^{T_m} a^2(t)dt \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (1)$$

where $a(t)$ is the recorded ground acceleration and T_m is the total length of the record. Example of this definition is shown in Fig. 1.

Hisada and Ando (1976) assumed that the duration of ground motion is the total time from the beginning of the record to the time when the amplitude of the wave becomes equal to one-tenth of the peak acceleration. They proposed the following relationship;

$$\log_{10}D=0.31\,M-0.77 \cdots\cdots\cdots\cdots\cdots\cdots (2)$$

Vanmarcke and Lai (1977) defined the duration of an accelerogram based on the assumption that the Arias intensity is uniformly distributed at constant average power $(RMS_a)^2$ over the strong motion interval. The strong motion duration (D) may be derived by the following equations.

$$D=[2\ln(2D/T_0)]\cdot(I/PGA^2)$$
$$\text{when}\quad D\geqq 1.36\,T_0 \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$
$$D=2\,I/PGA^2$$

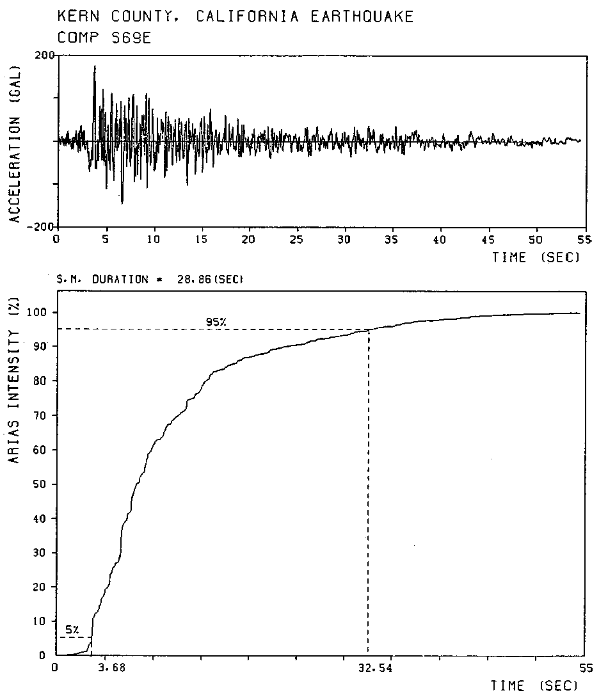

Fig. 1 Trifunac and Brady definition.

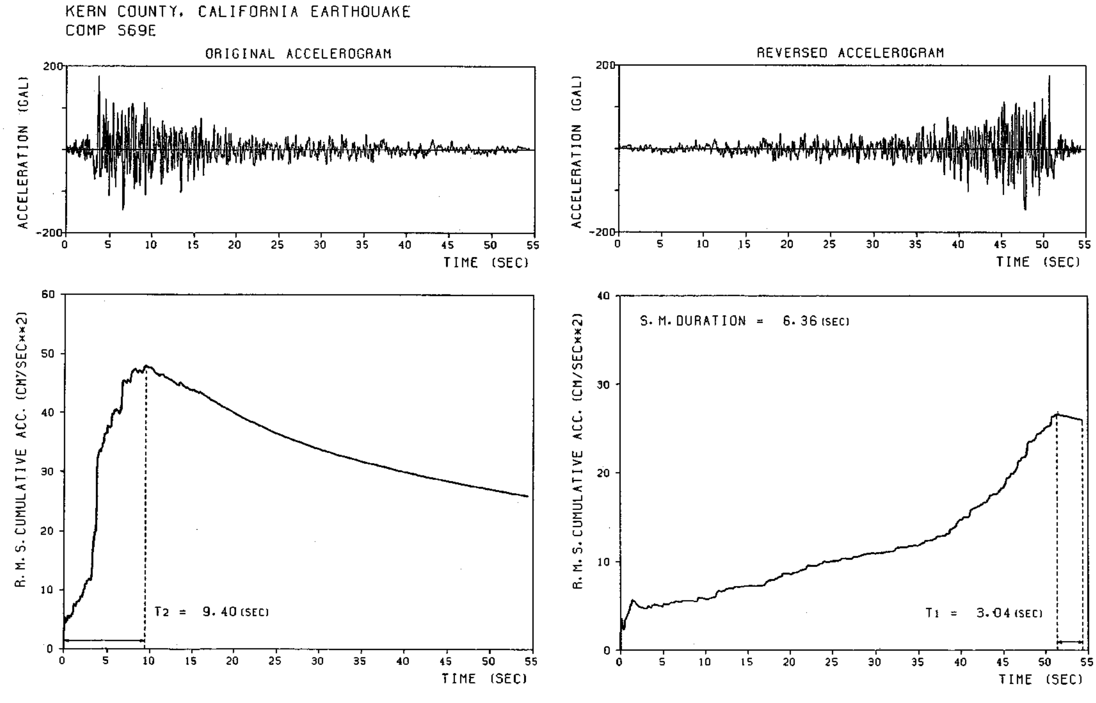

Fig. 2 McCann and Shah definition.

when $D < 1.36\, T_0$ ……………………………………………………………………………………… (4)
where T_0 is the predominant period, PGA is the peak ground acceleration, I is the total Arias intensity and RMS_a is the root mean square acceleration.

McCann and Shah (1980) defined the strong motion part of an accelerogram as that interval which exhibits a consistent root mean square acceleration (RMS_a) level. The beginning of the strong motion is obtained by forming the cumulative RMS_a function of the time reversed accelerogram and noting the time when the RMS_a begins a steady decline. The end of the strong ground motion is obtained in a similar manner using the original time history of the accelerogram. Example of this definition is shown in Fig. 2.

