A STATISTICAL EVALUATION OF STRONG MOTION DATA INCLUDING THE FEBRUARY 9, 1971 SAN FERNANDO EARTHQUAKE

by

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SYNOPSIS

The 1971 San Fernando earthquake allows a direct statistical study of an attenuation relationship for a single event. This attenuation relationship is explored and the effects of site conditions on attenuation are shown. The data are compared with published attenuation relationships. A data set of 670 strong motion acceleration values from international records was compiled and examined to estimate the effects of magnitude on the attenuation relationships. A relationship derived from this data is shown to produce numerical values similar to an acceleration attenuation relationship proposed by Nuttli for the eastern United States based on historical and instrumental seismological data.

INTRODUCTION

The attenuation of ground motion with distance is of major engineering importance and has been studied in several different ways. Because peak acceleration is the most readily available instrumental data value from presently used strong motion instruments, most studies have been based on the attenuation of peak acceleration values. The single peak acceleration value alone is not an effective measure of the damaging potential of an earthquake. When the estimated mean value of the peak acceleration is combined with other parameters, such as the size of the earthquake expressed in energy or magnitude terms, the duration, and the frequency distribution of energy within the motion, a reasonable description of ground motion is obtained.

The expected mean value of the peak acceleration referred to here must be distinguished from the extreme value of peak acceleration. A study of extreme values among data sets without considering their relation to the statistical means is of little use in seismic risk studies. As the data set enlarges, the probable individual extreme value increases continuously, while the expected mean value becomes more stable. Extremes of acceleration at very high frequencies which will not have engineering significance may be expected. This study has considered data from a wide variety of sources to estimate the attenuation of the mean peak acceleration with distance and some of the statistical parameters associated with the mean relationship.

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DATA SOURCES

The 1971 San Fernando earthquake has gained considerable notoriety for the few exceptionally large instrumental acceleration values obtained. The fact that this was the first single event which produced sufficient instrumental records over a wide enough range of distances to enable a statistical analysis of attenuation with distance, has not been widely realized. For this single event, the attenuation effects with distance can be examined independently of the magnitude and source mechanisms. The data set assembled from the 1971 San Fernando earthquake for this study used the peak acceleration values presented by Maley and Cloud (1971), and the distances to the energy center in kilometers computed by Duke et al (1972). Where known, the distance to the energy center is considered a better measure of distance for moderate sized earthquakes than the closest distance to the causative fault. For large events where a fault-rupture of many tens of kilometers is involved, the closest distance to the fault may be more appropriate.

The San Fernando data are representative of only one event. Strong motion records have been obtained at a steadily increasing rate since 1933. The acceleration data available at the present time are extensive, but exist only in widely scattered sources. The largest portion of the data set was obtained from instruments in Western North America, where the major historical concentration of strong motion instrumentation has been located. The set also contains more than 100 values obtained from published records of Japanese earthquakes. A small number of records from the Papua-New Guinea area provide data for another geographic region. The total list contains 678 strong motion acceleration values of which 214 values are from the 1971 San Fernando earthquake.

The data set is believed to contain most of the data which are available for accelerations greater than 50 gals, with the exception of recent small events of magnitudes less than 5 which have produced large accelerations. The data set is not considered exhaustive for small accelerations of less than 50 gals. A representative sampling of these more widely available smaller values was included.

The distribution of acceleration values within the data set is as follows:

Greater than 300 cm/sec^2	17
200 - 300 cm/sec^2	40
150 - 200 cm/sec^2	59
100 - 150 cm/sec^2	82
50 - 100 cm/sec^2	121
10 - 50 cm/sec^2	206
Less than 10 cm/sec^2	153
TOTAL	678

1971 SAN FERNANDO EARTHQUAKE

Statistical analyses of the February 9 San Fernando strong motion data have been presented elsewhere (Duke et al, 1972; Liu, 1972). Duke chose an attenuation relationship containing an exponential distance factor representing material damping together with a reciprocal factor to account for geometrical spreading. Liu used the relationship of the general form after Esteva and Rosenblueth (1963)

$$y = b_1 e^{b_2 m} R^{-b_3} \qquad (1)$$

where y is the acceleration in gals, m is the instrumental magnitude, R is the distance to the source in kilometers, and b_1, b_2 and b_3 are constants. Liu did not classify the data to include site characteristics. Equations of a form similar to (1) are readily suited to least squares fitting procedures. Of the 214 instrumental records of peak accelerations in the data set of the San Fernando earthquake equal to or greater than 10 gals, 56 values were recorded on rock sites or rocklike sites with very shallow soil cover. The distance exponential coefficient b_3 for the rock and alluvial site data obtained by fitting the data to (1) were 1.65 and 1.32, respectively. The b_3 value for rock between 1.5 and 2.0 is similar to that deduced by Lastrico (1970) and Schnabel and Seed (1972).

