SECTION 6
ESTIMATES OF THE PEAK ACCELERATION, VELOCITY AND DISPLACEMENT ON SEISMIC BED ROCK

If the local site amplification factors $\mathbf{AMP_i(a)}$, $\mathbf{AMP_i(v)}$ and $\mathbf{AMP_i(d)}$ are set equal to 1.0, Eqs. (5.1) to (5.6) give the peak values on seismic bed rock for acceleration, velocity and displacement. Such bed rock values depend on earthquake magnitude and hypocentral distance but not on local site conditions. As described in the preceding section, the seismic bed rock corresponds to the rock outcrops at HOROMAN, OFUNATO and HOROMAN for peak acceleration, velocity and displacement respectively. Figs. 6-1 to 6-3 show examples of the attenuation with hypocentral distance for the peak acceleration, velocity and displacement on seismic bed rock. In these figures, the attenuation curves are plotted versus earthquake magnitude. We can see from these figures that the peak acceleration in an epicentral area is limited to about **500 gal** irrespective of earthquake magnitude. Conversely the peak velocity and displacement in the epicentral area depend on earthquake magnitude having maxima of about **50 cm/sec** and **15 cm**, respectively, for an earthquake of magnitude of **8.0**. The validity of the peak values of each motion in Figs. 6-1 to 6-3 is confirmed in a later section by a comparison with actually observed peaks during earthquakes in the U.S. and Mexico. In this section we consider a different type of verification.

As is well known, for harmonic motion we have the following relations for the maximum amplitude of acceleration, velocity and displacement motions.

$$v = \frac{a}{2\pi} T_a \qquad (6.1)$$

$$d = \frac{v}{2\pi} T_v \qquad (6.2)$$

where **a** is the amplitude of acceleration, **v** is the amplitude of velocity, **d** is the amplitude of displacement, $\mathbf{T_a}$ is the period of the acceleration motion and $\mathbf{T_v}$ is the period of the velocity motion.

With respect to a random wave such as earthquake motions, of course, the simple relations in Eqs.(6.1) and (6.2) are not satisfied. However these equations are approximately correct for earthquake motions if we use the predominant period and maximum amplitude of earthquake motions. Given values for the peak acceleration, velocity and displacement, Eqs.(6.1) and (6.2) enable us to estimate predominant periods for acceleration and velocity motions.

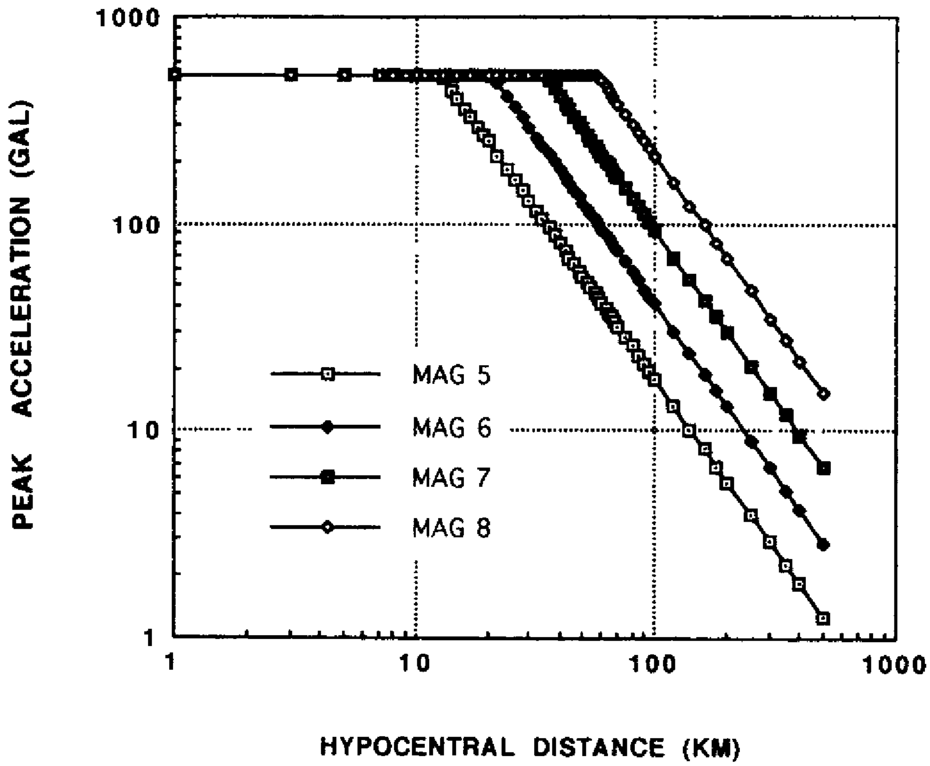

Fig.6-1 Attenuation Relationship for Peak Acceleration on Bed Rock from Proposed Semi-Empirical Model

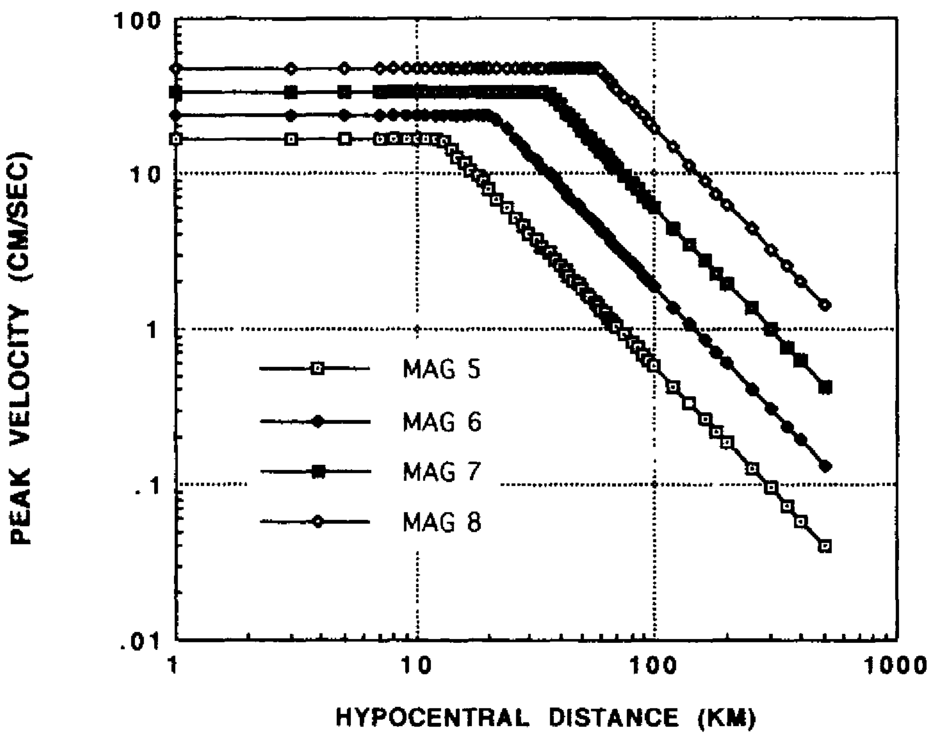

Fig.6-2 **Attenuation Relationship for Peak Velocity on Bed Rock from Proposed Semi-Empirical Model**

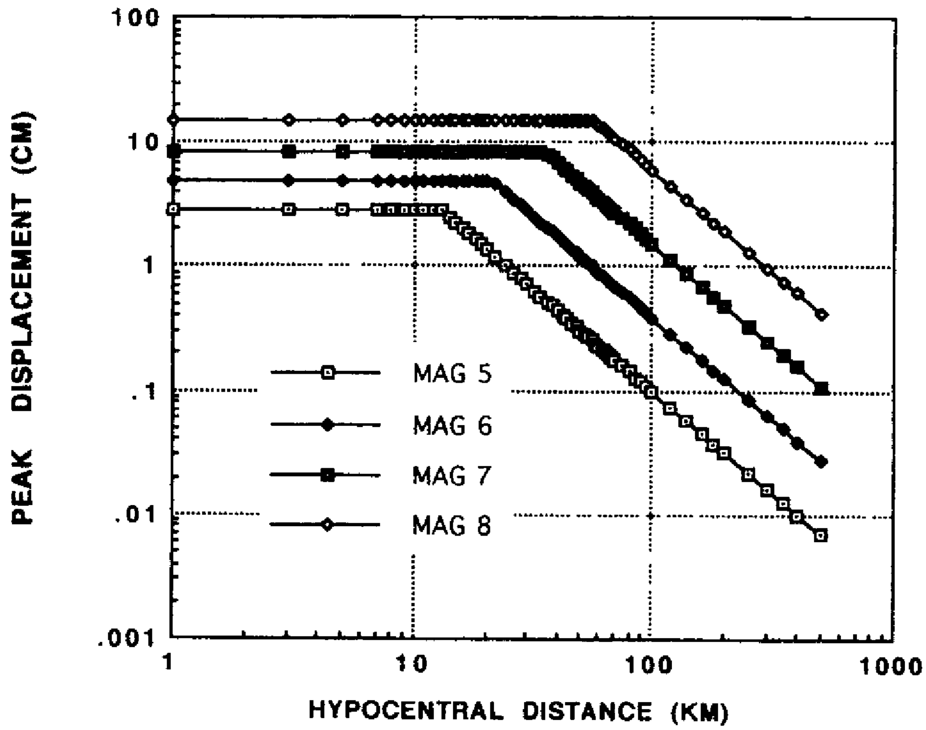

Fig.6-3 Attenuation Relationship for Peak Displacement on Bed Rock from Proposed Semi-Empirical Model

