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Correlations between Ground Motion and Building Damage

Engineering Intensity Scale Applied to the San Fernando Earthquake of February 1971

November 1977

Prepared under Contract EY-76-C-08-0099
for the Nevada Operations Office
United States Department of Energy

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Engineering Intensity Scale Applied to the San Fernando Earthquake of February 1971

by

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ABSTRACT

This study investigated the correlation between ground motion and building damage for the San Fernando earthquake of 1971. A series of iso-intensity maps was compiled to summarize the ground motion in terms of the Blume Engineering Intensity Scale (EIS). This involved the analysis of ground motion records from 62 stations in the Los Angeles area.

Damage information for low-rise buildings was obtained in the form of records of loans granted by the Small Business Administration to repair earthquake damage. High-rise damage evaluations were based on direct inquiry and building inspection. Damage factors (ratio of damage repair cost to building value) were calculated and summarized on contour maps.

A statistical study was then undertaken to determine relationships between ground motion and damage factor. Several parameters for ground motion were considered and evaluated by means of correlation coefficients.

It was found that the correlation between ground motion and damage factor for low-rise buildings was highest when the ground motion parameter was the first digit of the three-digit EIS intensity report. The following relationship was obtained:

$$\log(m_{DF}) = 8.86 \log(EI) - 7.94$$

with correlation coefficient, $\rho_{MD} = 0.614$

For high-rise buildings, the correlation was highest when the ground motion parameter was the second digit of the three-digit EIS intensity report. The high-rise relationship was found to be:

$$\log(m_{DF}) = 10.8 \log(EI) - 10.3$$

with correlation coefficient, $\rho_{MD} = 0.817$

INTRODUCTION

Background

This report is the result of a joint study by URS/John A. Blume & Associates, Engineers (URS/Blume), under the sponsorship of the United States Department of Energy, Nevada Operations Office (DOE-NV), and the Massachusetts Institute of Technology (MIT), under the sponsorship of the Earthquake Engineering Program of the National Science Foundation-Research Applied to National Needs (NSF-RANN). The low-rise building damage information ground motion data were analyzed by URS/Blume. High-rise damage data were analyzed by MIT.

The study is part of a continuing effort to improve techniques of predicting structural damage due to ground motion from either an underground nuclear explosion (UNE) or an earthquake. During URS/Blume's long-range research study in structural response for DOE-NV, various techniques for predicting damage were developed, including the Engineering Intensity Scale (EIS).[1] A basic objective of MIT's research program has been reduction of earthquake risk by acquiring new knowledge related to earthquake engineering.

Purpose and Scope

The purpose of this report is to quantify the relationship between ground motion, characterized by the EIS, and dollar damage to high-rise buildings (five stories or higher) and low-rise (one- and two-story) residential buildings. (Buildings of intermediate height were not considered.)

This report presents EIS ground motion intensities derived from strong ground motion records of the San Fernando earthquake from 62 instrument locations in the Los Angeles area. EIS intensities were calculated for the two period bands that correspond to the range of natural periods characteristic of low-rise and high-rise buildings. In addition, average envelope spectral acceleration values ($S_{\overline{ae}}$) were calculated for low-rise buildings.

An analysis of damage to low-rise buildings is presented. Relationships between this damage and the ground motion data are discussed and compared with previously reported results.

The EIS

The EIS was developed by Blume[1] to provide an estimate of the extent of area in which structures might be damaged from the effects of seismic ground motion. In addition, the scale is used to make a general evaluation of the incidence and degree of damage that structures might sustain. The scale is useful for evaluating both UNE- and earthquake-caused ground motions.

In the formulation of the scale, ground motion is characterized by 5%-damped spectral velocity (S_v), and structures are characterized by their fundamental mode vibration properties. Neglecting mode shape considerations, the important correlation variables for relating motion and damage are S_v amplitude and building period. The 5% damping value is used because damping in many real structures varies from about 2% to 10%; therefore, 5% has been made a standard reference level in the URS/Blume structural response program.

EIS numbers are assigned to various ranges of spectral velocity. The range of spectral velocities (S_v) and periods (T) applicable to civil engineering structures is divided into a 10 by 9 matrix, as shown in Figure 1. There are ten intensity levels, from 0 through 9, and nine period bands, I through IX, from 0.01 to 10 sec. Table 1 lists the 5%-damped S_v amplitude boundary values for the various intensity levels.

