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Recent studies of earthquake ground motion and amplification

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ABSTRACT: Records from major earthquakes are often analyzed to update and improve the recommendations and guidelines for earthquake resistance design. In the seventies and the eighties, major earthquakes provided an abundance of accelerograms that made it possible to study the influences of various parameters on ground motion, attenuation relationships, response spectra, etc., and to formulate new recommendations and guidelines for seismic design. Several considered the influence of soil condition on spectral shapes and amplification. The studies showed that soil condition influences spectral shapes and amplification significantly. The findings form the studies were incorporated in a joint publication by the Applied Technology Council, the National Bureau of Standards and the National Science Foundation for the development of seismic regulations for buildings, and later in the 1988 Uniform Building Code.

The Loma Prieta earthquake of October 17, 1989, provided a significant number of records from a major earthquake in northern California. This paper examines the recorded ground motion and the spectral shapes from the Loma Prieta earthquake and compares them to those from previous earthquakes. The influences of soil condition, duration of strong motion, source to site distance, and orientation of motion on ground motion and spectral shapes are presented and discussed. The similarities and differences between the results from recent studies and those from previous studies, as well as the reason for the differences, are examined.

1 INTRODUCTION

In designing structures or facilities to resist earthquake motion two parameters are of special interest: ground motion and the manner in which the motion is amplified when transmitted through the structure. Ground motion (acceleration, velocity, and displacement) at a site is estimated from the seismicity of the region, proximity to faults, and the geological condition of the site. Records from past earthquakes are often analyzed to determine the motion which may be expected in future earthquakes. The amplification of the motion is obtained by computing the response spectrum which is the response of a damped single degree of freedom system with different frequencies or periods to a specific ground motion. Response spectra from a number of stations recorded in different earthquakes are averaged and smoothed to arrive at earthquake design spectra and design amplification factors.

It is important to analyze records from any major earthquake in order to determine the similarities and differences in the new and previous data and to incorporate the new information in defining seismic design specifications. In the seventies and the eighties, major earthquakes provided an abundance of accelerograms which made it possible to study the influences of various parameters on ground motion, attenuation relationships, response spectra, etc. and to formulate new recommendations and guidelines for earthquake resistance design.

The Loma Prieta earthquake of October 17, 1989 provided a significant number of records from a major earthquake in northern California. This paper examines the recorded ground motion and the spectral shapes from the Loma Prieta earthquake and compares them to those from previous earthquakes. The influences of soil condition, duration of strong motion, source to site distance, and orientation of motion on ground motion and spectral shapes are presented and discussed. The similarities and differences between the results from recent studies and from previous studies, as well as the reason for the differences are examined.

2 BACKGROUND

One of the earliest design spectrum was proposed by Housner (1959). He computed the spectrum by normalizing the response spectra from eight accelerograms to a given spectral intensity and then averaging them. Another design spectrum which was used extensively in the nuclear power industry in the late sixties and early seventies was suggested by Newmark and Hall (1969). Their spectra consisted of straight lines in form of a trapezoid plotted on tripartite (four-way logarithmic) paper. They recommended a set of amplification factors which are multiplied by a specified set of ground motion (acceleration, velocity, displacement) to arrive at the design spectrum.

The San Fernando earthquake of February 9, 1971 provided the largest number of accelerograms recorded in an earthquake at the time. A limited number of

records were incorporated in two independent studies supported by the Atomic Energy Commission (later renamed the Nuclear Regulatory Commission) to arrive at improved earthquake design spectra for nuclear reactor facilities. These studies – one by Newmark and his associates (Mohraz et al., 1972) and the other by Blume and his associates (Blume et al., 1972) formed the basis for the NRC Regulatory Guide 1.60 (see Newmark et al., 1973). The NRC spectra was also used extensively for seismic design of non-nuclear facilities. The following discusses the influences of various parameters on ground motion and spectral shapes.

3 SITE GEOLOGY

None of the spectra mentioned in the previous section accounts for the influence of soil condition or other earthquake parameters that affect ground motion and response spectra. In the mid-seventies when all records from the San Fernando earthquake had been processed and became available, several studies addressed the influences of various parameters on ground motion and response spectra (McGuire, 1974; Hall et al., 1976; Trifunac and Brady, 1975a and b; Seed et al., 1976; Mohraz, 1976; McCann and Shah, 1979; Boore et al., 1980; Joyner and Boore, 1981). The studies by Seed and his colleagues and by Mohraz considered the influence of soil condition on spectral shapes and amplification. The studies showed that soil condition influences spectral shapes and amplification significantly. The findings from the studies were incorporated in a joint publication by the Applied Technology Council, the National Bureau of Standards, and the National Science Foundation (1978) for the development of seismic regulations for buildings, and later appeared in the Uniform Building Code (1988). The Code now recommends (see Figure 1) spectral shapes and amplification for three soil categories: rock and stiff soil (soil type 1), deep coheisonless or stiff clay soil (soil type 2), and soft to medium clays and sand (soil type 3).