Herein we examined the magnitude-dependence of predominant periods for the acceleration and velocity motions on bed rock. Table 6-I shows the predominant periods of the bed rock acceleration and velocity motions in an epicentral area (the flat area in Figs.6-1 through 6-3) estimated for various earthquake magnitudes using Eqs. (6.1) and (6.2) as well as Figs.6-1 through 6-3. As shown in Table 6-I the predominant periods of the bed rock motions become larger with the increasing earthquake magnitude. The magnitude dependence of predominant period has been noted in other studies. For example Seed et al.[25] graphically presented predominant periods of acceleration motions in an epicentral area resulting from earthquakes in California. The Seed et al. relation is shown in Fig.6-4. A comparison of Table 6-I against the results by Seed et al. indicates that the predominant periods from the model proposed herein are relatively compatible with the Seed et al. results. This provides support for the appropriateness of our semi-empirical model.

Table 6-I Predominant Periods for Bed Rock Acceleration and Velocity from Proposed Semi-Empirical Model

MAGNITUDE M	PREDOMINANT PERIOD(SEC) (ACCELERATION)	PREDOMINANT PERIOD(SEC) (VELOCITY)
5	0.20	1.07
6	0.29	1.30
7	0.41	1.57
8	0.58	1.90

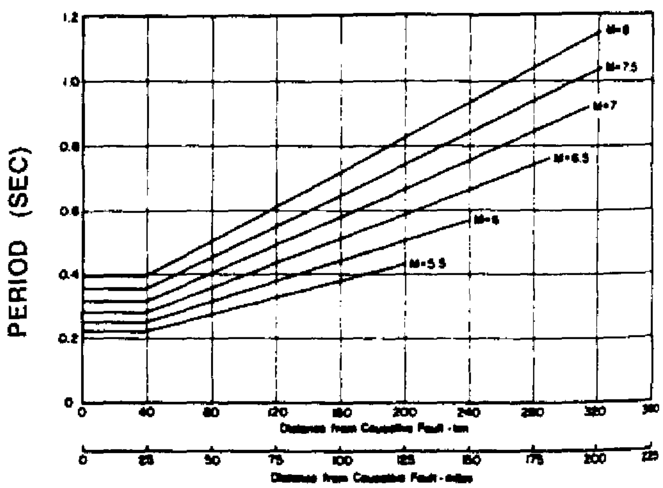

Fig.6-4 Predominant Periods for Acceleration on Rock (after Seed et al.[25])

SECTION 7
COMPARISON WITH OTHER EMPIRICAL RELATIONSHIPS

As mentioned in the introduction, many researchers have developed empirical relations for peak values of strong motions. Herein we compare our proposed semi-empirical model with empirical results by others. We restrict our comparison to peak velocity at rock sites which correspond to the seismic bed rock in our model and correspond to various rocks in the others. We chose peak velocity because the primary focus of our study is lifeline earthquake engineering for which peak velocity is the ground motion parameter of interest. Rock sites are chosen to simplify the comparison by elimination of local soil effects. Trifunac[12], McGuire[26], Joyner and Boore[27], Campbell[28], Sabetta[29], Ohsaki et al.[30], Watabe and Tohdo[31], and Kawashima et al.[32] have developed empirical relationships for peak velocity at rock sites or nearly rock sites. All these empirical expressions for peak velocity are dependent on earthquake magnitude and source-to-site distance. Figs 7-1 and 7-2 show a comparison of the proposed peak velocity attenuation for an earthquake magnitude of 7.0 with these available relations. The first figure shows a comparison with existing relations mainly from the U.S. while the second is for existing relations from Japan. It should be noted that the distance in Figs.7-1 and 7-2 is either epicentral distance, hypocentral distance, or closest distance to fault rupture, depending on what the individual researches choose as the source-to-site distance. That is, the proposed model uses hypocentral distance; Trifunac[12], McGuire[27], Ohsaki et al.[30], Watabe and Tohdo[31] and Kawashima et al.[32] use epicentral distance; and Joyner and Boore[27], Campbell[28] and Sabetta[29] use closest distance to fault rupture.

It is clear in Fig.7-1 that the proposed semi-empirical model yields peak velocities smaller than most of the U.S. empirical models in the near field, while the converse is true for source-to-site distance greater than about 30 km. On the other hand, Fig.7-2 shows that the proposed model predicts larger values than Kawashima et al.[32] at almost all distances. Considering that the data in the present study overlap in part with the more comprehensive data used by. Kawashima et al.[32], the comparison in Fig.7-2 shows that the resulting expressions depend greatly on the initial model choice. In other words, both Figs.7-1 and 7-2 show not only the importance of the data set to be analyzed but also the importance of the analysis model. In any case, the validity for each expression in Fig.7-1 and 7-2 should be eventually judged in reference to a comparison against new observation data not included in their analyses. Such a comparison is performed in the following section.

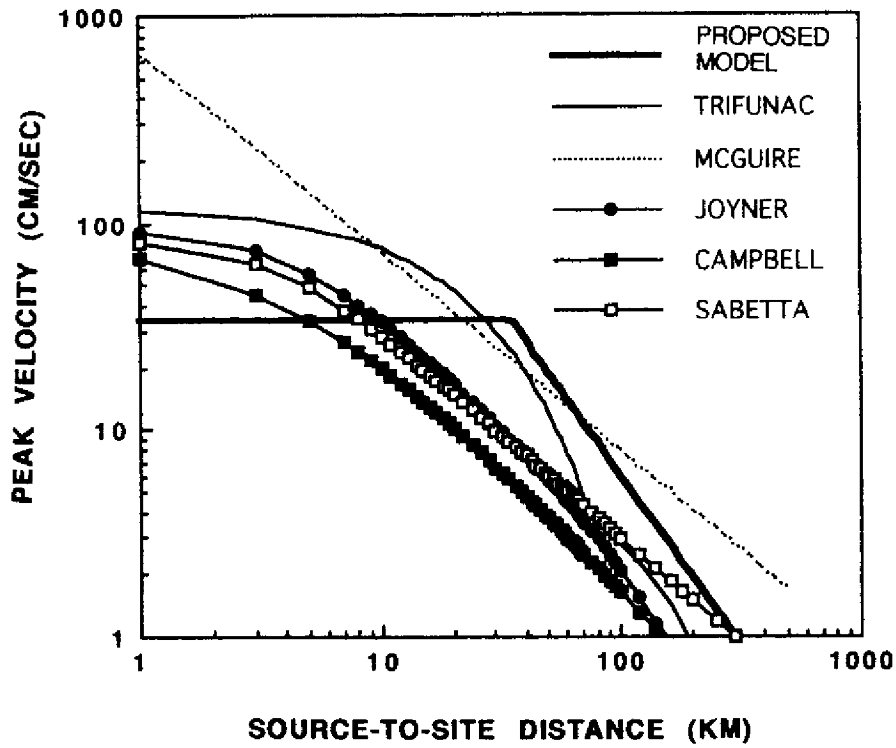

Fig.7-1 Comparison of Proposed Model with Currently Existing Models from the US. and Italy for Magnitude 7.0 Earthquake