Kawashima et al. (1985) defined the duration of an accelerogram as the interval between the time when acceleration amplitude firstly exceeds (a) times ($0 < a < 1$) of PGA and the time when the acceleration becomes less than (a) times of PGA in the last.

3. DEFINITION OF STRONG MOTION DURATION

It is assumed that any acceleration record with total duration T_m, is composed of three parts. The first part represents the P-wave arrivals, is characterized by low amplitudes and has duration T_1. The second one is mainly associated with direct S-wave arrivals, has relatively high amplitudes, high frequencies and duration D, which is mainly controlled by the duration of rupture at the causative fault. The beginning of the second part is assumed to be the time at which the first S-wave arrival is observed. Of course, it cannot be neglected the continuation of P-wave arrivals at the second part of the motion. The last part is closely related to the surface wave presence or to the delayed indirect body wave arrivals, has low frequencies and amplitudes ranging from low to moderately high, depending on the local soil conditions, site topography and the distance from the center of energy release. The end of the direct S-wave arrivals, as well as, the beginning of the surface wave arrivals are difficult to be distinguished clearly. The most of the times is observed an overlap of the second and the third part, in other words the beginning of the third part occurs before the end of S-wave arrivals. In the case of vertical components of near field earthquake records, the high frequency first part also seems to have high amplitudes.

In order to correlate the strong motion duration with the distribution of wave energy over the time history the following function of time, was proposed.

$$E(t) = I(t+dt) - I(t) \quad \cdots\cdots (5)$$

where dt is the time increment and $I(t)$ is the Arias intensity function as defined by equation 1, with integration limits from 0 to t.

This function represents the energy added at each time increment of the earthquake motion. The weighted by $E(t)$ average value (μ) of t can be calculated as follows;

$$\mu = \sum_{\nu=1}^{N} \nu \cdot dt \cdot E(\nu \cdot dt) \Big/ \sum_{\nu=1}^{N} E(\nu \cdot dt) \quad \cdots\cdots (6)$$

The weighted by $E(t)$ standard deviation (σ) of t can be calculated as follows;

$$\sigma = \left[\sum_{\nu=1}^{N} (\nu \cdot dt - \mu) E(\nu \cdot dt) \Big/ \sum_{\nu=1}^{N} E(\nu \cdot dt) \right]^{1/2} \quad \cdots\cdots (7)$$

where N is the total number of data, $N = T_m/dt$, and T_m is the total duration of the record.

The end of the strong motion duration T_2 is obtained as;

$$T_2 = \mu + \sigma \quad \cdots\cdots (8)$$

After defining a threshold value, the beginning of the strong motion duration T_1 is determined as the time at which this threshold is first exceeded in the time history. The threshold used in this study is equal to the value of the function $E(t)$ at the end of the strong motion interval $[E(T_2)]$. For better visualization, the function $E(t)$ is normalized to its maximum value at all figures of this paper. Example of the proposed definition is shown in Fig. 3.

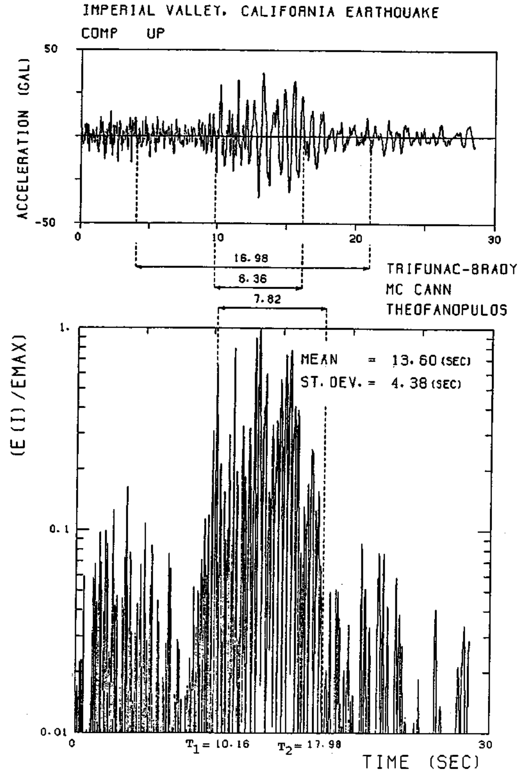

Fig. 3 The proposed definition.

4. METHOD OF ANALYSIS—RESULTS

To examine the strong motion duration of both horizontal and vertical components, digitized strong motion records from 43 earthquakes (Table 1) were used. The data base was composed of records obtained in Japan, U. S., Mexico and Greece. Although the mechanism of generation and travel path conditions of the earthquakes recorded at various countries were different, it was considered more relevant to take into account all these records because a spherical information about their duration characteristics could be obtained.

Only stations for which information on the subsoil conditions was available, have been used in the study. All accelerograms recorded on deep alluvium or otherwise "soft" sedimentary deposits, have been classified under 2. The stations located on "hard" basement rocks were labeled by 0, whereas the stations located on "intermediate" type rocks or in a complex environment which could not be identified as either 0 or 2 have all been grouped under 1.