Mohraz and Tiv (1991) using the accelerograms from the Loma Prieta earthquake computed new spectral shapes and amplification and compared them with those Mohraz (1976) had computed from the accelerograms in previous earthquakes. They addressed the question "Do the recommended specifications that are based on previous earthquakes measure up to and prove adequate for the Loma Prieta earthquake?" Their findings indicated that while the ground motion and spectral shapes for alluvium from the Loma Prieta were in agreement with those from previous earthquakes, the ground motion and spectral shapes for rock were substantially greater than their counterpart from previous earthquakes and were, indeed, close to those for alluvium, Fig. 2. Figures 3 and 4 show the UBC spectral shapes for soils type 1, 2, and 3 superimposed on the average acceleration amplification from the Loma Prieta and previous earthquakes. The figures show that while the amplification for alluvium is smaller than those specified by UBC, the amplification for rock is substantially greater. Figure 5 shows the Kanai (1957) – Tajimi (1960) normalized power spectral densities computed from groups of accelerograms recorded on alluvium and on rock during the Loma Prieta and other earthquakes in the past. The figure shows similar differences and agreements.

Regionalization maps for seismic design generally specify horizontal peak ground acceleration or effective peak ground acceleration. Estimates of ground velocity and ground displacement are obtained from the

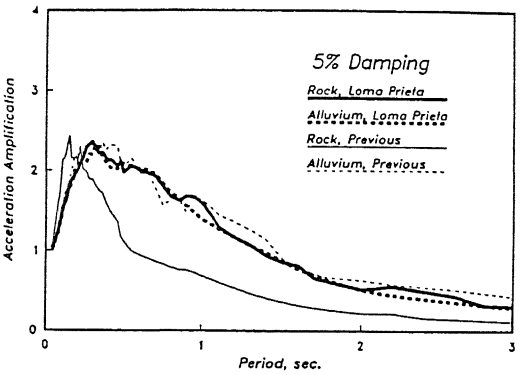

Figure 2. Comparison of average acceleration amplification for horizontal motion.

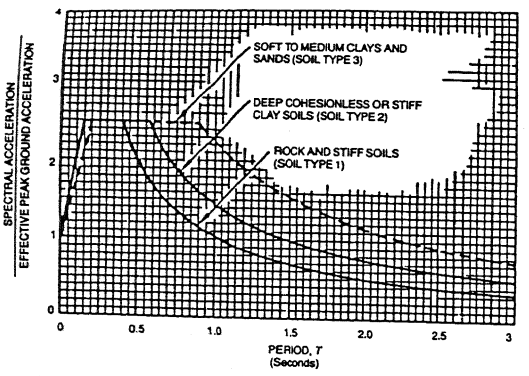

Figure 1. Normalized response spectra shapes (after UBC 1988).

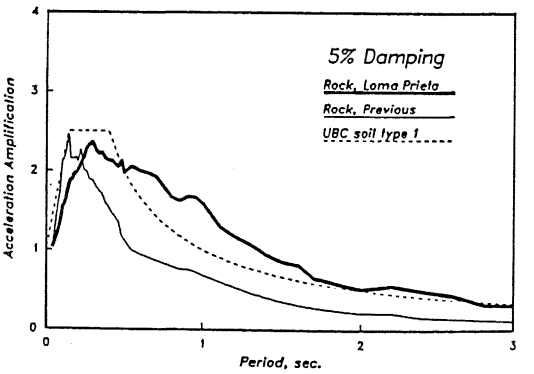

Figure 3. Average acceleration amplification for rock.

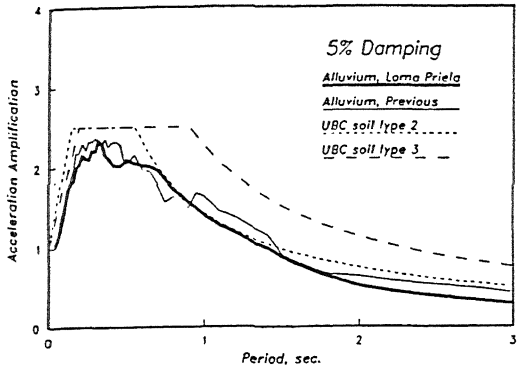

Figure 4. Average acceleration amplification for alluvium.

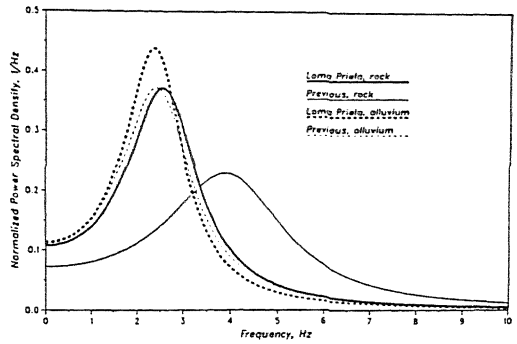

Figure 5. Kanai-Tajimi normalized power spectral densities for horizontal motion.

relationships between peak acceleration, velocity, and displacement. The ratio of velocity to acceleration, v/a, and the ratio of the product of the acceleration and displacement to the square of the velocity, $ad/v2$, are used to estimate the velocity and displacement for a unit acceleration. The choice of v/a is obvious. The reason for estimating the displacement from the $ad/v2$ ratio rather than directly from d/a or d/v ratios is that the integrated velocities and particularly the integrated displacements are sensitive to baseline adjustment and large errors may arise and accumulate during the integration. By selecting $ad/v2$ the error which may arise is distributed among the ground motion parameters; furthermore, certain ground motion and response spectrum characteristics can be correlated to the $ad/v2$ ratio (Newmark and Rosenblueth, 1971).