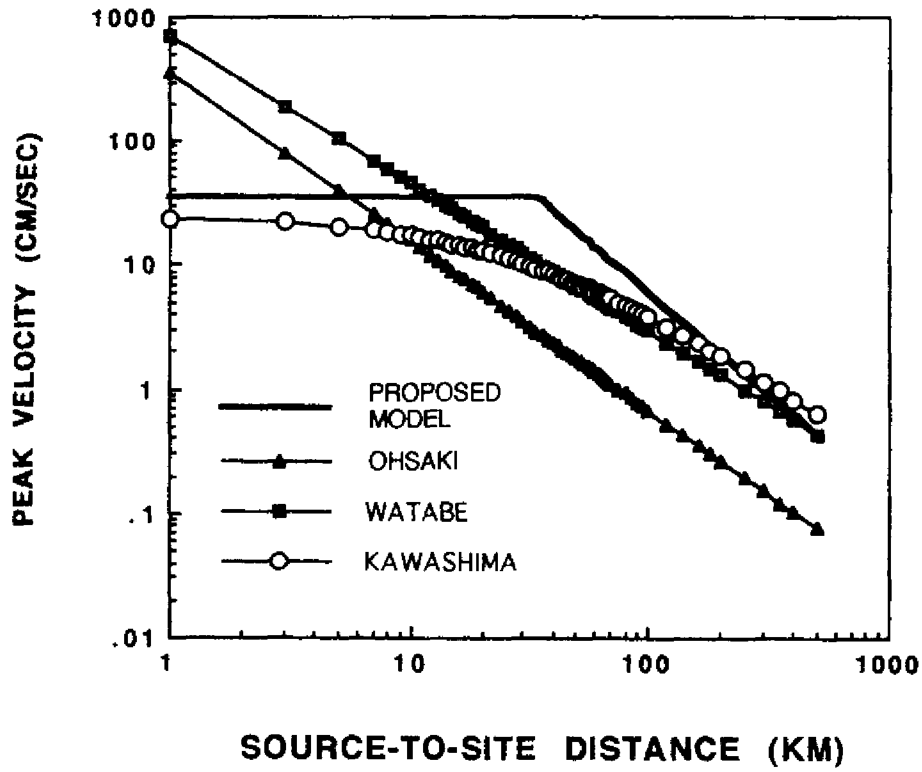

Fig.7-2 Comparison of Proposed Model with Currently Existing Models from Japan for Magnitude 7.0 Earthquake

SECTION 8
COMPARISON BETWEEN THE PROPOSED MODEL AND OSBERVATIONS DURING EARTHQUAKES IN THE U.S. AND MEXICO

The proposed semi-empirical model was developed using only earthquake data observed in Japan. Information from theoretical seismic source models was used to overcome the lack of near field strong-motion data. It is of primary interest, therefore, to investigate how consistent the proposed model is with observed strong-motion data from other countries that are relatively rich in near field data. In addition to confirming the validity of the proposed model, such an investigation is also essential to judge whether or not strong-motion characteristics vary from country to country. In this section, we investigate the validity of the proposed model by comparing its predicted results with the strong-motion data observed during three earthquakes: the 1989 Loma Prieta earthquake in the U.S., the 1985 Michoacan earthquake in Mexico and the 1971 San Fernando earthquake in the U.S. These earthquakes were chosen because they offer strong-motion records from both the near field and far field. Comparing velocity and displacement motions from different countries is complicated by the fact that different filters are used in determining velocity and displacement from original accelerograms. The filter used for the Japanese records was already illustrated in Fig.3-2. It has a flat part between periods of about 0.09 sec and 4.5 sec. Although somewhat different filters are used by different researchers, it seems that the flat portions of the filters are practically the same regardless of country. Herein we use the reported peak acceleration, velocity and displacement from the original text publishing the relevant earthquake data. That is, the effects if any of using filters different from that in Fig.3-2 are neglected. Also we compare exclusively strong motions on rock sites or nearly rock sites because they are less affected by local site conditions.

8.1 1989 Loma Prieta Earthquake

Many useful strong-motion records were obtained at the stations of the California Strong Motion Instrumentation Program (CSMIP) during the 1989 Loma Prieta earthquake. The estimated earthquake location and magnitude are:

Epicenter : 37.037 N, 121.883 W
Depth : 18 km
Magnitude : 7.0 (ML)

The strong-motion data including the geological characteristics of the stations are available in a report from CSMIP[33]. We picked strong-motion data at rock sites from the report and compared them with the predicted values from the proposed semi-empirical model. Since we consider only rock sites in the comparison, $\mathbf{AMP_i(a)}$, $\mathbf{AMP_i(v)}$ and $\mathbf{AMP_i(d)}$ were set equal to one in Eqs.(5.1) through (5-6). In the comparison, the magnitude scale ML was regarded as identical to the JMA magnitude scale employed in the proposed model.

Figs.8-1 to 8-3 show respectively the comparison between the observed and predicted peak accelerations, peak velocities and peak displacements. In each figure, the error bands of prediction based on the one standard deviation of the regression analysis are plotted in addition to predicted mean values. The standard deviation for the the peak acceleration analysis is shown in Table 4-I(r_c =5.3 km) and those for the peak velocity and displacement are shown in Table 4-IV. Note that there is a good agreement between the observed and predicted values in Figs.8-1 to 8-3, especially for peak velocity of Fig.8-2. Since the proposed model does not use earthquake fault parameters like rupture directivity but uses only simple parameters such as earthquake magnitude and hypocentral distance, some discrepancy between the observed and predicted values is inevitable. However most of the observed peak velocities are distributed within the error band of the prediction.

8.2 1985 Michoacan Earthquake

The 1985 Michoacan earthquake was a large event that caused severe damage in Mexico City and some damage in the epicentral region. The event provided strong motion records in both the near and far fields. Since earthquake engineering design is often based upon such large events, the prediction of strong motions for this type of event is a goal of our semi-empirical model. The location and magnitude of the earthquake are outlined as follows:

Epicenter: 18.14 N, 102.71 W
Depth: 16 km
Magnitude: 8.1 (Ms)

Strong-motion records for this event are contained in a UNAM report[34]. Strong motions obtained at rock sites, especially along the coast of Guerrero during the earthquake are compared with predicted values from the proposed model in Figs.8-4 to 8-6. In this comparison, the earthquake magnitude Ms was treated as equivalent to the JMA magnitude. In contrast to the 1989 Loma Prieta earthquake, Figs.8-4 to 8-6 show that the 1985 Michoacan earthquake motions were somewhat smaller than the predicted values in the near field. However relatively good agreement between the observed and predicted values is notable at intermediate to long distances, giving implicit support for the proposed model.

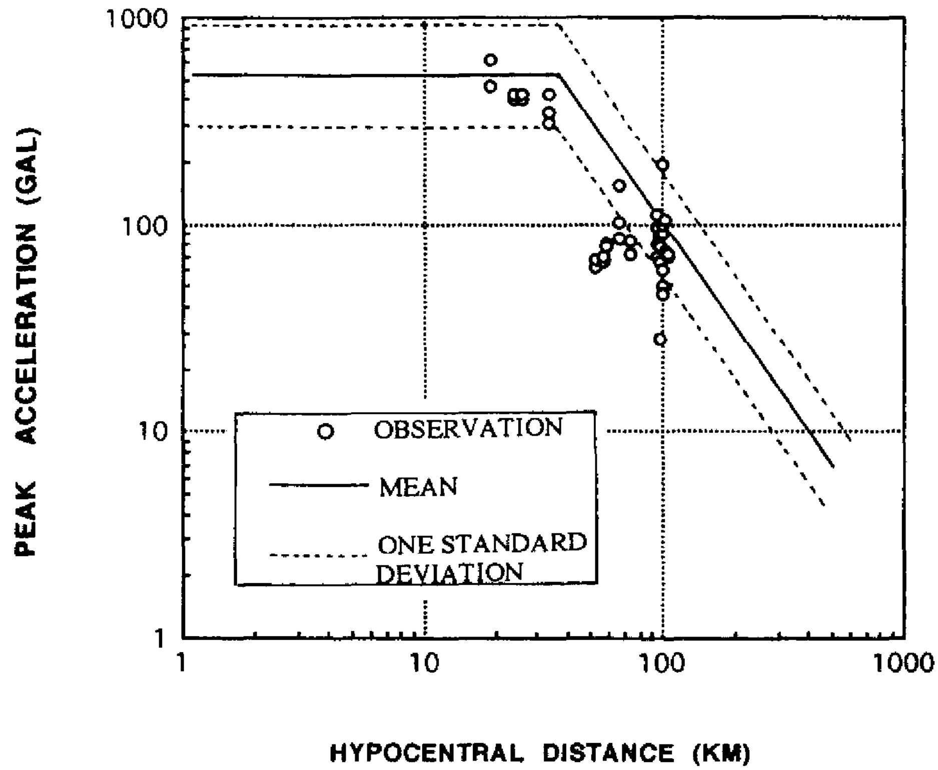

Fig.8-1 Comparison of Peak Acceleration at Rock Sites for the 1989 Loma Prieta Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=7.0