The EIS technique used for prediction of damage from a UNE or from an earthquake is a relatively simple three-step procedure. First, ground motion is predicted and expressed as 5%-damped spectral velocity. The second step consists of converting the S_v data to a 9-digit EIS report, each digit representing the intensity associated with a given period range.

Finally, relationships between the EIS values and structural damage are used to produce the damage estimate.

Damage to low-rise buildings has been shown to be related to an average value of spectral acceleration (S_a). This acceleration remains fairly constant at low-rise period values.[2] The average envelope spectral acceleration, $S_{\overline{ae}}$, was obtained by averaging the maximum horizontal component S_a

values for several periods. The relationship between this $S_{\overline{ae}}$ and low-rise building damage was compared to other EIS relationships.

GROUND MOTION ANALYSIS

The San Fernando Earthquake

The main shock of the San Fernando earthquake occurred at 06:00:41.7 PST, February 9, 1971. The California Institute of Technology (CIT) reported a Richter Magnitude of 6.6.[3] The epicentral location was near the Soledad Canyon fault in the San Gabriel Mountains (34° 24.0' N, 118° 23.7' W), about 3 miles north of Pacoima Dam. The earthquake resulted in 64 deaths and $0.5 billion damage to residences, commercial structures, and other engineered structures, including dams, railways, streets, bridges, and natural gas lines.

A statistical study was possible because of the large amount of available data. More strong ground motion records were obtained during this earthquake than for any previous single earthquake. In addition, damage data were available in the form of claims filed with the Small Business Administration for low-interest damage-repair loans.

The geographical area considered in this study, shown in Figure 2, consists of approximately 1,000 square miles comprising the metropolitan areas of Los Angeles and cities in the northwest portion of Orange County.

Recorded Accelerometer Data

At the time of the San Fernando earthquake, approximately 175 strong motion instruments had been installed in the Los Angeles area. These instruments were operated by what was then the Seismological Field Survey unit of the National Oceanic and Atmospheric Administration. These accelerometers were located both at the ground level and on various floors of high-rise buildings. Sixty-two ground stations recorded motion time histories, which were subsequently digitized and corrected.[4]

Five types of instruments recorded motion during the San Fernando earthquake: the Coast & Geodetic Survey Standard, the Victoria Engineering MO-2, the Kinemetric SMA-1, and Teledyne Geotech's AR-240 and RFT-250. The characteristics of these instruments are described in Reference 5. Three pairs of sample ground-level horizontal-component accelerograms from the San Fernando earthquake are shown in Figure 3.

Calculation of S_v Curves

Response spectrum velocity (S_v) curves were calculated from the ground motion histories by CIT,[4] first digitizing the raw ground motion data and then correcting them to eliminate high- and low-frequency errors and other errors caused by the digitization process. Spectral velocity, also known as pseudo relative response velocity, is related to the relative response displacement (S_d) of a single-degree-of-freedom oscillator as follows:

$$S_v = \left(\frac{2\pi}{T}\right) S_d$$

The relative displacement of a single-degree-of-freedom oscillator for a given natural period and critical damping ratio is the maximum relative response displacement of that oscillator responding to the earthquake base motion. A response spectrum curve is obtained by plotting the relative displacements as a function of natural period for a constant critical damping ratio. Response spectra corresponding to the accelerograms in Figure 3 are shown in Figure 4.

Calculation of EIS Values

The envelope S_v curve is the maximum of the two horizontal component spectral velocity curves at each period in the response spectrum. A graphic explanation of the envelope S_v curve is shown in Figure 5. EIS numbers are obtained by overlaying the 10 x 9 EIS matrix on the envelope S_v curves and selecting an average intensity number for each period band. An EIS matrix superimposed on the response spectra curves of the three example ground motion records is shown in Figure 6. Note that the envelope curve for each station is obtained from the maximum values of the two horizontal component S_v curves.