Table 1. Summary of v/a and ad/v^2 ratios for horizontal motion.

Earthquake	Soil	Components	v/a (in/sec/g)	ad/v
Loma Prieta	Rock	28	51	2.8
	Alluvium	50	49	2.6
Previous	Rock	26	28	6.8
	Alluvium	50	56	4.0

Table 1 shows the v/a and $ad/v2$ ratios for the group of accelerograms recorded on rock and alluvium during the Loma Prieta earthquake. Also shown are the ratios from a previous study by the author (Mohraz, 1976). All ratios were computed using a log-normal distribution which indicated a better distribution of the data than a normal distribution. The table shows that for alluvium, the mean v/a ratio for the Loma Prieta accelerograms (49 *in/sec/g*) is slightly smaller than the ratio for previous earthquakes (56 *in/sec/g*). For rock, however, the mean v/a ratio (51 *in/sec/g*) for the Loma Prieta accelerograms is substantially greater than the ratio (28 *in/sec/g*) for previous earthquakes and is, in fact, nearly the same as the ratio of 49 *in/sec/g* for alluvium.

While the UBC spectral shapes and amplification are used in design of buildings, design spectra similar to those recommended by Newmark and Hall (1969) and by the U.S. Nuclear Regulatory Commission (1973) are used in the design of nuclear reactor facilities, fossil power plants, petrochemical facilities, etc. These spectra are plotted on a tripartite paper using spectral ordinates obtained from the product of ground motion and amplification. Tables 2 and 3 give the acceleration, velocity, and displacement amplification factors for different damping for alluvium and for rock for the Loma Prieta accelerograms and accelerograms recorded

Table 2. Amplification summaries for horizontal motion on rock.

Damping	Loma Prieta						Previous					
	DISP.		VEL.		ACC.		DISP.		VEL.		ACC.	
	50	84.1	50	84.1	50	84.1	50	84.1	50	84.1	50	84.1
0	3.04	4.94	2.41	4.14	4.94	7.71	2.60	4.12	2.31	3.71	4.83	7.55
2	2.52	3.79	1.71	2.72	2.53	3.61	2.16	3.19	1.64	2.44	2.77	3.96
5	2.15	3.08	1.38	2.09	2.02	2.69	1.84	2.64	1.34	1.89	2.11	2.92
10	1.79	2.45	1.19	1.60	1.67	2.08	1.55	2.11	1.09	1.49	1.68	2.18
20	1.42	1.85	0.84	1.15	1.37	1.58	1.24	1.58	0.84	1.11	1.29	1.57

Table 3. Amplification summaries for horizontal motion on alluvium.

Damping	Loma Prieta						Previous					
	DISP.		VEL.		ACC.		DISP.		VEL.		ACC.	
	50	84.1	50	84.1	50	84.1	50	84.1	50	84.1	50	84.1
0	2.77	4.57	2.68	4.51	4.31	7.08	3.11	4.50	2.81	4.69	5.25	8.38
2	2.32	3.54	1.86	2.88	2.53	3.67	2.51	3.39	1.81	2.74	2.78	3.79
5	2.01	2.86	1.49	2.20	2.00	2.71	2.12	2.75	1.41	2.05	2.13	2.74
10	1.72	2.29	1.19	1.69	1.65	2.08	1.74	2.18	1.10	1.56	1.71	2.11
20	1.41	1.75	0.90	1.22	1.33	1.55	1.34	1.63	0.82	1.12	1.37	1.59

in previous earthquakes. The amplification factors were obtained by computing the mean-plus-one standard deviation amplification at different frequencies and averaging them within specified frequency regions. The frequency regions used to obtain the values in the tables were 0.1 – 0.3 Hz for displacement, 0.3 – 3.0 Hz for velocity, and 3.0 – 8.0 Hz for acceleration. The details of the computations are explained in Mohraz (1976). Figure 6 shows the smooth spectra for the horizontal motion for 1.0 g ground acceleration using the information in Tables 1–3. The figure shows that for frequencies greater than approximately 3 Hz the four spectra have the same ordinates. For frequencies less than 3 Hz, however, the spectral ordinates for rock for Loma Prieta are substantially greater than the ordinates for rock for previous earthquakes.

Plots similar to Fig. 2 and 6 but for vertical motion are presented in Figs. 7 and 8. Contrary to the horizontal motion, the spectral shapes for the vertical motion, Figs. 7 and 8, indicate a wider variation in amplification and spectral ordinates. The Kanai-Tajimi power spectral density for the vertical motion (Fig. 9) also shows more pronounced variation in frequency content than the one for the horizontal motion (Fig. 5).