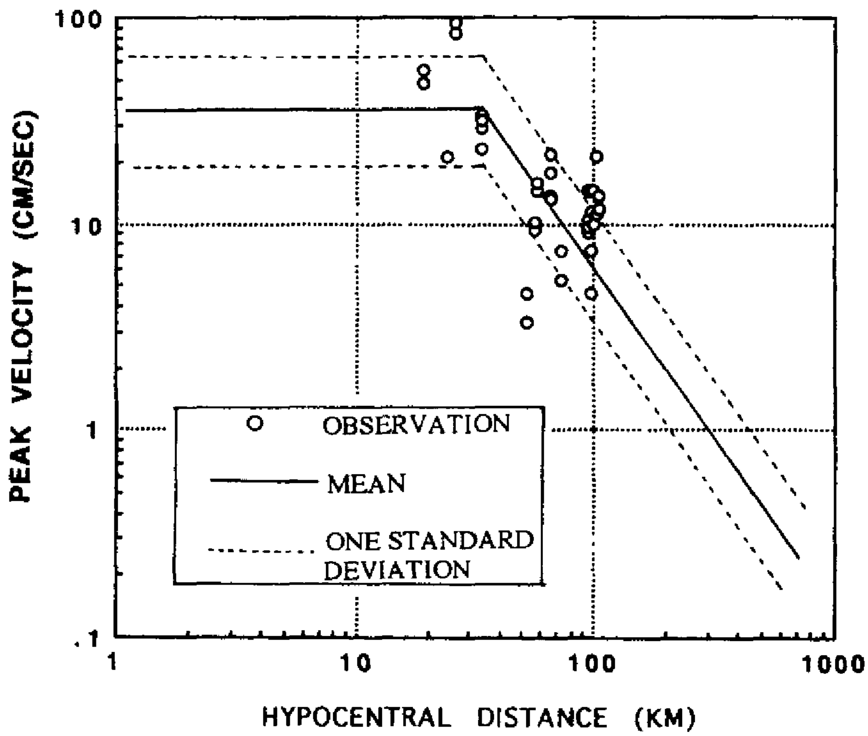

Fig.8-2 Comparison of Peak Velocity at Rock Sites for the 1989 Loma Prieta Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=7.0

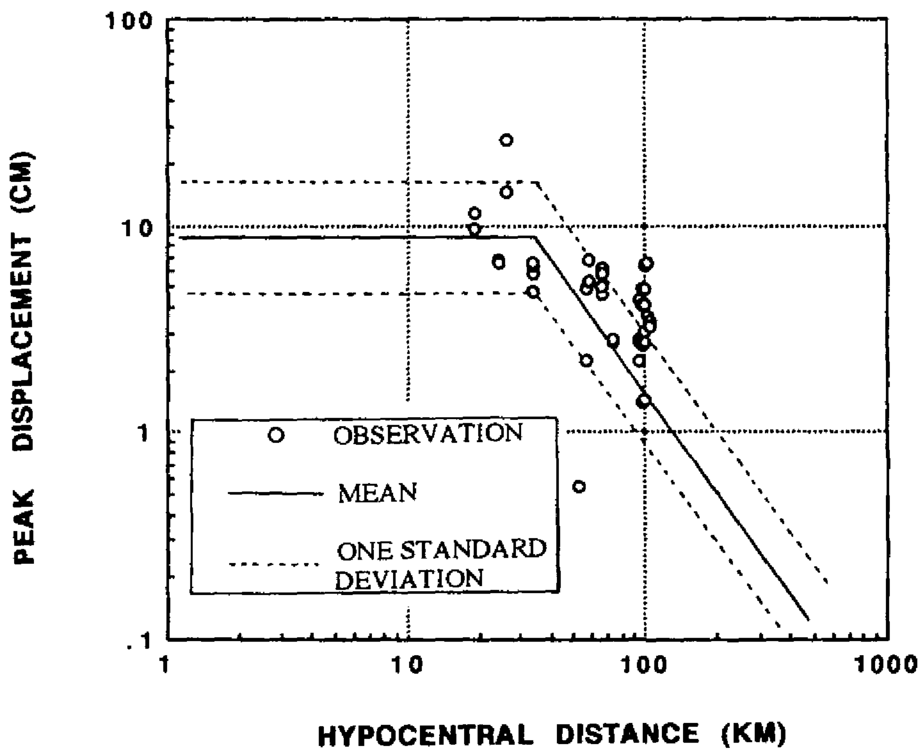

Fig.8-3 **Comparison of Peak Displacement at Rock Sites for the 1989 Loma Prieta Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=7.0**

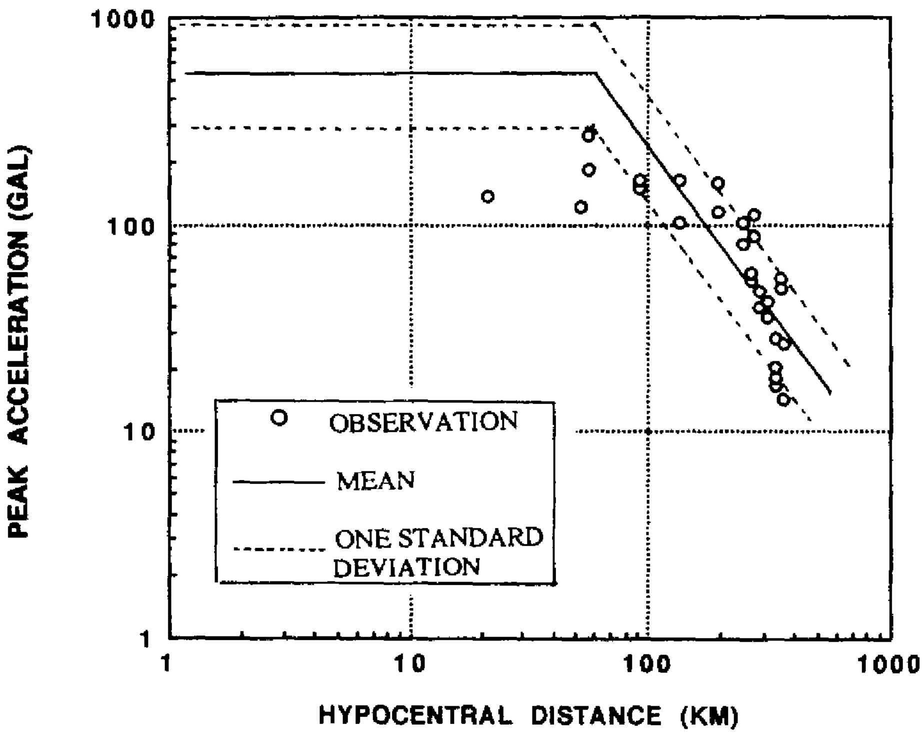

Fig.8-4 Comparison of Peak Acceleration at Rock Sites for the 1985 Michoacan Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=8.1

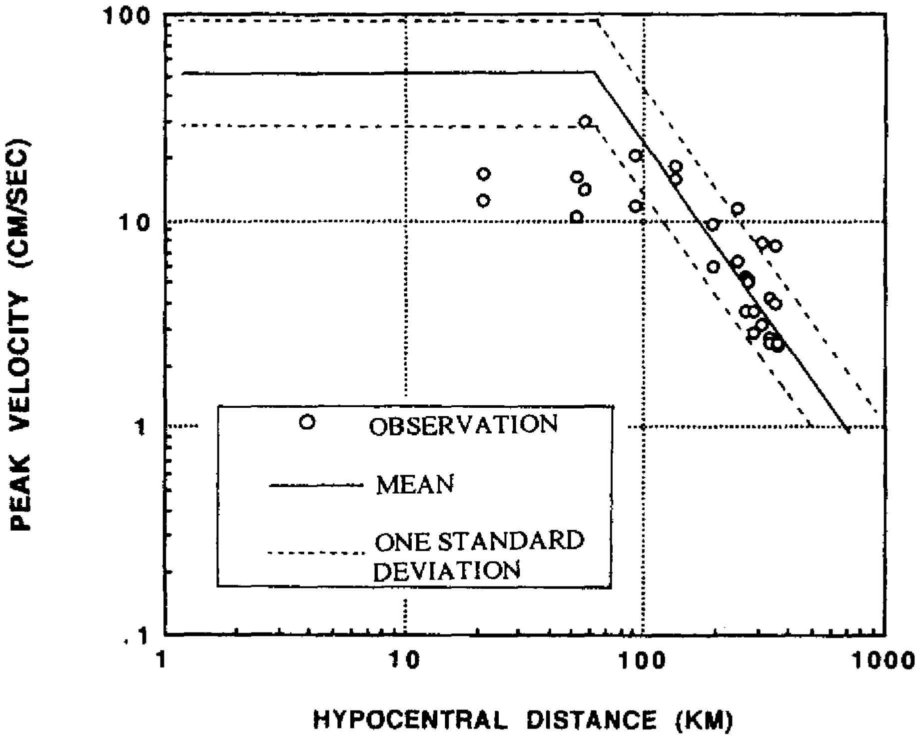

Fig.8-5 Comparison of Peak Velocity at Rock Sites for the 1985 Michoacan Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=8.1