The study was restricted to earthquake magnitudes of 5.1 or greater because these are of greatest engineering interest. The magnitude scale (M) used in this paper is similar to that used by Campbell (1981). It was defined as Japan Meteorological Agency magnitude (M_{JMA}) for recordings obtained in Japan or as surface wave magnitude (M_S) for recordings obtained in other parts of the world when both local magnitude (M_L) and M_{JMA} or M_S were greater or equal to 6.0, and it was defined as local magnitude when both local magnitude (M_L) and M_{JMA} or M_S were below this value. In some events where both M_{JMA} or M_S and M_L were not available, an appropriate value was estimated by the use of the empirical relationships among magnitude scales proposed by Utsu (1982).

Furthermore, the records used were restricted to recording stations for which an accurate estimate of the shortest distance between the station and the fault rupture was available or could be determined. The distance to the fault used in this study leads to more realistic estimates of the strong motion duration from the developed relationships, in the case of a future event, for which only the fault information will be available.

Following the above described algorithms, the strong motion duration D using Trifunac and Brady, McCann and Shah and authors' definition was calculated for each strong motion record.

Fig. 4 shows two soft soil records (horizontal components) of the same earthquake obtained at different fault distances together with their corresponding energy distribution plots. It can be observed that the total duration T_m of the records yields to greater values when the fault distance indreases. The beginning of the strong motion duration T_1 delays when the distance to the fault increases. The strong motion duration D also increases with the distance to the center of energy release. The strong motion duration part includes mainly S-wave arrivals. The fraction of the energy contained in the strong motion interval seems to increase with distance, probably due to the increased number of refractions, reflections and scatterings and also due to the increased importance of surface waves at greater distances.

Fig. 5 shows the same behavior in the case of vertical components. The Trifunac-Brady definition yields

Table 1 Earthquake Data.

Earthquake	Magnitude	Date	No. of components
Long Beach	6.2	3/10/33	3
Southern California	5.4	10/02/33	6
Lower California	6.5	12/30/34	3
Helena-Montana	5.5	10/31/35	3
1st Northwest California	5.5	9/11/38	3
Imperial Valley	7.1	5/18/40	3
2nd Northwest California	6.6	2/09/41	3
Western Washington	7.1	4/13/49	6
Northwest California	6.0	10/07/51	3
Kern Country	7.7	7/21/52	15
Northern California	5.5	9/22/52	3
Wheeler Ridge	5.9	1/12/54	3
Eureka	6.5	12/21/54	6
San Jose	5.8	9/04/55	3
El Alamo,Baja	6.8	2/09/56	6
Near South Coast of Honshu	5.7	2/14/56	1
Central Chiba Pref.	5.9	9/30/56	2
San Francisco	5.3	3/22/57	15
Hollister	5.6	4/08/61	3
Northern Miyagi Pref.	5.5	4/30/62	2
Off Headland of Echizen	6.5	3/27/63	8
Off Ibaragi Pref.	5.4	5/08/63	4
SW Ibaragi Pref.	5.2	12/24/63	8
Off Ibaragi Pref.	5.3	2/05/64	6
Niigata	7.5	6/16/64	1
Puget Sound,Washington	6.5	4/29/65	3
Parkfield,California	6.0	6/27/66	17
2nd Northern California	5.8	12/10/67	3
Borrego Mountain	6.7	4/08/68	9
Off Tokati	7.9	5/16/68	2
Middle Saitama Pref.	6.1	7/01/68	49
San Fernando	6.6	2/09/71	95
Off Miyagi Pref.	6.7	2/20/78	3
Off Miyagi Pref.	7.4	6/12/78	3
Salonika,Greece	6.5	6/20/78	2
Salonika,aftershock	5.1	7/05/78	2
Imperial Valley	6.9	10/15/79	66
Corinth,Greece	6.7	2/24/81	2
Corinth,aftershock	6.4	2/25/81	2
Mexico	8.1	9/15/85	38
Palm Springs	5.9	7/08/86	15
Kalamata,Greece	6.2	9/13/86	5
Kalamata,aftershock	5.4	9/15/86	7

to longer and McCann-Shah definition to shorter estimates of strong motion duration than these of the proposed definition. The high frequency first part of the records was included in the strong motion interval, because the wave energy at this part seems to be very high.

Fig. 6 shows three records (horizontal components) of the same earthquake obtained at three different stations located on hard, intermediate and soft soil, which have approximately the same fault distance, together with their corresponding energy distribution plots.

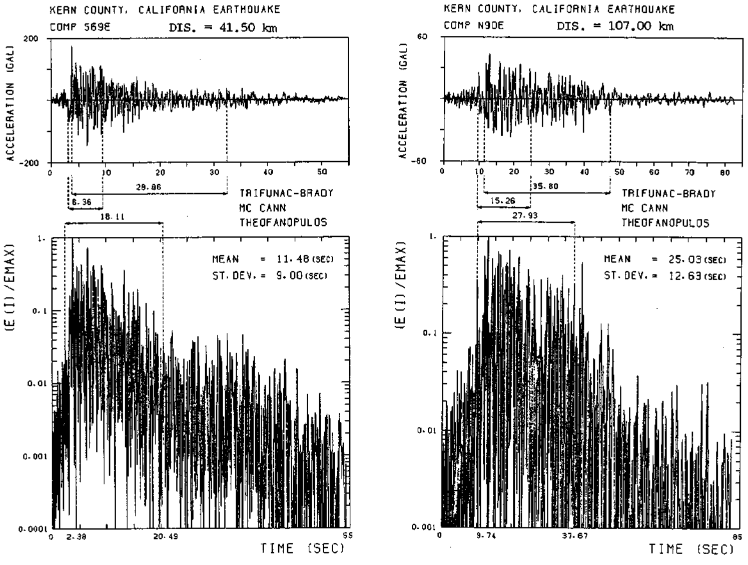

Fig. 4 Comparison of the SMD estimates for two different distances to the fault (Horizontal components).