4 DISTANCE

Examination of the records from the Loma Prieta and other earthquakes reveals that the distance of the

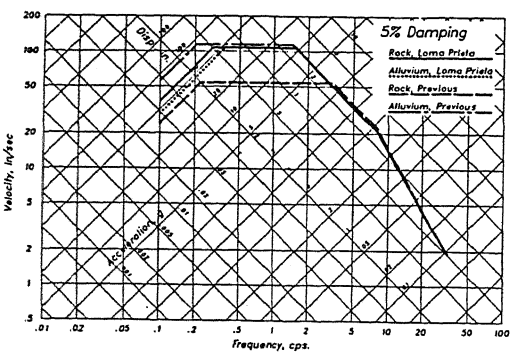

Figure 6. Smooth spectra for horizontal motion.

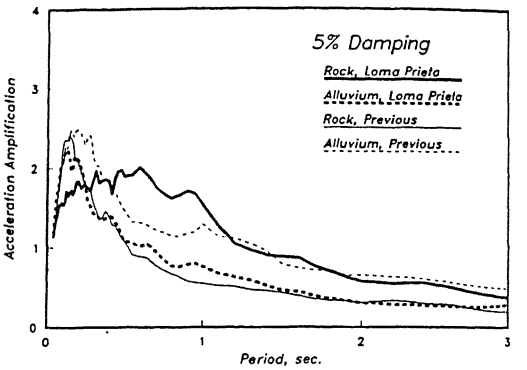

Figure 7. Comparison of average acceleration amplification for vertical motion.

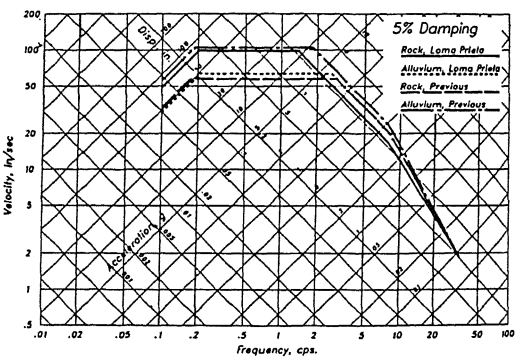

Figure 8. Smooth spectra for vertical motion.

recording station from the source of energy release can cause the differences in the spectral shapes for rock discussed in the previous section. The average source to site distance of the accelerograms on rock from the Loma Prieta earthquake is 50 *km* as compared to the 28 *km* identified in the previous study. Similar comparisons for alluvium, however, show an average distance of 41 *km* for the Loma Prieta and 55 *km* for the previous accelerograms. These observations led to investigating the influence of source-to-site distance on

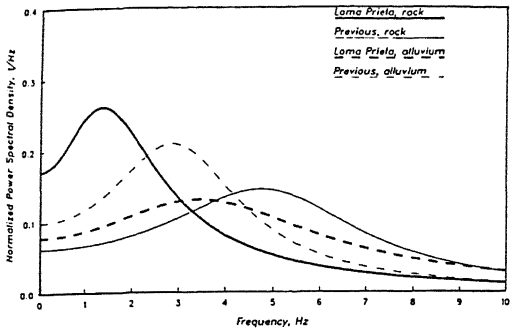

Figure 9. Kanai-Tajimi normalized power spectral densities for vertical motion.

ground motion and spectral shapes. Consequently, the accelerograms on rock and on alluvium from the Loma Prieta earthquake were divided into three subgroups. The accelerograms with a distance of the recording station to the ground projection of the ruptured surface of less than 20 *km* were labeled as "near-field," those with a distance between 20 *km* and 50 *km* as "mid-field," and those with a distance greater than 50 *km* as "far-field." The 20 and 50 *km* limits were chosen so that the sub-groups included a reasonable number of accelerograms. Table 4 shows a summary of the average source-to-site distance of the recording stations from the Loma Prieta and previous earthquakes.

Table 4. Average source-to-site distance in *km* of the recording stations from the Loma Prieta and previous earthquakes.

Category*	ROCK			ALLUVIUM		
	Comp.	Average	Range	Comp.	Average	Range
Near-field	6	17	15-19	12	13	1-20
Mid-field	10	40	36-44	24	35	25-48
Far-field	12	73	53-80	14	75	53-119
All Records	28	50	15-80	50	41	1-119
Previous	26	28	6-42	50	55	12-127

*Near-field is less than 20 km; mid-field 20-50 km; far-field, greater than 50 km.

A summary of v/a and ad/v^2 ratios for the three subgroups as well as the average ratios for the records from previous earthquakes are given in Table 5. The table shows that for the accelerograms in the near-field, the average v/a ratio of 26 *in/sec*/g is in agreement with the ratio of 28 *in/sec*/g for all accelerogram on rock from previous earthquakes. It is also substantially smaller than the average v/a ratio of 63 *in/sec*/g for the accelerograms in the mid-field.