EIS reports of three digits are obtained from nine-digit reports by the averaging process demonstrated in Table 2 for the ground motion station at Pacoima Dam. The nine-digit report is divided into three groups of three digits. The average of the first three digits, rounded to the nearest whole integer value, then becomes the first number of the three-digit report, and so on for the other two groups of digits. Similarly, a one-digit report is obtained by averaging the digits of the three-digit report. The use of a minus sign, a plus sign, or no sign at all increases the number of possible values for a one-digit report from 10 to 30.

The nine-, three-, and one-digit EIS reports for the envelope S_v curves corresponding to the 62 stations in this analysis are summarized in Table 3.

Preparation of EIS Maps

The street addresses of the ground motion stations are listed in Table 4 and plotted on an outline map of the Los Angeles area in Figure 7.

The EIS numbers corresponding to several different period bands of interest were taken from the envelope S_v curves and plotted on maps of the analysis area. Contours (iso-EIS lines) were drawn between points of equal EIS intensity with the assumption that EIS values varied linearly between data points.

The five iso-EIS maps constructed in this manner are shown in Figures 8 through 12. Figures 8, 9, and 10 display iso-EIS maps for each digit of the three-digit EIS reports. For example, Figure 8 shows the contours produced for the average EIS value in period bands I, II, and III.

Figures 11 and 12 were prepared to correspond more closely to the periods of low-rise and high-rise buildings, respectively. Analysis of the latter representations was included to determine if damage is more highly correlated with them than with the standard EIS period band groupings. Figure 11 shows contours of the average of EIS bands I and II; this average corresponds to the period of low-rise buildings (less than 0.2 sec). Figure 12 shows contours of the average of EIS bands V, VI, and VII; this average corresponds to the period of high-rise buildings in the Los Angeles area (between 0.6 and 4.0 sec). On the longer-period EIS maps, the elongation of the iso-EIS lines in a southeasterly direction is seen to correspond generally to the axis of the Los Angeles basin, where the deepest thickness of alluvium is found.[6]

Low-Rise Iso-S_a Maps

By definition, pseudo absolute acceleration (S_a) is given by

$$S_a = \left(\frac{2\pi}{T}\right)^2 S_d$$

S_a values were computed by CIT from the S_v values for the 62 San Fernando earthquake ground stations.[4] Figure 4 shows that S_a has a fairly low range of variation in the region of low-rise building periods (below 0.2 sec). The average envelope S_a below a period of 0.2 sec has been previously shown to be a reasonable measure of ground motion intensity due to a UNE for low-rise buildings.[7] The example response spectra indicate that S_a due to the San Fernando earthquake was most constant in the period range of 0.2 to 0.6 sec, which extends above the normal low-rise range.

A sample calculation showing the computation of the average envelope S_a for periods between 0.04 and 0.2 sec for the ground station at Pacoima Dam is presented in Table 5. First, the component S_a values at each period are determined and compared (columns 2 and 3). The envelope S_a value is obtained by taking the larger (underlined) S_a value from the two columns. The average envelope acceleration, $S_{\overline{ae}}$, is obtained by dividing the sum of the individual S_{ae} values by the number of periods. The average envelope S_a values for the stations in this study are summarized in Table 6. The considerations used in preparation of the five EIS intensity maps were also used in plotting the low-rise iso-S_a lines shown in Figure 13.

LOW-RISE BUILDING DAMAGE ANALYSIS

Sources of Data

Zip code zones were used as the areas for the low-rise building analysis because both low-rise building replacement value and damage repair costs were available by zip code zones. The number and value of low-rise buildings is based on 1970 census data obtained from the Western Economic Research Company.[8,9]

The low-rise damage data for each zip code zone were obtained from the files of the Small Business Administration (SBA), which granted loans to home owners and businessmen to repair damage that occurred from the San Fernando earthquake. Each loan was preceded by a two-step qualifying procedure consisting of (1) submittal to SBA of a written damage claim, including contractor's damage repair cost estimate, and (2) inspection of damage by a claim investigator to determine if the damage was credible. The principal limitation of the SBA data is that some of the damaged buildings were located outside the zip code zone corresponding to the owner's address, the only address recorded in the SBA files. This was the case for many apartment buildings owned by individuals living in another zip code zone; as many as 10% of the paid damage claims may be subject to this inaccuracy.