The strong motion duration D increases significantly from the hard to the soft soil. At soft soil sites in addition to the part associated with direct S-wave arrivals a subsequent moderate part with longer periods and somewhat lower amplitudes is also present. This long-period part is clearly associated with the difference in dynamic characteristics between hard and soft soils (high-impedance ratio, Dobry et al., 1978). This additional part changes the energy distribution over the time history and consequently influences the strong motion estimates.

Fig. 7 shows horizontal and vertical components of two soft soil records due to different earthquakes obtained at distances greater than 100 km along with their corresponding energy distribution plots. It is clearly seen that the strong motion duration depends directly on the earthquake magnitude. As pointed out by many researchers (Thatcher and Hanks, 1973) when the earthquake becomes larger, the fault dimensions increase, whereas the dislocation velocity does not change significantly. Therefore, the duration of an earthquake is closely related to the duration of the fault rupture that generally increases with the earthquake magnitude.

Fig. 8 shows examples of the strong motion duration estimates using all three definitions for white noise like type, shock type and low predominant frequency type earthquake motions.

Fig. 9 (a) ~ (d) shows strong motion duration estimates, which were derived by the use of the proposed in this paper

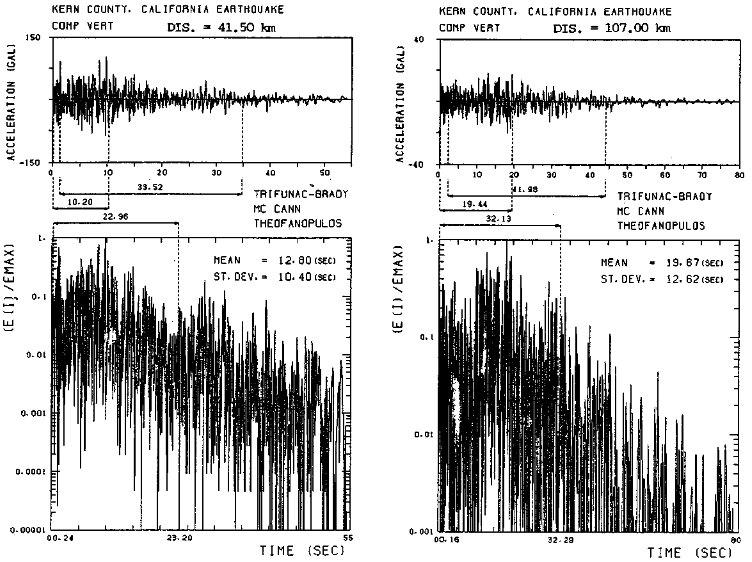

Fig. 5 Comparison of the SMD estimates for two different distances to the fault (Vertical components).

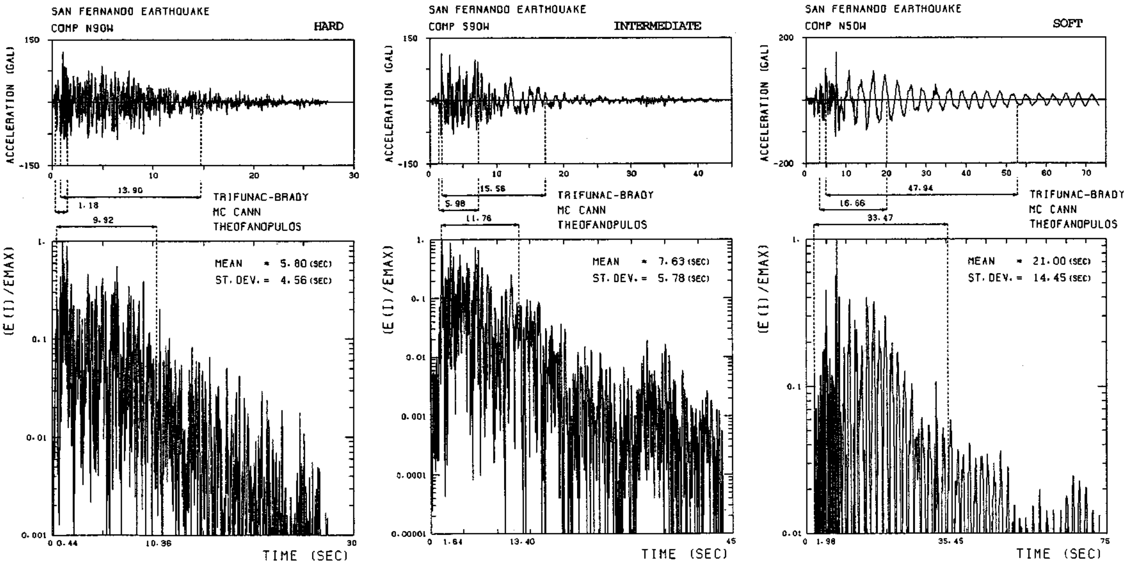

Fig. 6 Comparison of the SMD estimates for a hard, interme-diate and soft soil respectively (Horizontal components).

method, plotted versus magnitude and fault distance for horizontal and vertical components respectively. In the case of strong motion duration-magnitude plots the corresponding fault distance and in the case of strong motion duration-fault distance plots the corresponding magnitude are also indicated. From these plots it can be observed a considerable scatter of data, but the general trend with distance and magnitude is apparent. In order to reduce this scatter we will try to derive empirical correlations that reflect the average trends of data for different soil conditions, earthquake magnitudes and fault distances.