Esteva (1970) suggested an empirical modification to (1) by the addition of a constant term, to give

$$y = b_1 e^{b_2 m} (R+25)^{-b_3} \qquad (2).$$

The constant term controls the maximum acceleration value at small distances and approximately models the varying distance exponential suggested by fault geometry at distances less than 100 kilometers. The computed acceleration values obtained by least squares fitting with either equation are quite similar except at small distances. Although empirical in nature, the constant factor used in (2) provides a closer fit to the actual recorded data than (1). The individual data points are shown on Figure 1 together with dotted lines showing the fitted relationships for the two site classification groups using (2), and dashed and solid lines for the fitted relationships for the total San Fernando data set using (1) and (2) respectively. The slower attenuation of acceleration with distance on alluvial soil sites is readily apparent together with the smaller values of expected peak acceleration on soil sites when the distance to the energy center is less than 60 kilometers. The 1971 San Fernando earthquake strong motion data provides the first direct statistical evidence of the effects of site conditions in modifying ground motions. This reversal of the expected maximum values between the two types of sites with decreasing acceleration has been anticipated by soils engineers. The different attenuation relationship is a direct example of the effects of the nonlinearity of the dynamic response of soils. At large acceleration levels, higher damping and lower strength values reduce the level of motion transmitted in soils. This relationship which changes with differing motion levels prevents the extrapolation of measured site response during small earthquakes to estimate the response to large earthquakes.

Gumbel (1958) suggested a simple means by which the distribution of the residuals about the mean relationship could be approximated. This procedure consists of dividing the measured value by the computed value, sorting the resulting values into order and then providing a numerical probability value for each of the sorted values. The values can then be plotted on probability paper to graphically demonstrate the distribution of the residuals. A plot of the logarithm of the ratio for the total San Fernando data set plotted to a normal probability scale is shown on Figure 2. The standard deviation is 0.48. The linear relationship of the points to the probability paper scaling shown on Figure 2 suggests that the residuals of the data points about the computed mean relationships are well represented by a normal distribution. The normal distribution effects are more clearly demonstrated on Figure 3 by re-examining the data values when the mean curve is plotted with curves representing one and two standard deviations above, and below, the mean. It should be emphasized that these data are considered on a purely statistical basis without inclusion of the effects of special conditions which may increase or decrease the level of motion. The Pacoima Dam record therefore corresponds to a high level extreme value which has a very small probability of being exceeded. The use of extreme peak values as the basis upon which broad banded response spectra, of the type developed by Newmark and Hall (1969), are constructed as has been recommended by Page et al (1972), is not justified. The more significant quantities for engineering purposes are the mean relationship, which is representative of non-special site conditions, and the probable distribution of values about the mean. These quantities are believed to be the most appropriate values for engineering purposes, and can be readily used in seismic risk studies.

The San Fernando event also provides an excellent opportunity to compare acceleration attenuation relationships which have been published with the acceleration attenuation data from a single earthquake. This comparison is presented on Figure 4 for relationships obtained from eight separate sources. The wide variation is readily apparent. The mean relation for the recorded data from Figure 1 is also shown on Figure 4. Of the attenuation relations shown, the mean relationship is most closely approximated by the results of Schnabel and Seed (1972). This should be expected, however, as they based their results upon San Fernando data values. The relationship between the San Fernando attenuation data can be compared to the data sets obtained for other earthquake records on Figure 4 by the curve representing a least squares fit to equation (2), using all the data except the San Fernando with acceleration maxima exceeding 10 gals. The higher accelerations, at longer distances on the wide data set, are believed to be due to the inclusion of a wider variety of soil types, many of which are capable of amplifying lower levels of acceleration. Of special interest on Figure 4 is a curve developed by Nuttli (1973) estimating the attenuation of acceleration in Eastern North America. The similarity to the other curves based on Western North American data is surprising and will be considered in more detail later in this paper.