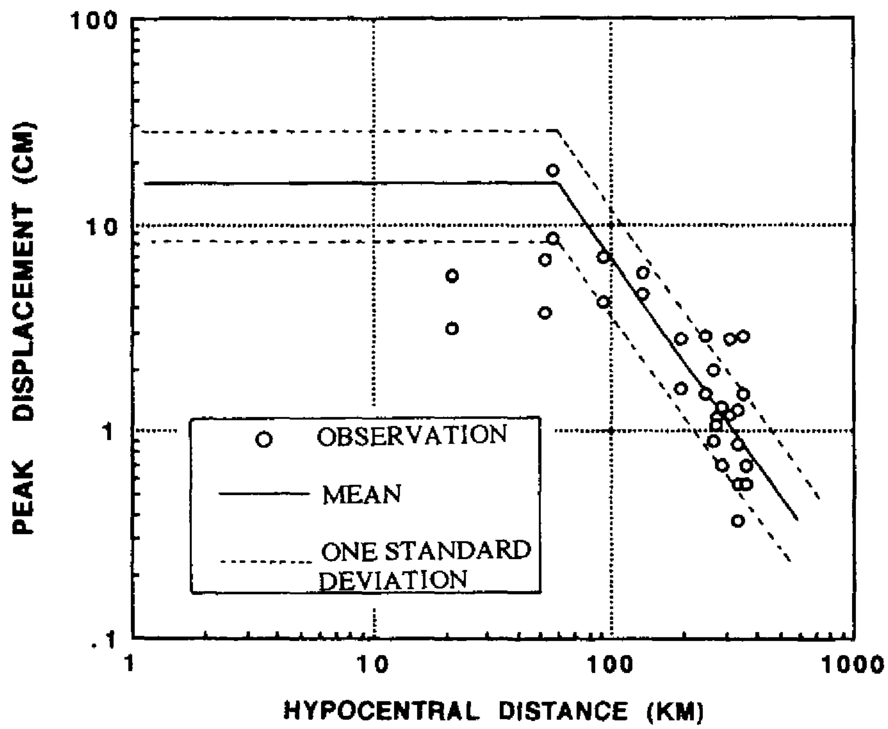

Fig.8-6 Comparison of Peak Displacement at Rock Sites for the 1985 Michoacan Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=8.1

8.3 1971 San Fernando Earthquake

The 1971 San Fernando earthquake was a major source of data for empirical analyses of strong motions by other researchers. This is particularly true for the U.S. empirical expressions discussed in Section 7. Hence a comparison of this earthquake data with the proposed semi-empirical model is meaningful. The strong-motion data and site geological information for this earthquake were taken from a Caltech report[35] General information for the earthquake is:

Epicenter : 34.40 N, 118.43 W
Depth: 13 km
Magnitude 6.6 (ML)

Taking the Richter magnitude ML as being identical to the JMA magnitude, the peak motion values for the earthquake were estimated by the proposed model using Eqs.(5-1) to (5-6) with $\mathbf{AMP_i} = \mathbf{1.0}$ and compared with the observed peaks at rock sites and nearly rock sites, as shown in Figs. 8-7 to 8-9. It is obvious in Fig.8-7 that the proposed model gives systematically larger acceleration peaks than were observed, whereas a relatively good agreement is found in the cases of velocity and displacement shown in Figs.8-8 and 8-9. It is beyond the scope of this study to explain such differences. However the consistency between the predicted and observed peak velocities lends additional support for our model because we are primarily interested in the prediction of peak velocity.

8.4 Discussion

Among the comparisons shown in Figs.8-1 through 8-9, the observed velocity motions for the three earthquakes match best the predicted values from the proposed semi-empirical model. Except for the observed near field values for the 1985 Michoacan earthquake, the proposed model for peak velocity could serve as a statistical prediction method. This is desirable because the primary goal of this study is to develop an empirical model for estimating peak velocity in connection with the seismic performance of lifelines. In the case of peak acceleration, on the other hand, the observed values for the 1971 San Fernando earthquake are systematically smaller than the predicted values despite relatively good agreement of the predicted values with the observed values for the other earthquakes. However, since the 1971 San Fernando earthquake gives a similar trend in the peak velocity comparison, the systematic difference for the acceleration comparison may be due to the peculiarity of the earthquake. For peak displacement the predicted values for the three earthquakes agree relatively well with the observed values although one may have expected difference due to the different filters used to numerically obtain displacement records. We can see

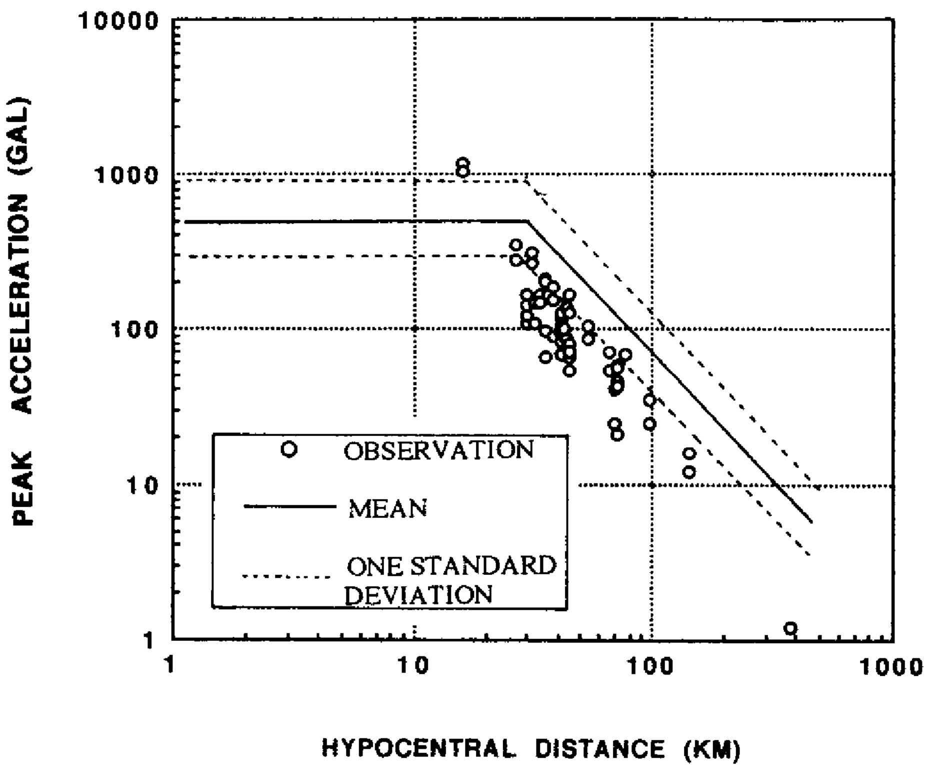

Fig.8-7 Comparison of Peak Acceleration at Rock Sites for the 1971 San Fernando Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=6.6