5. REGRESSION ANALYSIS

Non-linear weighted regression analyses (Theofanopoulos et al., 1987) of the above three sets of duration estimates were conducted. The mathematical models were selected on the basis of simplicity and fundamental physical arguments that lead to the basic functional dependence of the strong motion duration on independent variables such as, magnitude M, distance to the fault R and soil conditions S. The mathematical relationship used in this study is expressed by the following equation ;

$$D=a+b\exp(c.M)+d.R+e.S \quad \cdots\cdots (9)$$

where D is the strong motion duration, M is the magnitude, R is the fault distance, S the soil conditions and a, b, c, d, e are the regression coefficients.

As mentioned above the strong motion duration D is closely related to the total rupture time at the causative fault. The total rupture time d_R at the source can be expressed as ;

$$d_R=L/V \quad \cdots\cdots\cdots\cdots\cdots (10)$$

where L is the length of the fault and V is the rupture velocity ranging in the most of cases between 2.1 and 3.0 km/s. According to the empirical formulae obtained by Thatcher-Hanks (1973) and Irikura-Muramatsu (1981) the local magnitude (M_L) and the fault rupture length can be related as follows ;

$$L=0.0108\exp(1.151\,M_L) \quad \cdots\cdots\cdots\cdots\cdots\cdots (11)$$

Considering an averaged value of rupture velocity equal to 2.5

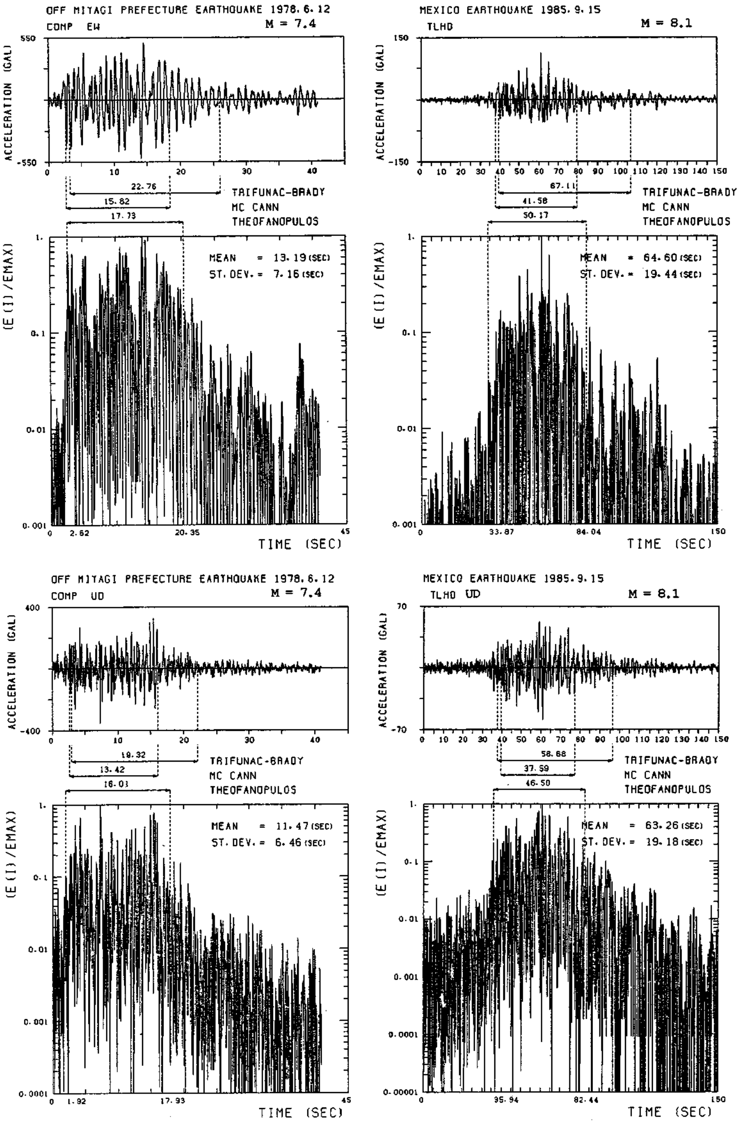

Fig. 7 Comparison of the SMD estimates for two different earthquake magnitudes for horizontal and vertical components respectively.