Figure 10 shows the spectral shapes for the three distance subgroups computed for 5 percent damping using the horizontal components of accelerograms recorded on rock in the Loma Prieta earthquake. The figure shows that the amplification for the near-field is substantially smaller than the amplification for mid- or far-field for periods greater than about 0.5 *sec*. For periods less than 0.5 *sec*, however, the amplification for the near-field is greater. Plots of the spectral shapes for alluvium, similar to Fig. 10 (for rock) are shown in Fig. 11. This figure indicates that distance also influences the spectral shapes, for alluvium, but the influence, at least for the Loma Prieta accelerograms, is not as pronounced as it is for rock. It is interesting to note (Table 5) that the v/a ratios for alluvium do not vary significantly with distance.

Table 5. Summary of v/a and ad/v^2 ratios for diffferent source to site distances.

Category*	ROCK		ALLUVIUM	
	v/a (*in/sec/g*)	ad/v^2	v/a (*in/sec/g*)	ad/v^2
	Loma Prieta			
Near-field	26	3.8	40	2.9
Mid-field	63	2.3	53	2.9
Far-field	54	2.8	48	2.0
	Previous			
All Records	28	6.8	56	4.0

*Near-field is less than 20 km; mid-field 20-50 km; far-field, greater than 50 km.

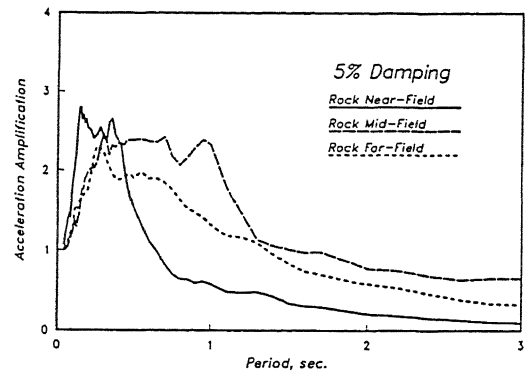

Figure 10. Average acceleration amplification for different distances.

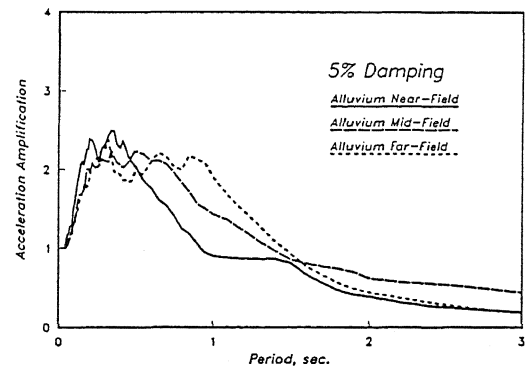

Figure 11. Average acceleration amplification for different distances.

Figure 12 compares the amplification for 5 percent damping for rock and alluvium in the near-field for the Loma Prieta earthquake. It shows that the amplification for rock is smaller than the amplification for alluvium for periods greater than 0.3 – 0.4 *sec*. For periods smaller than 0.3 – 0.4 *sec*, the amplification for rock is slightly greater. This observation is consistent with that made previously by the author (Mohraz, 1976) for accelerograms recorded prior to and including the San Fernando earthquake. Aki (1988) has also made a similar observation regarding amplification for different site geology regardless of the distance. According to his study a cross-over period exists where for periods greater, the soil site shows a higher amplification and for periods smaller, the trend is reversed. The cross-over period according to Aki is about 0.2 *sec*.

Joyner and Boore (1988) proposed expressions where one can estimate amplification for a given distance. Figure 12 also shows plots of acceleration amplification using their expressions and the average distances for the accelerograms in the near-field, Table 4. The figure shows that the amplification predicted by their expression is on the conservative side. Figures 13 and 14 present similar plots for mid- and far-fields. The figures again include the amplification estimated from the Joyner and Boore expressions for the average distances in Table 4. The figures indicate that unlike the near-field (Fig 12), the predicted response in the mid- and far-field is substantially smaller than the computed response from the Loma Prieta accelerograms, particularly for rock.

Figures 15 and 16 presents smoothed spectral shapes similar to UBC shapes for the tree distance subgroups for rock and alluvium.

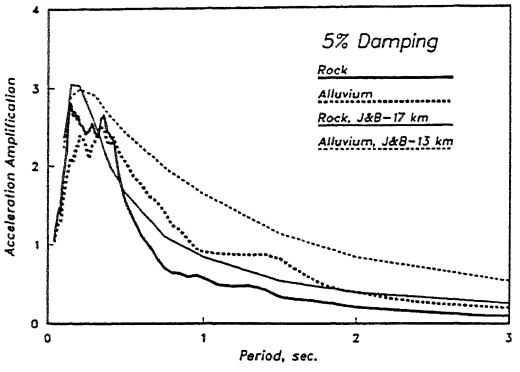

Figure 12. Comparison of average acceleration amplification in the near-field with those recommended by Joyner and Boore (1988) for the Loma Prieta earthquake.