Low-Rise Damage Factor Analysis

The damage factor, DF, for an individual building is defined as follows:

$$DF = \frac{\text{Repair Cost}}{\text{Building Replacement Value}}$$

The mean damage factor, m_{DF}, for a group of n buildings in an area is calculated using the formula:

$$m_{DF} = \frac{1}{n}\sum_{i=1}^{n} DF_i$$

In this study, individual damage factors for low-rise buildings were not calculated because the building replacement value and damage repair cost for each low-rise building could not be matched. In calculating the mean damage factor, it was assumed that the mean replacement value of damaged buildings (m'_{RV}) is the same as that for undamaged buildings (m_{RV}). Because the mean damage factor is not the mean repair cost divided by the mean building value, special analysis was required. This analysis is described next.

The mean repair cost for each zip code zone, for damaged buildings only, was computed from the SBA data as follows:

$$m_{DC|D} = \frac{1}{N_D} \sum_{i=1}^{N_D} LV_i$$

where:

$m_{DC|D}$ = the mean damage cost, given that the building is damaged

N_D = the number of damaged buildings

LV_i = the loan value (repair cost) of the ith damaged building

Appendix A, "Nomenclature," explains mathematical terms used in this report.

The mean repair cost for all buildings was found by multiplying by the ratio of damaged buildings to total buildings:

$$m_{DC} = \frac{N_D}{N_T} m_{DC|D}$$

where:

m_{DC} = the mean damage cost for all buildings

N_T = the total number of buildings

The uncertainty in the damage repair cost is measured by the standard deviation and coefficient of variation. The standard deviation repair cost for each zip code zone, for damaged buildings only, $\sigma_{DC|D}$, is:

$$\sigma_{DC|D} = \sqrt{\frac{1}{N_D}\left[\sum_{i=1}^{N_D}\left(LV_i - m_{DC|D}\right)^2\right]}$$

The coefficient of variation repair cost for damaged buildings only, $V_{DC|D}$, is defined as:

$$V_{DC|D} = \frac{\sigma_{DC|D}}{m_{DC|D}}$$

For all buildings (damaged plus undamaged), the corresponding coefficient of variation, V_{DC}, is:

$$V_{DC} = \sqrt{\frac{N_T}{N_D}\left(V_{DC|D}^2 + 1\right) - 1}$$

The mean damage factor depends not only on the mean damage cost, m_{DC}, and the mean building replacement value, m_{RV}, but also on higher-order terms, which include the coefficient of variation damage cost, V_{DC}, the coefficient of variation replacement value, V_{RV}, and the correlation coefficient between building replacement value and building damage cost. A second-order Taylor series expansion gives the following relationship for the mean damage factor, m_{DF}:

$$m_{DF} = \frac{m_{DC}}{m_{RV}}\left(1 + V_{RV}^2 - \rho_{RV,DC}V_{RV}V_{DC}\right)$$

where $\rho_{RV,DC}$ is the correlation coefficient between building replacement value and building damage cost. Note that the m_{RV} and V_{RV} were obtained directly from the Western Economic Research Company data recorded for each zip code zone.[8,9]

This correlation coefficient, as defined above, is bounded by the limits of ±1 on the corresponding correlation coefficient between building replacement value and building damage cost for only damaged buildings, $\rho_{RV,DC}$. This occurs because the correlation coefficient between building damage cost and building value is zero for buildings without damage. Analytically, this limitation is expressed as follows:

$$|\rho_{RV,DC}| \leq \frac{V_{DC|D}}{V_{DC}}$$

The expression for the corresponding damage factor coefficient of variation is:

$$V_{DF} = \frac{\sqrt{V_{RV}^2 + V_{DC}^2 - 2\rho_{RV,DC}V_{RV}V_{DC}}}{1 + V_{RV}^2 - \rho_{RV,DC}V_{RV}V_{DC}}$$