TOTAL DATA SET

The total data set requires the introduction of earthquake size into the attenuation relationship. The geometric effects of attenuation (Lastrico, 1970) when related to the size of fault rupture probably offers the most realistic approach to attenuation. The extent of fault rupture and its direction are rarely known however. As more extensive geologic and instrumental data become available in the future, the source mechanism may be included into attenuation relationships. The present study examines the interrelated effects of magnitude and distance on the attenuation of peak acceleration using the empirical equation (2). By using portions of the total data set, the interrelationships between distance and magnitude can be examined.

The values in the full data set are shown on Figure 5 where the peak accelerations are plotted against distances. The magnitude of the data value is indicated by the numerical symbol used to display the point. The envelope curve suggested by Cloud and Perez (1971) is shown as a lightly dotted line. A least squares fit to the data set with magnitude not considered is also shown. To directly illustrate the effects of what is believed to be soil modification of the motion at low strain levels, the least squares relationship derived from the San Fernando data is also shown on Figure 5. The San Fernando data set does not contain values recorded on saturated soils and the attenuation is therefore more rapid. Soil modification suggests that attenuation with distance is much lower than is expected for the physical mechanisms producing earthquakes and the geometric spreading of the seismic energy. A statistical sample also becomes biased to the larger values when the mean value is small because instruments at sites where motion was not great enough to produce triggering do not become part of the data set.

By considering portions of the data set, some distinct trends can be noticed. There is not sufficient space to describe these in detail so the results will be presented very briefly. For values recorded close to the source of the earthquake the maximum acceleration is very weakly related to magnitude. High peak acceleration values close to the source may be expected in suitable circumstances from even moderate earthquakes. The correlation of the mean peak acceleration with magnitude increases with increasing distance from the source. The magnitude exponential, constant b_2 in equation (2), increases from 0.3 to 0.6 as the acceleration values included in the least squares procedure are extended to include smaller and smaller numbers. Similarly, the constant b_3 in equation (2) increases as the acceleration values included are extended to include larger distances from the source. The combination of these two effects show that magnitude and distance cannot be considered as independent variables in an attenuation relationship. Attenuation comparisons between magnitude at distance cannot be extrapolated to distances close to the source.

In Figure 6 the distribution of the residual values obtained following fitting of the data using equation (2) with a b_2 coefficient of 0.5 is shown. The linear relationship with the data set including values of acceleration exceeding 10 gals is still evident even though the standard deviation has increased to 0.71. The attenuation equation obtained is

$$y = 1080\ e^{0.5m}\ (R+25)^{-1.32} \qquad (3).$$

This curve represented by equation (3) is shown with normalized acceleration data points on Figure 7. Equation (3) represents a conservative estimate of mean peak acceleration on sites with 20 feet or more of soil overlying the rock. It was shown on Figure 1 that rock surface acceleration attenuates more rapidly with distance. This differing rate of attenuation is a combination of the inability of soils to transmit high frequency acceleration maxima and the ability of soils to modify and possibly amplify low levels of acceleration.

By a very thorough review of old newspaper and other records relating to the Mississippi Valley earthquakes of 1811 and 1812, Nuttli (1973) has been able to reconstruct the isoseismic information for the first major event on December 16, 1811. Using a comparison of this information with seismic instrumental data from recent smaller earthquakes in the area, Nuttli has estimated attenuation relationships for velocity and acceleration in Eastern North America. These values are shown on Figure 8 for 0.3 second, 1.0 second and 3.0 second period Rayleigh waves attenuating from an event with a magnitude equal to that inferred for the December 16, 1811 event (m_b = 7.2). The attenuation curve using equation (3) for the same magnitude is also plotted on Figure 8. Except for the zone close to the source, the similarity between the curves is remarkable. The assumption of a point source for the Nuttli relationships and the neglect of body wave effects are the reasons for the divergence in the near-field region.

The comparison between the curves on Figure 8 where two separate seismic regions are involved is superior to that between most of the curves shown on Figure 4. The data by Nuttli suggests that the attenuation of acceleration with distance is the same in Eastern and Western North America. The greater areas of damage for similar magnitude events in the Eastern United States reaffirms the statement made in the introduction, that acceleration values when used alone are not an effective parameter for describing the damaging effects of earthquakes. Higher particle velocities and longer durations of shaking are believed to be the reasons for these greater damage areas.