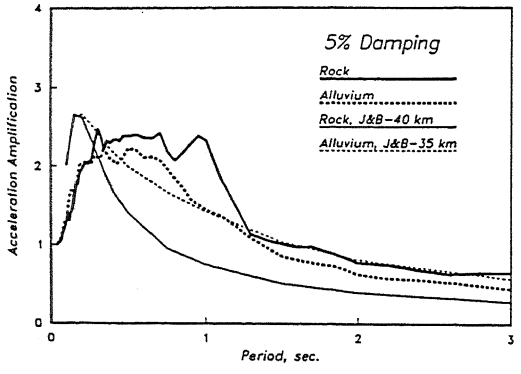

Figure 13. Comparison of average acceleration amplification in the mid-field with those recommended by Joyner and Boore (1988) for the Loma Prieta earthquake.

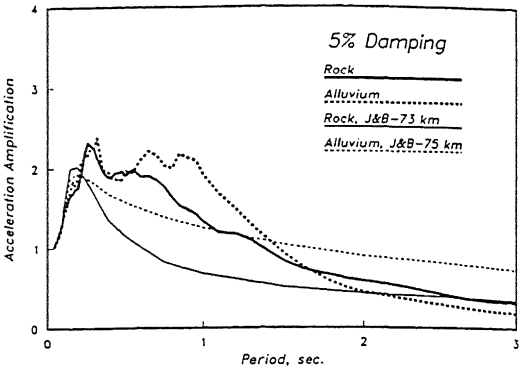

Figure 14. Comparison of average acceleration amplification in the far-field with those recommended by Joyner and Boore (1988) for the Loma Prieta earthquake.

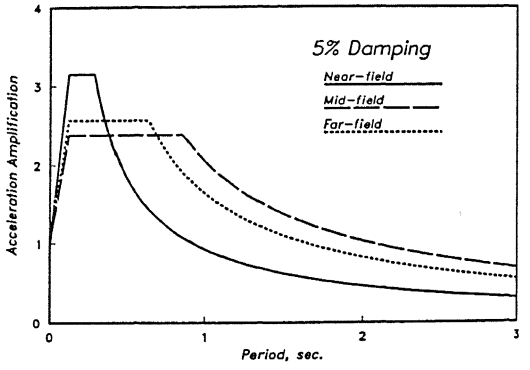

Figure 15. Acceleration amplification for rock for different distances for the Loma Prieta earthquake.

5 DURATION

The duration of strong motion also influences ground motion, amplification, and spectral shapes. No universally accepted definition for duration of strong motion exists. Several investigators have proposed procedures for extracting a strong motion segment from an accelerogram. Bolt (1969) and Page et al. (1972) used a "bracketed duration" which is the time interval between the first and the last acceleration peaks exceeding a specified value (usually 0.05 g). Page and

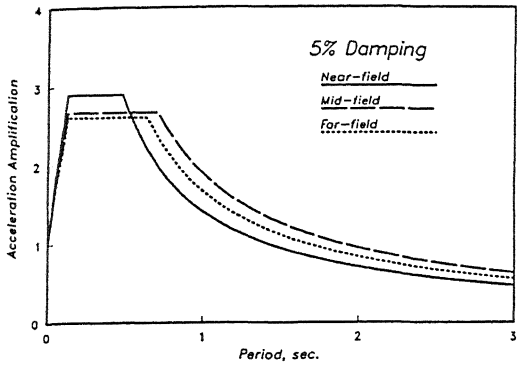

Figure 16. Acceleration amplification for alluvium for different distances for the Loma Prieta earthquake.

his colleagues concluded that for a given earthquake magnitude, duration decreases with an increase in distance from the source. Chang and Krinitzsky (1977) used the bracketed duration to propose a set of plots for estimating the duration of strong motion for rock and alluvium. They concluded that for a given magnitude, the duration of strong motion for sites on alluvium is about twice the duration for sites on rock. Trifunac and Brady (1975b) used the middle 90 percent contribution of the acceleration intensity ($\int a^2 dt$) as a measure of the duration. They concluded that the average duration for soil is approximately 10-12 *sec* longer than that for rock, and it increases by approximately 1.0 – 1.5 *sec* for every 10 *km* increase in distance. A third definition for the duration was proposed by McCann and Shah (1979) and is based on the average energy arrival rate, i.e. the segment of the accelerogram between two times beyond which the rate of change of the cumulative root-mean-square acceleration becomes negative and remains negative for the remainder of the record. Figure 17 shows a comparison of strong motion duration for the S69E component of Taft, California earthquake of July 21, 1982 using the three definitions. The figure indicates that the durations computed from the acceleration intensity and energy arrival rate are close to each

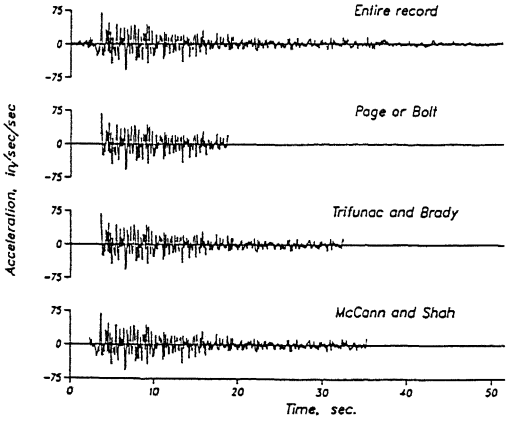

Figure 17. Comparison of strong motion duration.