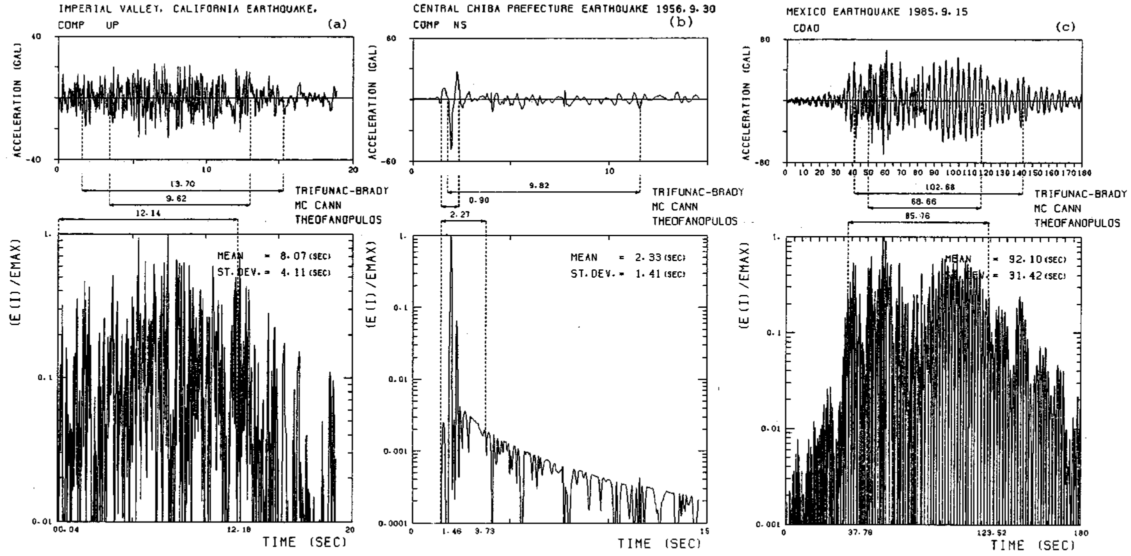

Fig. 8 Comparison of the SMD estimates for (a) white-noise like, (b) shock type, (c) low predominant frequency type.

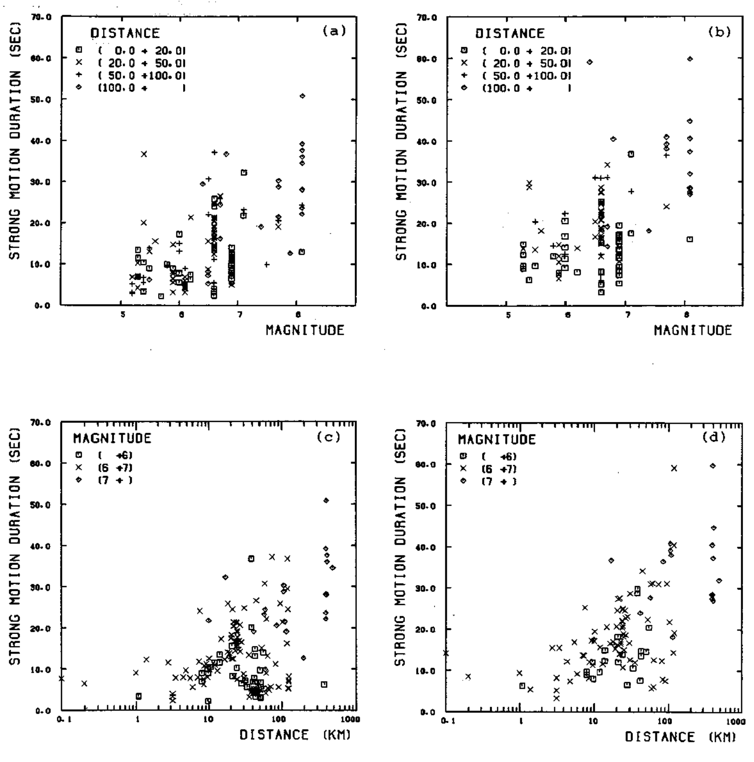

Fig. 9 SMD estimates by the proposed definition versus magnitude and distance for horizontal [(a), (c)] and vertical [(b), (d)] components respectively.

km/s and combining the equations 10 and 11 the total rupture time d_R can be expressed as;

$$d_R=0.00432\exp(1.151\,M_L) \quad \cdots\cdots\cdots\cdots (12)$$

For this reason the magnitude depended term in the mathematical equation (9), which will be used for the estimation of the strong motion duration, assumed to have exponential form.

Weights were assigned to each record in the multiple non-linear regression analysis in order to control the influence of the well-recorded events in the data base. As shown in Table 1, the 1968 Middle Saitama Prefecture, the 1971 San Fernando and the 1979 Imperial Valley earthquakes represent the 47.5 % of the records in the data set. If an unweighted analysis had been followed the contribution of the poorly recorded events would be small.

The weighting scheme used in this study is based on consideration of magnitude, distance and soil conditions. First the data set was divided into three subsets. Each subset contained earthquakes recorded at hard, intermediate and soft soil sites respectively. Then, in each subset the total distance range was

Table 2 Regression Analysis Results for the Strong Motion Duration.

D = a + b Exp(cM) + dR + eS

Strong Motion Duration (D)	Constants					Conditional Standard Deviation	Mean normalized weighted residual	Component
	a	b	c	d	e			
Trifunac-Brady	2.201	0.02489	0.860	0.05335	2.883	9.64	0.052	Hor.
	-124.500	120.70000	0.019	0.08641	4.352	11.80	-0.088	Vert.
Mc Cann-Shah	-2.707	0.02811	0.757	0.03290	1.224	4.30	-0.047	Hor.
	-3.678	0.28770	0.463	0.03413	1.480	4.79	-0.099	Vert.
Theofanopulos Watabe	-13.230	4.36900	0.253	0.03672	2.121	5.92	0.036	Hor.
	-13.080	9.97000	0.139	0.04212	3.601	6.16	-0.042	Vert.