CONCLUSIONS

From the results of these studies the following conclusions were obtained:

1. It is possible to observe some of the effects of site geology on ground motion using direct statistical procedures;
2. The scatter of individual acceleration data points about the mean is large enough to disguise the difference between differing site conditions when statistical techniques are not used;
3. Extreme values of ground acceleration may occur under special conditions. These will usually be at high frequencies and not of special engineering significance;
4. Magnitude and distance are dependent variables and difficulties will always occur in attenuation relationships where they are considered to be independent; and,
5. Acceleration attenuation is similar in Eastern and Western North America. Other seismic parameters control the inconsistencies between the isoseismic area effects in the two regions.

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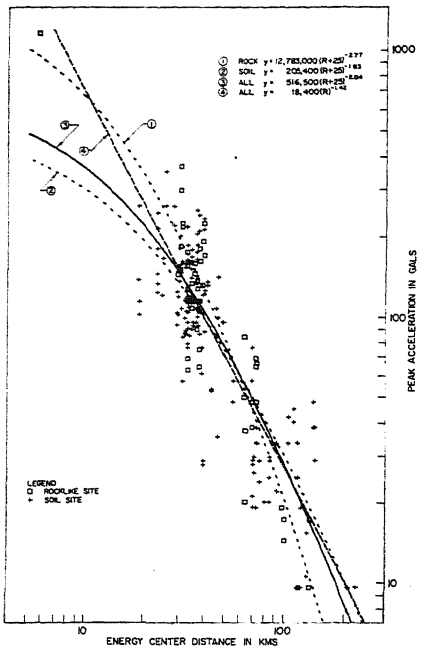
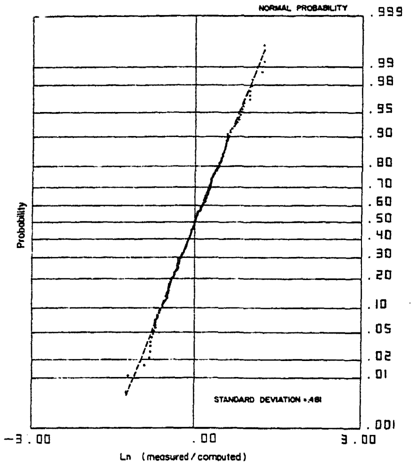
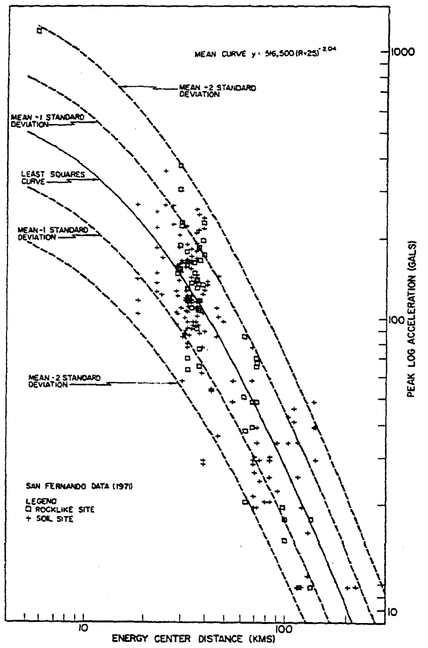


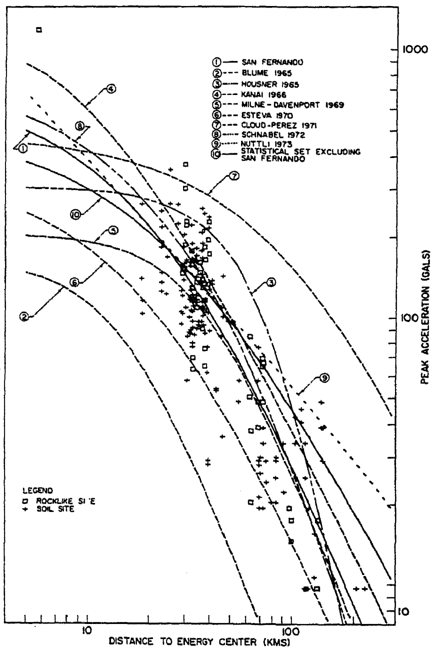
LEAST SQUARES
FIT TO PEAK GROUND ACCELERATIONS
FEBRUARY 9, 1971 SAN FERNANDO EARTHQUAKE
FIGURE 1