Table 6. Average duration of strong motion in *sec* for accelerograms recorded in the Loma Prieta earthquake.

Category*	Page et al.		Trifunac & Brady		McCann & Shah	
	Rock	Alluvium	Rock	Alluvium	Rock	Alluvium
Near-field	11.6	14.4	8.5	10.5	10.0	11.6
Mid-field	6.2	12.5	15.6	18.6	15.9	19.8
Far-field	1.9	6.7	11.6	11.5	14.7	14.8

*Near-field is less than 20 km; mid-field 20-50 km; far-field, greater than 50 km.

other and are nearly twice the bracketed duration.

Table 6 shows the average duration of strong motion from the three definitions for accelerograms in near-, mid-, and far-field recorded in the Loma Prieta earthquake. The duration of strong motion computed from the bracketed duration decrease with an increase in distance whereas the duration computed from the acceleration intensity or energy arrival rate are shortest for near-field. Although there is a contradiction between the results from the bracketed duration and the other two, the difference stems from different definitions. The bracketed duration is based on the absolute acceleration level (0.05 g) and at longer distances the acceleration peaks become smaller and a shorter duration is to be expected. The other two definitions are based on the relative rather than the absolute contribution to the acceleration intensity and to the cumulative root-mean-square acceleration. Conceivably, a more intense shaking within a shorter duration may take place in the near-field and a less intense shaking over a longer time interval may occur at longer distances. This is the case when one computes the root-mean-square accelerations (Table 7) with the durations from different definitions. The table shows that regardless of the definition used the intensity is the largest for the near-field.

Correlations between the duration of strong motion and spectral intensity indicate that the strongest correlation is obtained for the bracketed duration. Consequently, only the influence of the bracketed duration on ground motion and spectral shapes is presented. To determine the influence, the accelerograms on rock and on alluvium were divided into three subgroups: those with a duration of less than 5 *sec*, those with a duration between 5-10 *sec*, and those with

Table 7. Average root-mean-square acceleration in *cm/sec/sec* for accelerograms recorded in the Loma Prieta earthquake.

Category*	Page et al.		Trifunac & Brady		McCann & Shah	
	Rock	Alluvium	Rock	Alluvium	Rock	Alluvium
Near-field	86.9	87.9	103.7	102.7	98.0	101.3
Mid-field	43.9	51.9	30.8	46.2	30.6	46.7
Far-field	35.3	52.5	19.8	44.4	18.6	40.2

*Near-field is less than 20 km; mid-field 20-50 km; far-field, greater than 50 km.

a duration greater than 10 *sec*. Ratios of v/a and $ad/v2$ for each subgroup in each geological group were computed. Examination of the average ratios for both the Loma Prieta earthquake and previous earthquakes indicate that the influence of the duration on v/a and $ad/v2$ is minimal and no significant trend is apparent.

Figure 18 shows smoothed spectral shapes for rock for the three duration categories. Similar plots for alluvium are shown in Fig. 19. The figures indicate that only in the case of rock is the spectral shape for durations greater than 10 *sec* appreciably different than others. Further studies on larger collections of records are needed before specific recommendation can be made on how the duration of strong motion should be accounted for in arriving at spectral shapes.

6 ORIENTATION

Motion induced by an earthquake is a spatial phenomenon. In its most general form the motion can be described by three translational and three rotational components. Except for certain structures such as tall buildings, the rotational component of ground motion may be neglected since they do not significantly affect the safety of the structure. Newmark (1969) and Rosenbleuth (1976) suggested procedures for estimating the rotational components in terms of the translational ones.

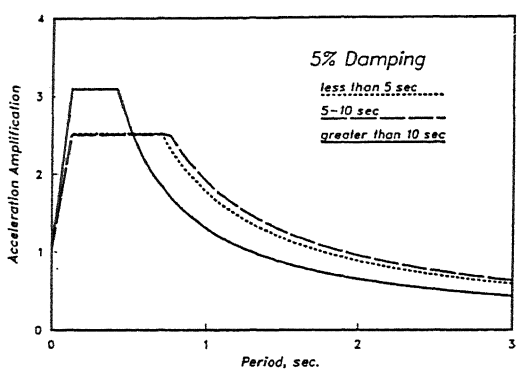

Figure 18. Acceleration amplification for rock for different bracketed durations for the Loma Prieta earthquake.

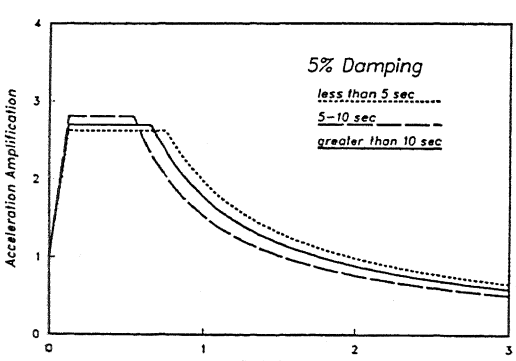

Figure 19. Acceleration amplification for alluvium for different bracketed durations for the Loma Prieta earthquake.