M : Earthquake Magnitude
R : Distance to the Fault
S : Soil Condition, 0,1,2 for hard,intermediate and soft soil respectively

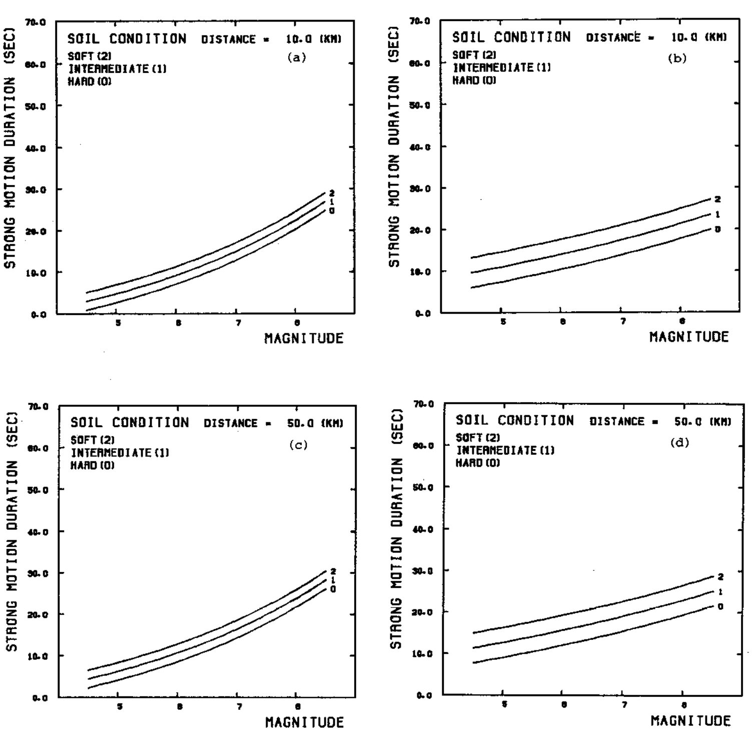

Fig. 10 Resulted relationships for the proposed definition at two different fault distances for horizontal [(a), (c)] and vertical [(b), (d)] components.

subdivided into smaller distance bins. The number of bins used in this study was 13 for both horizontal and vertical components. The average of the strong motion duration estimates for the two horizontal components of each recording was used in the regression analysis.

The weights were determined as follows;

$$W_j = 1/(n_{ij} \cdot f_i) \cdots\cdots\cdots (13)$$

where W_j is the assigned weight to the j th record within the bin i, n_{ij} is the number of records within the bin i with magnitudes that satisfy the following condition;

$$|M_j - M_k| \leqq 0.1 \cdots\cdots\cdots (14)$$

where M_j is the magnitude of the under consideration j th record and the check is made for values of k ranging from 1 to r, where r is the total number of the data within the bin i.

The variable f_i was determined as follows;

$$f_i = \sum_{m=1}^{r} \frac{l_m}{m} \cdots\cdots\cdots (15)$$

where l_m is the number of n_{ij} equal to m.

This procedure was followed for all distance bins of the three subsets. Then, the resulted weights were normalized to have sum equal to the total number of data in order to ensure that the statistics of the regression have the correct number of degrees of freedom.

Table 2 summarizes the results of regression analysis for each strong motion duration measure and the

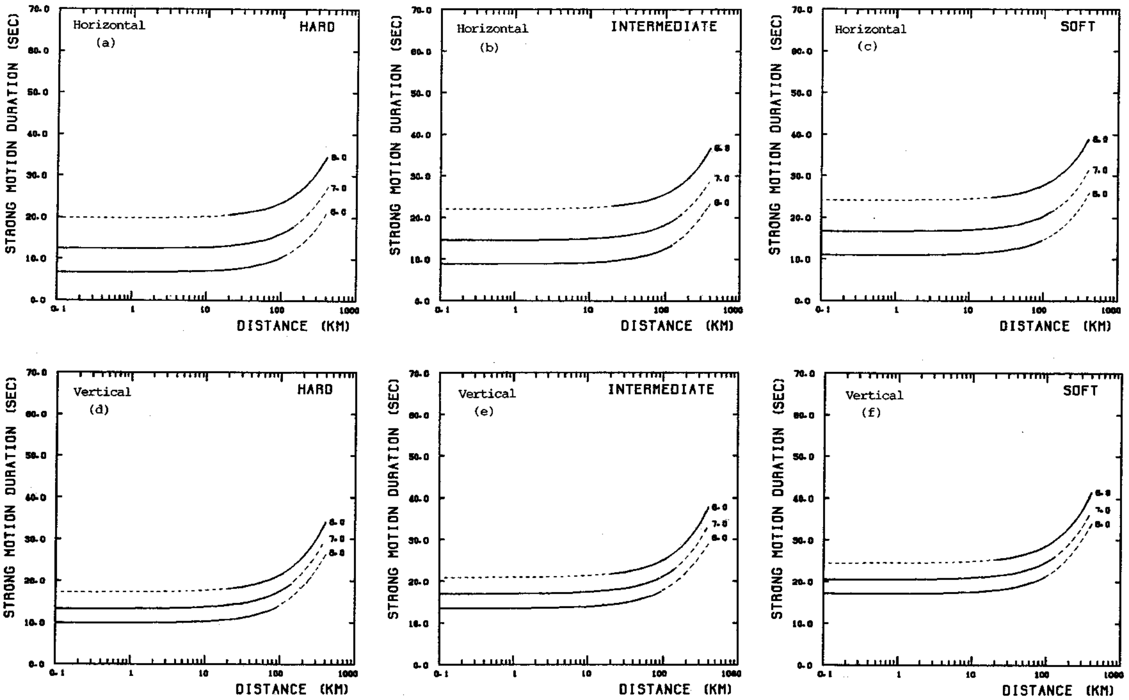

Fig. 11 Resulted relationships for the proposed definition at hard, intermediate and soft soil sites for horizontal [(a), (b), (c)] and vertical [(d), (e), (f)] components.