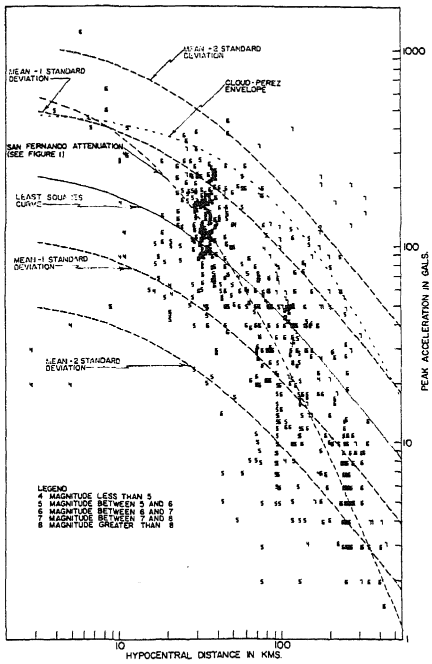
DISTRIBUTION OF
MEASURED / COMPUTED PEAK GROUND
ACCELERATIONS
FEBRUARY 9, 1971 SAN FERNANDO EARTHQUAKE
FIGURE 2



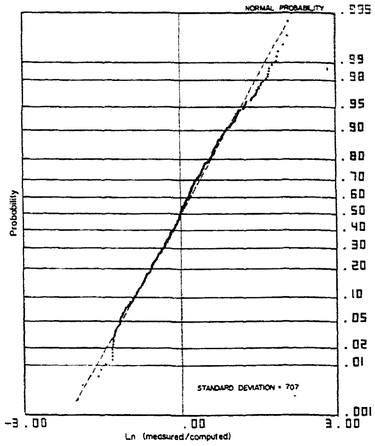
PEAK GROUND ATTENUATION
MEAN LEAST SQARES CURVE WITH ONE AND TWO
STANDARD DEVIATION RELATIONSHIPS FEBRUARY 9, 1971
SAN FERNANDO EARTHQUAKE
FIGURE 3



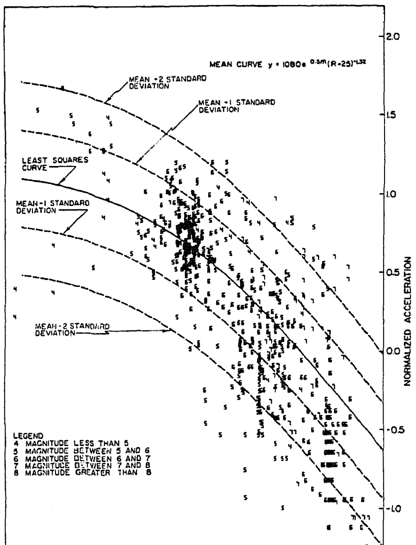
ATTENUATION EQUATIONS FOR MAGNITUDE 6.5
COMPARED TO DATA FROM STRONG MOTION STATIONS
RECORDING THE FEBRUARY 9, 1971 SAN FERNANDO EARTHQUAKE
FIGURE 4



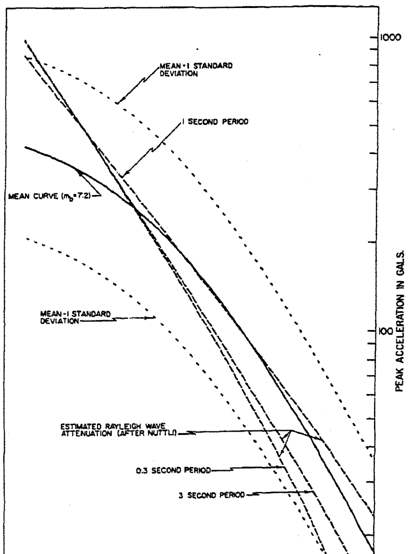
STRONG MOTION ACCELERATION
678 POINT DATA SET
FIGURE 5



DISTRIBUTION OF MAGNITUDE NORMALIZED
MEASURED/COMPUTED PEAK GROUND ACCELERATION
BASED ON 550 STRONG MOTION RECORDS
WITH PEAK ACCELERATION GREATER THAN 10 GALS.
FIGURE 6



STRONG MOTION DATA NORMALIZED BY MAGNITUDE
(DATA SET OF 678 VALUES)
FIGURE 7



ESTIMATED RAYLEIGH WAVE ATTENUATION
AND STRONG MOTION ATTENUATION
COMPARISON BETWEEN THE ESTIMATED RAYLEIGH WAVE ATTENUATION
OF THE DECEMBER 16, 1811 MISSISSIPPI VALLEY EARTHQUAKE
(AFTER NUTTLI) AND THE DERIVED STRONG MOTION ATTENUATION
FIGURE 8