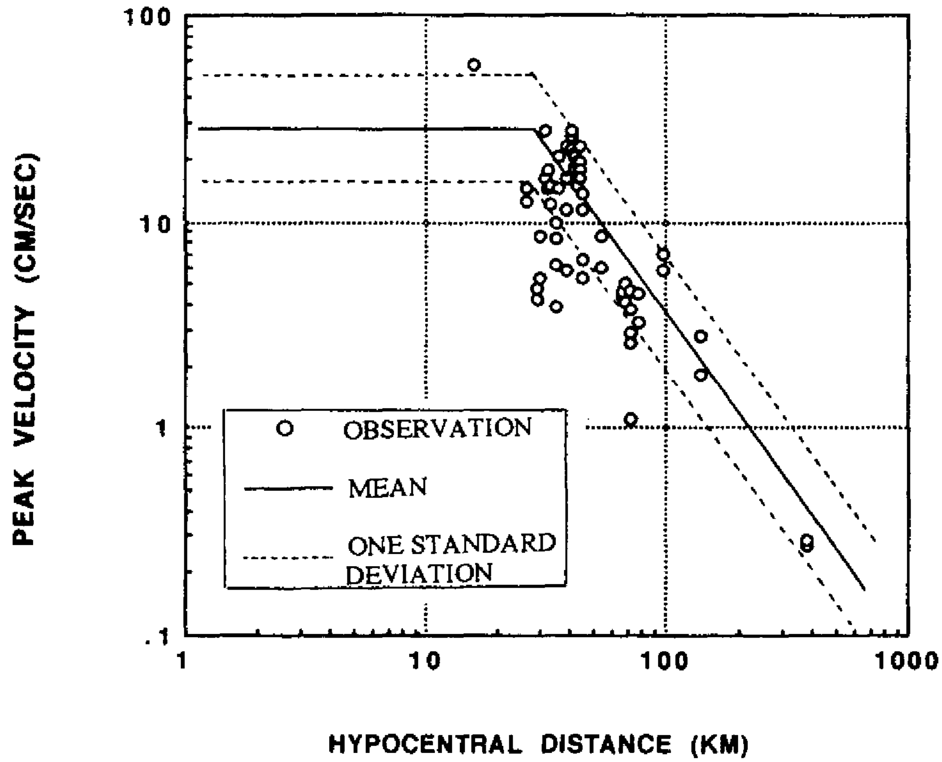

Fig.8-8 Comparison of Peak Velocity at Rock Sites for the 1971 San Fernando Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=6.6

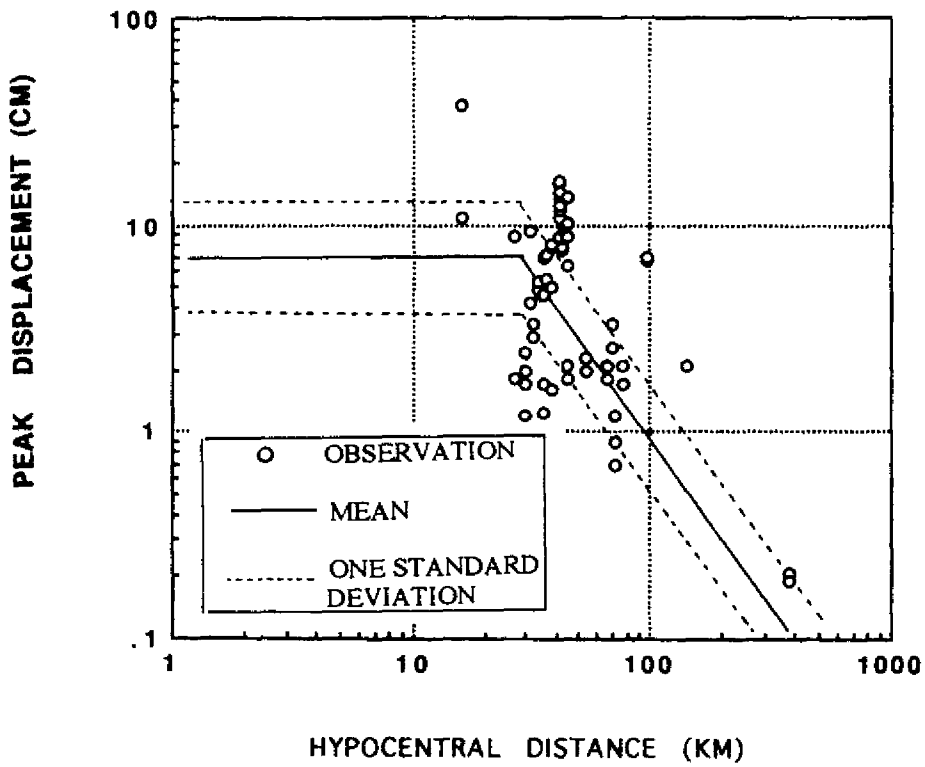

Fig.8-9 Comparison of Peak Displacement at Rock Sites for the 1971 San Fernando Earthquake with Value Predicted by the Proposed Semi-Empirical Model for M=6.6

from the overall comparisons in Figs.8-1 through 8-9 that the present model is applicable to various types of earthquakes. It should be emphasized that the proposed semi-empirical model was based only on earthquake data obtained in Japan. This suggests that earthquakes share a similar attenuation law for strong-motion peaks irrespective of their country of origin.

The observed values in Figs.8-1 through 8-9 were chosen regardless of the detailed material characteristics of rock partly because of a lack of information. On the other hand, the predicted values for the proposed model are estimates for the seismic bed rock which was defined based upon the renovation of the amplification factors. In spite of such variation in the definition of rock the predicted and observed values agree reasonably well. Hence the definition of rock can presumably be flexible for peak value prediction, particularly peak velocity prediction as opposed to spectra and time history predictions.

In this section, we have compared the proposed semi-empirical model, which was based on Japanese data, with earthquakes in the U.S. and Mexico. It is also illustrative to compare the existing U.S. empirical attenuation relations, which were based on U.S. data composed primarily of the 1971 San Fernando data, with the more recent 1989 Loma Prieta and 1985 Michoacan data. Fig.8-10 shows a comparison of the predicted values from Trifunac[12] and McGuire[26] with the observed values for the 1989 Loma Prieta event (M=7.0). Both predicted and observed values are plotted in terms of epicentral distance. We can see from a comparison between Fig.8-2 and Fig.8-10 that Trifunac[12] and McGuire[26] do not give better estimates for the observed values of the Loma Prieta event than the proposed model even though the McGuire estimates are fairly consistent. The predicted values from Joyner and Boore[27], Campbell[28] and Sabetta[29], which use closest distance to fault rupture to characterize source-to-site distance, are compared with the observed values from the Loma Prieta event in Fig.8-11. Note in Fig.8-11 that these three empirical relations underestimate the observed values in the Loma Prieta event. Hence although the existing U.S. empirical attenuation relations are based primarily on U.S. data and in some cases use fairly sophisticated measures for site-to-source distance, they do not provide significantly better estimates for observed peak velocity on rock and in some cases (Fig.8-11) provide significantly worse estimates. A similar comparison for the 1985 Michoacan earthquake (M=8.1) is illustrated in Figs.8-12 and 8-13. Fig.8-12 is a comparison between the observed values for peak velocity at rock sites from the 1985 Michoacan event and the empirical estimates by Trifunac[12] and McGuire[26]. A comparison between Fig.8-5 and Fig.8-12 shows that Trifunac[12] and McGuire[26] give worse estimates than the proposed model for the 1985 Michoacan event. Fig.8-13 compares the observed peak velocities with the empirical estimates from Joyner and Boore[27], Campbell[28] and Sabetta[29] in terms of closest distance to fault

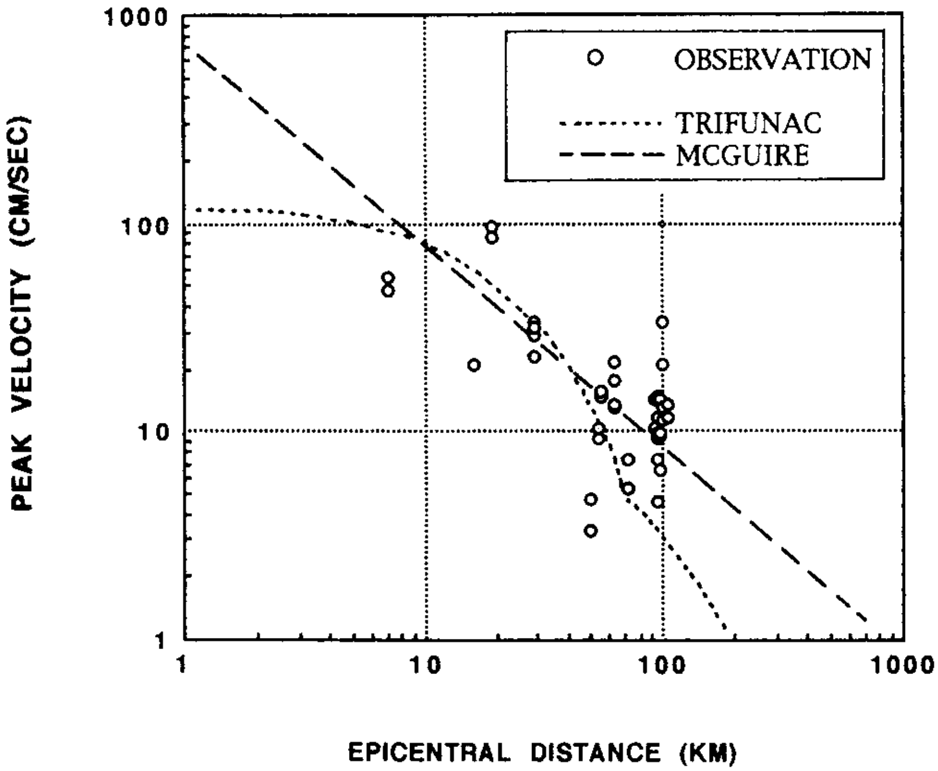

Fig.8-10 Comparison of Observed Peak Velocity at Rock Sites for the 1989 Loma Prieta Earthquake with Empirical Estimates for a Magnitude 7.0 Event by Trifunac and McGuire