Derivations of the expressions for the damage factor mean and coefficient of variation are set forth in Appendix B, "Derivations: Statistical Formulas." The expression for the limitation on the value-damage correlation coefficient for all buildings is also derived in this appendix. A measure of the reliability of the mean damage factor is given by the coefficient of variation of the mean, which is:

$$V_{\overline{DF}} = \frac{V_{DF}}{\sqrt{N_T}}$$

Table 7 gives the m_{DF} and $V_{\overline{DF}}$ values for each zip code zone. Note that the mean damage factor and coefficient of variation are computed for three special cases of correlation between building value and building damage cost for damaged buildings only: complete negative correlation ($\rho'_{RV,DC} = -1$), no correlation ($\rho'_{RV,DC} = 0$), and complete positive correlation ($\rho'_{RV,DC} = 1$). Note that this correlation coefficient may vary between ±1 even though the value of the correlation coefficient between building value and damage state (damage or no damage) is restricted to zero because of the assumption of equal replacement values of damaged and undamaged buildings. Because the number of undamaged buildings in most zip code zones analyzed is relatively large, m_{DF} (shown in Table 7 for $\rho'_{RV,DC} = 0$) is a reasonable estimate of μ_{DF}, the true mean damage factor. That the $V_{\overline{DF}}$ values are small also validates the reliability of the m_{DF} estimate. Also, it is shown in the next chapter that $\rho_{RV,DC}$ has very little effect on the relationship between motion and damage. Table 8 gives a sample calculation of the pertinent damage factor statistics for zip code zone 90048.

The mean damage factor assuming no correlation between building replacement value and damage cost was plotted for each zip code zone on a map of the EIS analysis area. Lines of equal damage factor were constructed, taking into consideration that the damage factor could vary between the damage factor values corresponding to $\rho'_{RV,DC} = \pm 1$. The low-rise iso-*DF* map for the analysis area is shown in Figure 14.

Comparison of Data to Other Low-Rise Damage Summaries

Slosson[10] reported damage summaries of San Fernando and Los Angeles city and county. He reports that 1,500 of 5,210 living units in the city of San Fernando sustained appreciable damage, for a dollar loss of $12,125,000. In the area that includes the city of San Fernando and the county and city of Los Angeles, Slosson gives a total of 22,670 damaged buildings, with a corresponding dollar loss of $97 million.

A comparison with SBA data is difficult to make because the areas analyzed are different for each study. The areas for the SBA data were zip code zones. As shown in Figure 15, zone 91340 includes more than just the 2.4-square-mile area of the city of San Fernando. For zone 91340, the total number of damaged buildings was 4,500 out of 7,644 total housing units, and the corresponding total damage was $14,145,000, which compares reasonably well with Slosson's values. The corresponding figure for the total EIS study area includes more than just Los Angeles and San Fernando. For the total analysis area, the SBA files give 63,498 damaged buildings, with a corresponding dollar loss of $182 million.

Scholl[11] reports mean damage factors for two areas in the city of Glendale. The damage factors may be compared with the damage factors of the zip code zones that include these areas. For Area One, Scholl reports a damage factor of 2.09%, while the corresponding zip code zone had a damage factor of 1.03%. Area Two had a damage factor of 0.87%, while the corresponding zip code zone had a damage factor of 0.59%.

LOW-RISE MOTION-DAMAGE RELATIONSHIPS

Introduction

Because the relationships between ground motion (as expressed by the EIS values) and building damage provide a basis for predicting damage from a future earthquake or UNE, the relationships between EIS intensity (also S_a for low-rise buildings) and damage were studied and compared to the results of previous studies.

Low-Rise Motion-Damage Analysis

Intensities for each zip code zone were assigned either as the value corresponding to the iso-intensity line lying in the zip code zone or as an interpolated value between the two iso-intensity lines nearest the zip code zone. The intensities and the damage factors obtained for each zone appeared to be exponentially related. Therefore, analysis of the data was conducted in the log-log domain. In the analysis, the few zip code zones with zero damage were excluded because log-log analysis is not possible for zero or negative data.