Earthquake motion is recorded in three orthogonal directions – two horizontal and one vertical. Knowing the three components, the acceleration-time history along other directions can be found by transformation. Several studies have examined the influence of orientation on response of structures. Hadjian (1978,1981) considered the correlation coefficient between the two horizontal components of ground motion and presented a probability distribution for the correlation coefficient for use in seismic design. Penzien and Watabe (1975) made the analogy that the variances and covariances associated with the three components of ground motion are analogous to the state of stress at a point in a solid. The response of a particular point in a structural system in the form of displacements, forces, or stresses under the simultaneous action of multi-directional components of ground motion have been studied by a number of investigators; see for example: Newmark (1969), Rosenblueth (1976), Wilson and Button (1982), Di Paola and Muscolino (1984), Ghafori-Ashtiani and Singh (1986), and Cakeroglu (1987).

For most structures only the response in the horizontal direction is of interest. The response to vertical motion is important for rigid massive structure such as nuclear reactor facilities. When only the horizontal motion is of interest in a symmetrical structure, it is customary to apply the two components separately along the axes of the structure. For an unsymmetrical structure the inertia forces in the horizontal direction cause rotation about the vertical axis.

Since the recorded directions of the accelerograms are predetermined, they do not necessary represent the most intense motion. In addition, because the components of ground motion depend on each other, correlations between the components exists.

Twenty-five pairs of accelerograms recorded on alluvium in horizontal directions during the Loma Prieta earthquake were used to study the influence of the orientation of ground motion. In addition to the recorded directions, ground motion corresponding to three other orientations were determined by transformation. These included 1) the principal direction, 2) the epicentral direction, and 3) the absolute peak acceleration direction. The principal direction was determined by taking the expected value of the acceleration transformation relationship and setting it to zero to obtain the angle. For the absolute peak acceleration direction, the magnitude and the orientation of the resultant acceleration was computed at each acceleration reading (time interval) and the orientation corresponding to the maximum of the resultant acceleration was used to transform the entire accelerogram.

Spectral shapes computed from the four orientations indicate that orientation does not significantly influence the response. Consequently, the recorded directions can be used in computing the response. For symmetric and unsymmetric space frames, however, orientation makes a difference. Figure 20 shows the response of a single story symmetric space frame to different orientations.

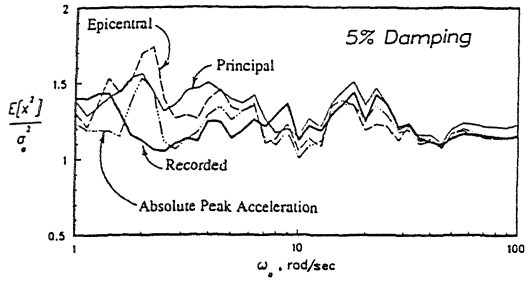

Figure 20. Response of a symmetric space frame to different orientations.

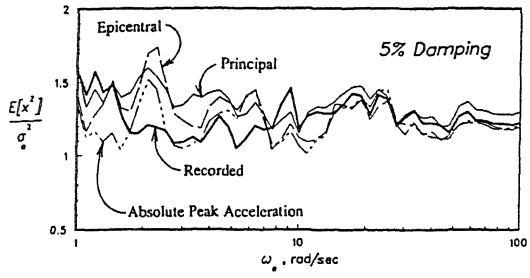

Figure 21. Response of a nonsymmetric space frame with 10% eccentricity to different orientations.

The response is presented in terms of the ratio $E[x^2]/\sigma_0^2$ where $E[x^2]$ is the maximum mean square response of the frame along one of the two axes to a specified ground motion orientation, and σ_0^2 is the mean square response of a single degree of freedom system with natural frequency ω_0 to the average power spectral density of the 50 horizontal components of the recorded motion (see Tiv and Mohraz, 1992 for details). The figure shows that in the high frequency region the influence of orientation is small, whereas in the low frequency region, the difference in response may be as large as 50 percent. Figure 21 shows similar results and observation for an unsymmetric (torsionally coupled) single story space frame with ten percent eccentricity. Both figures indicate that orientation can influence the response and should be accounted for when computing the response of space structures.

7 CONCLUSIONS

Recent studies of earthquake ground motion and amplification indicate that in addition to site geology, the distance of the site to the source of energy release and possibly the duration of strong motion influence ground motion and spectral shapes. The orientation of motion does not appreciably affect the response of single-degree-of-freedom systems, but it does affect the response of space structures.

Although the influences of distance, duration, and orientation on ground motion, amplification, and spectral shapes show definite trends, further studies are needed before the influences can be considered in arriving at recommendations for design specification. Because design spectra and specifications are based on records from previous earthquakes, it is important to incorporate data from new major earthquakes in redefining spectral shapes, amplification, and design specifications.

8 ACKNOWLEDGMENTS

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