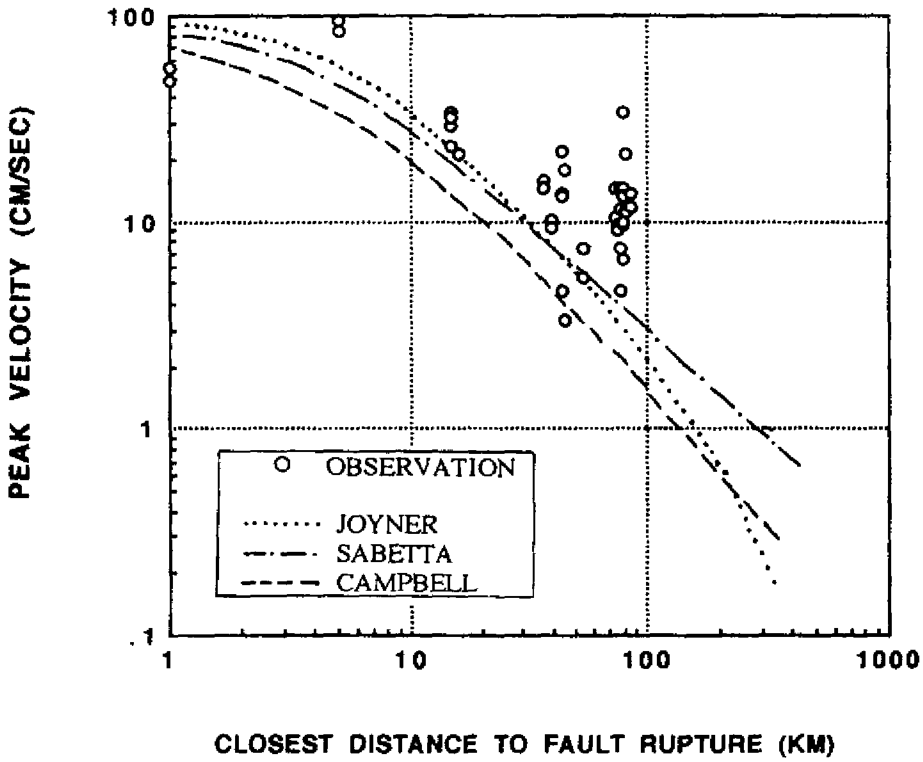

Fig.8-11 **Comparison of Observed Peak Velocity at Rock Sites for the 1989 Loma Prieta Earthquake with Empirical Estimates for a Magnitude 7.0 Event by Joyner and Boore, Campbell and Sabetta**

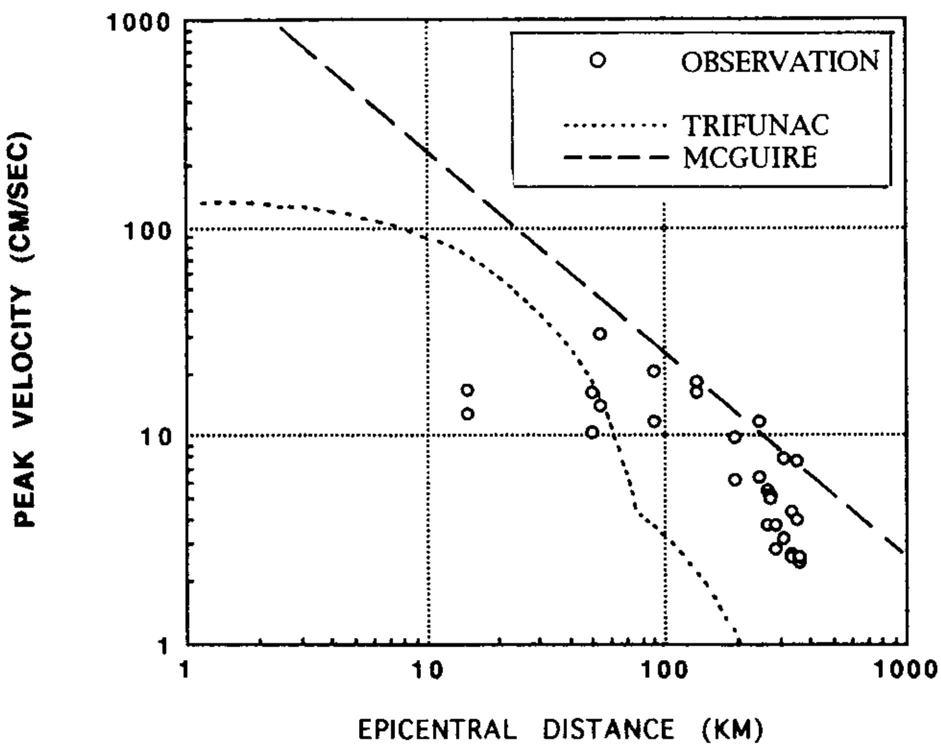

Fig.8-12 Comparison of Observed Peak Velocity at Rock Sites for the 1985 Michoacan Earthquake with Empirical Estimates for a Magnitude 8.1 Event by Trifunac and McGuire

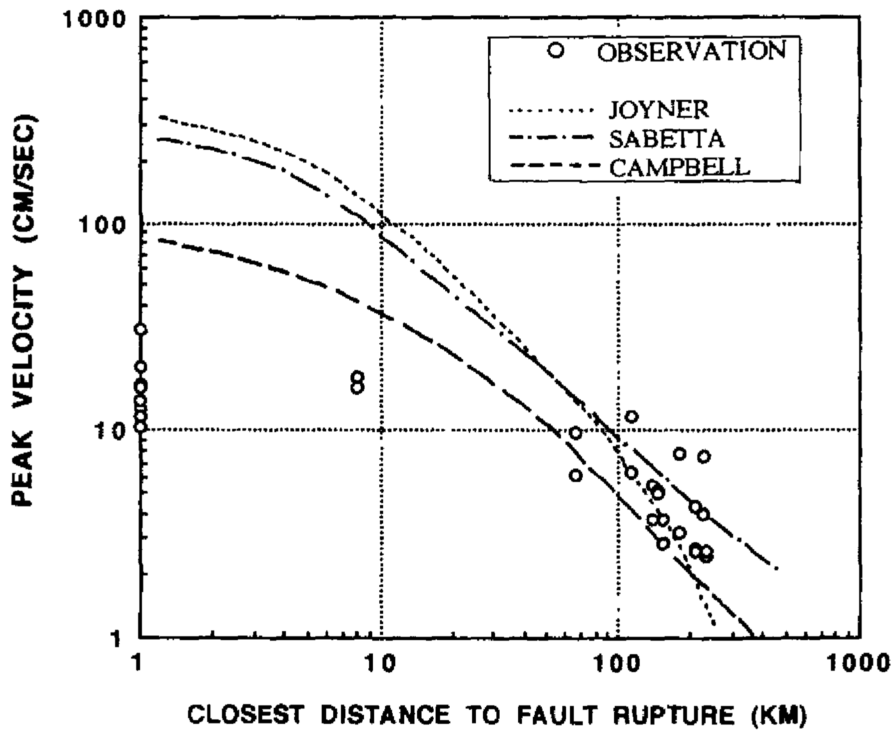

Fig.8-13 Comparison of Observed Peak Velocity at Rock Sites for the1985 Michoacan Earthquake with Empirical Estimates for a Magnitude 8.1 Event by Joyner and Boore, Campbell and Sabetta

rupture. In this figure, the observed values in the fault area are plotted with distance=1 km. Note that the predicted values are good for distance greater than about 80 km but significantly overestimate the observed values at short distances. Hence it is concluded from these comparisons that the existing U.S. empirical relations do not provide more reasonable estimates of peak velocity than the proposed model.