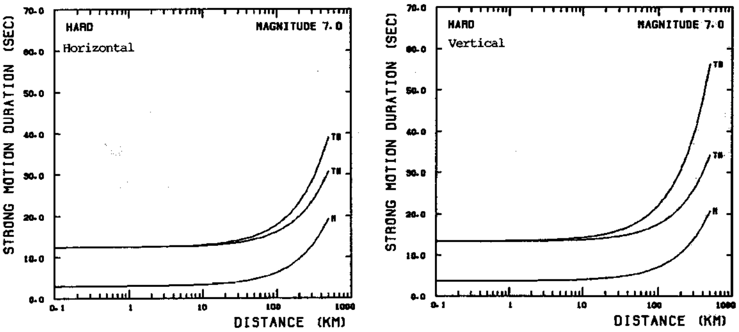

Fig. 12 Comparison of the resulted relationships for the three definitions when $M=7.0$ at a hard soil site.

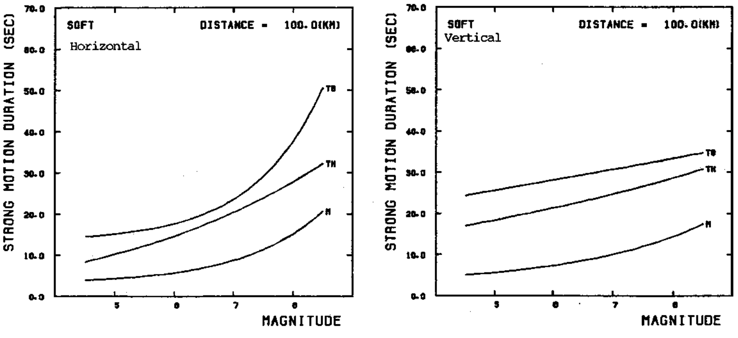

Fig. 13 Comparison of the resulted relationships for the three definitions at a soft soil site 100 km from the fault.

corresponding conditional standard deviations and the values of mean normalized weighted residuals.

The adequacy of the models was assessed from residuals analyses. The residuals were normalized to have a mean of zero and a standard deviation of unity. The residuals were weighted by the same weights used in the regression analysis. The normalized weighted residuals were plotted versus the predicted values of strong motion duration, the earthquake magnitudes and the fault distances. Furthermore, three subsets of residuals, selected on the basis of different soil conditions ("hard", "intermediate" and "soft" soils) were plotted versus the predicted values of the strong motion duration. There were no apparent trends in any residual plots and the variance was constant at all cases.

Plots of relationships using the proposed definition are shown in Fig. 10 and 11. In Fig. 10 it can be observed a shifting of the regression curves to the greater values when the fault distance changes from 10 to 50 km, for both horizontal and vertical components. The strong motion duration increases with magnitude at all cases and the duration of vertical components is generally longer than that of horizontal ones. In Fig. 11 is shown the influence of different soil conditions on the strong motion duration-fault distance curves, for horizontal and vertical components. The dashed lines indicate extrapolations of the relationships in the range of magnitudes and distances for which little or no data were used in the regression analysis. It must be also mentioned that the strong motion duration of a record from a magnitude 6 or less earthquake at distances greater than approximately 100 km is meaningless.

Comparisons among the three definitions are shown in Fig. 12 and 13. The comparison of the results for hard soil sites and earthquake magnitude equal to 7, leads to the conclusion that the proposed definition generally yields to strong motion duration estimates longer than McCann-Shah and shorter than Trifunac-Brady ones. It is also observed that using McCann and Shah definition, the beginning of the strong motion can be defined accurately, whereas using Trifunac and Brady definition sometimes the strong motion duration is overestimated, incorporating a very weak part of the motion that has not any particular particula importance to the response of structures or soils. The results using McCann-Shah and authors' approach for the beginning of the strong motion interval, are approximately the same. The definition given in this study is also closely related to the part that contributes significantly to the seismic energy and consequently does not include only the part of the motion with high amplitudes and high frequencies, but sometimes the subsequent part of moderately high amplitudes and low frequencies, too.

Finally, it must be remembered that the proposed relationships are quite useful to detect the general trends of data but they can not be used safely in the range of magnitudes and distances for which little or no earthquake records have been obtained.

6. CONCLUSIONS

The work described in this paper deals with the assessment of the duration characteristics of horizontal and vertical components using Trifunac-Brady, McCann-Shah and the proposed in this paper definitions. In order to detect the general trends of the obtained results and to find out the prominent factors that govern these trends, strong motion duration relationships with magnitude, distance to the fault and local soil conditions for all definitions were developed. The weighting scheme that takes into account the influence of magnitude, distance and soil conditions provided an increased accuracy to the resulted relationships (higher values of multiple correlation coefficients than those of the non-weighted regression analysis, Theofanopoulos et al., 1987).

The Trifunac and Brady definition yields to longer and McCann and Shah definition to shorter estimates than the proposed one. The results using McCann-Shah and authors' approach for the beginning of the strong motion interval are approximately the same.

The strong motion duration, using the proposed definition, at a soft soil site is on average 6 sec longer than that at a hard soil site, while for every 10 km of distance increases about 0.3 to 0.4 sec for both horizontal and vertical components.

The strong motion duration of vertical components is on average longer than the duration of horizontal components.

At soft soil sites the additional duration may be caused by repeated wave scatterings from different material discontinuities or from irregular surface topography.

The duration increases with distance probably due to the increased number of arrivals of reflected, refracted and scattered body waves, which followed indirect and multiple paths between source and station and maybe due to the contribution of surface waves at greater distances.

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