As shown above, the proposed semi-empirical model appears superior to presently existing empirical relations. However there is disparity between the observed and predicted values for the model. The disparity is attributable to several reasons including incompleteness of the model and the peculiarities of each earthquake. Some of the incompleteness result from the simplification of the proposed model being developed for engineering application. In particular, the proposed model does not consider the faulting process at the seismic source which affects peak values of strong motions. Regarding the peculiarities of each earthquake, characteristic scatter of observed peak values is often discussed based on the polarization of the azimuth from seismic focus to observation sites. Such polarization is associated with the rupture directivity of faulting. This suggests that the effects of rupture directivity can explain some of the scatter of observed values about the semi-empirical model. For example, Fig.8-14 shows the observed values of peak velocity at rock sites during the 1989 Loma Prieta earthquake for the sites south and north of the epicenter. Note that the sites situated south of the epicenter generally have smaller peak values than those north, implying that a characteristic rupture directivity of the earthquake influences peak values at each observation site. The effects of rupture directivity are easy to grasp if the rupture is assumed to progress in a uniform manner as illustrated in Fig.8-15. Assuming a unilaterally uniform rupture directivity, Hirasawa and Stauder[36] has shown that amplitude coefficient is given as a function of the azimuth angle ψ by

$$\frac{1}{1-\frac{v}{\beta}\cos\psi} \qquad (8.1)$$

where **v** is the rupture propagation velocity and β is the shear wave velocity.
Eq. (8.1) explains the well-known phenomenon that the amplitudes of motions are larger at sites located in the direction of the rupture progress.

Now assuming that the case of $\psi = \frac{\pi}{2}$ in Eq.(8.1) is equivalent to the mean value estimated by the proposed semi-empirical model as well as assuming $\frac{v}{\beta} = 0.8$, we obtained expected scatters on the basis of the directivity effect. Such upper and lower bounds for predicted value are drawn

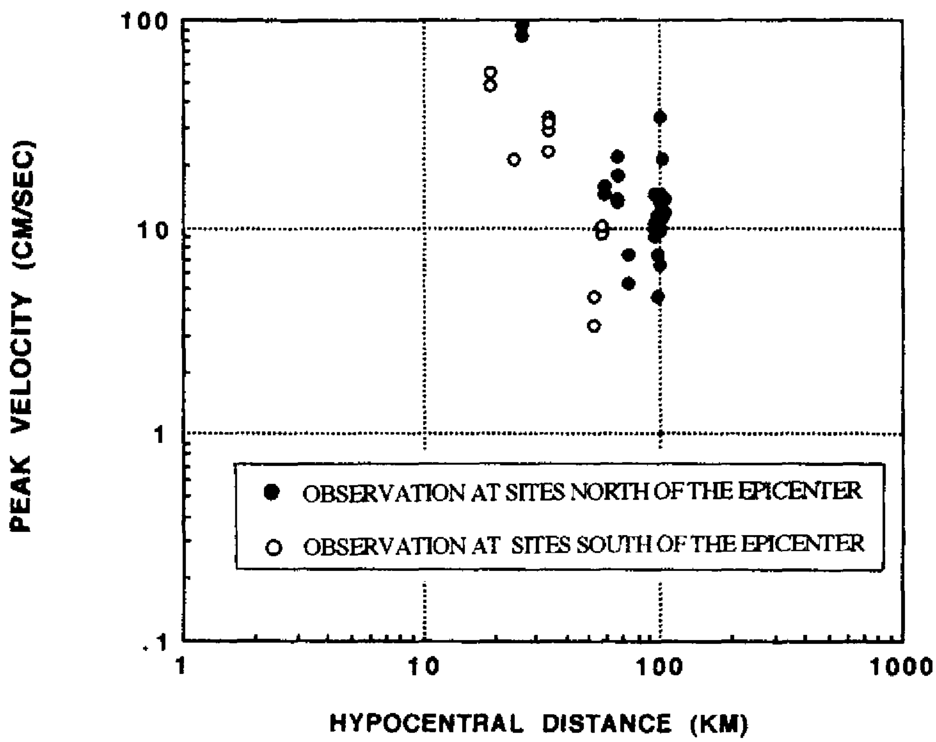

Fig.8-14 Peak Velocity at Rock Sites North and South of the Epicenter, Loma Prieta 1989

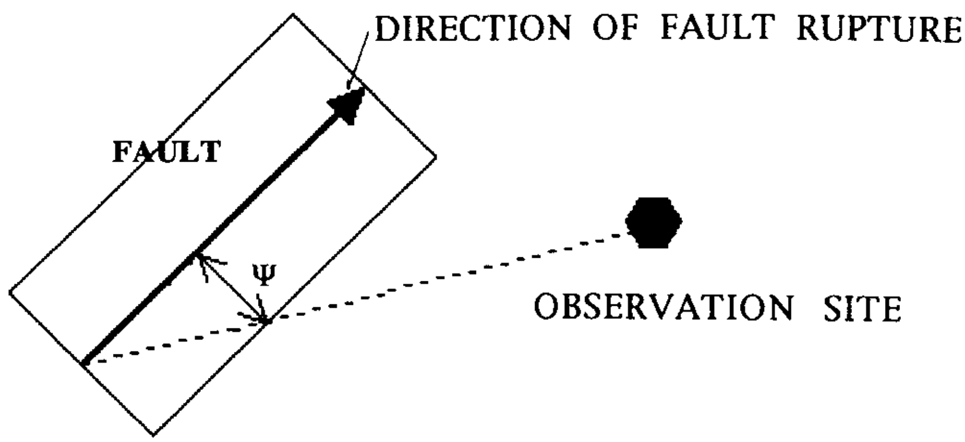

Fig.8-15 Sketch showing Azimuth Angle for an Arbitrary Observation Site with Respect to the Direction of Fault Rupture

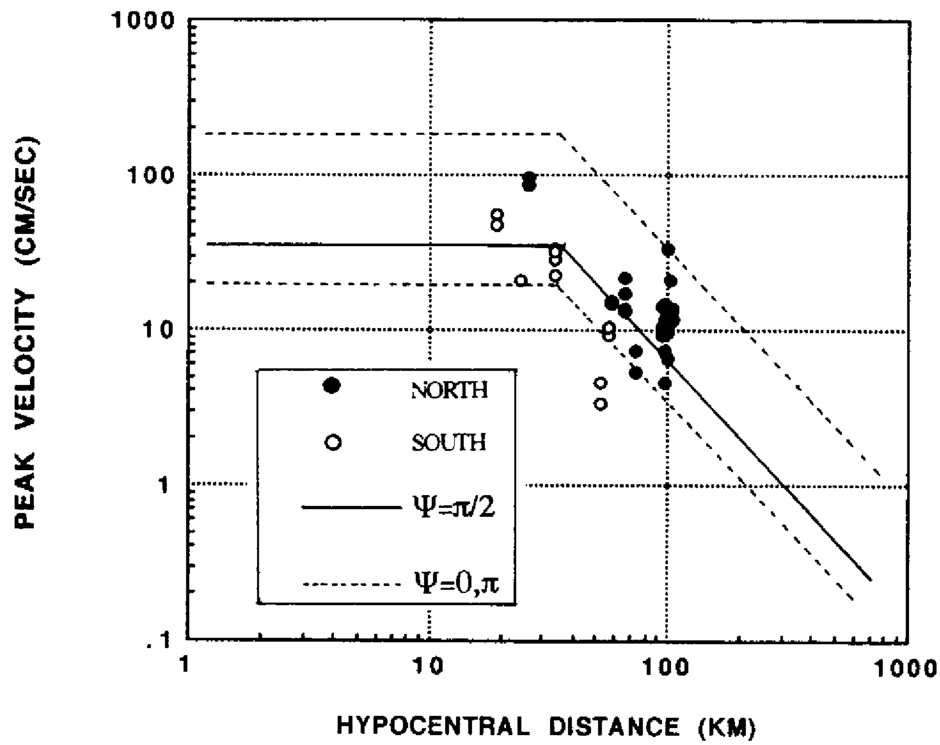

Fig.8-16 Peak Velocity at Rock Sites for the Loma Prieta Event with Scatter Bands Based upon Rupture Directivity in Fig.8-15

in Fig.8-16 together with the mean prediction value. This figure shows that the scatter of observed values about the predicted value from the proposed model, at least for the case of peak rock velocity from the 1989 Loma Prieta event, is explained by fault rupture directivity effects. However fault rupture directivity is not included in the proposed model because it is not known a priori.

As mentioned in **Section 2**, we derived our semi-empirical model of strong-motion peaks based on the assumption that peak acceleration in a fault zone is independent of earthquake magnitude. The validity of this assumption can be judged by a comparison between the predicted and observed values. However the comparisons shown in Figs.8-1, 8-4 and 8-7 are not enough to judge the validity because observed data within the fault zones are few. We need more strong-motion records observed on rock sites in a fault zone having different size to finally judge our assumption.