A least-squares analysis was performed on the data pairs of ground motion and damage factor statistics to obtain parameters of the equation:

$$\log y = m \log x + b$$

where:

- y = the damage factor statistic
- x = the ground motion statistic
- m = the slope of the best-fit line, in the log-log domain
- b = the value of the y-intercept

A correlation coefficient, ρ_{MD}, is defined as:

$$\rho_{MD} = \frac{\mathrm{Cov}(\log x, \log y)}{\sigma_{\log x}\, \sigma_{\log y}}$$

where:

$\mathrm{Cov}(\log x, \log y)$ = the covariance of log x and log y

$\sigma_{\log x}$ = the standard deviation of the log of the ground motion statistic

$\sigma_{\log y}$ = the standard deviation of the log of the damage factor statistic

The covariance is defined as:

$$\mathrm{Cov}(w, z) = E[wz] - m_w m_z$$

where:

$E[wz]$ = the mean product of w and z

m_w = the mean value of w

m_z = the mean value of z

The subscript MD denotes the correlation coefficient between ground motion and building damage. The correlation coefficient is a measure of the linear correlation between log y and log x. If data lie on a perfectly straight line, ρ_{MD} is equal to either +1 or -1, depending on the sign of the slope. If the data are completely uncorrelated, ρ_{MD} is equal to 0.

Figure 16 shows the relationship found between mean damage factor and ground motion expressed as the EIS rating in the low-period range (average of bands I, II, and III). The best-fit line was obtained by the least-squares method. The correlation between building value and building damage, $\rho'_{RV,DC}$, was assumed to be zero.

Least-squares analyses were also performed using the average of EIS bands I and II and the average envelope S_a statistics as the ground motion parameters. The analysis was performed for values of the building value-damage correlation coefficient, $\rho'_{RV,DC}$, equal to 0 and ±1. The results summarized in Table 9 demonstrate that the effect of $\rho'_{RV,DC}$ is insignificant when compared to the size of other uncertainties.

Figure 17 shows the relationship between the coefficient of variation of damage factor and the mean damage factor. This relationship demonstrates that there is greater uncertainty in damage at lower levels of damage and hence low levels of ground motion. Table 10 presents the results of the analysis of the relationship between the coefficient of variation of damage factor versus mean damage factor for building value-damage correlation, $\rho'_{RV,DC}$, equal to 0 and ±1.

The results of the analysis show that the mean damage factor is most highly correlated with the ground motion statistic expressed as the average of EIS bands I, II, and III. The correlation is also highest when it is assumed that the correlation coefficient between building value and building damage, $\rho'_{RV,DC}$, is equal to -1.

The correlation between mean damage factor and coefficient of variation of damage factor is also highest when $\rho'_{RV,DC} = -1$. However, the differences between the three choices of $\rho'_{RV,DC}$ are statistically small. It is reasonable to use $\rho'_{RV,DC} = 0$.

The coefficient of variation of the mean damage factor is also related to the EIS values. Coefficients of variation were computed for all mean damage factors occurring for small slices of the EIS axis. When these values are plotted, it is seen that the coefficient of variation decreases with increasing ground motion. Figure 18 is a plot of the coefficient of variation of the mean damage factor (assuming $\rho'_{RV,DC} = 0$) versus the average of EIS bands I, II, and III. The decreasing trend is similar to the relationship shown in Figure 17.

Comparison with Other Low-Rise Motion-Damage Curves

Using data from Project RULISON, a 1969 Plowshare project in Colorado, the relationship between the spectral acceleration and mean damage factor was determined. The best fit of these data points was reported by Scholl and Farhoomand.[7] Figure 19 shows this best-fit curve and the associated standard error of estimate. A similar curve was obtained from the San Fernando earthquake data assuming no correlation between building value and building damage. Note that the slopes of the curves are very close, and that the San Fernando curve falls within the standard error of estimate of the RULISON data in the range of accelerations common to both events.

Recently, URS/Blume established a relationship between the average of the first two digits of the nine-digit EIS report and the low-rise damage factor.[12] The data used were from Project RULISON and from Glendale, California, a community affected by the San Fernando earthquake. Figure 20 shows that the low-rise motion-damage relationship obtained in this previous work agrees with the results of the present report.

HIGH-RISE DAMAGE FACTOR ANALYSIS

In most cases, high-rise (five stories or higher) building values were obtained by multiplying the permit value at the time of construction by a cost escalation factor to bring the value to 1971 levels. When no permit value was available, other methods were used: one of these methods was to multiply the floor area by a value of $25 per square foot; another was to use the market value, assumed to be four times the assessed building value.

The high-rise damage cost data were taken from questionnaires whenever the data were available in this form. Other sources of these data were the damage permit repair value and preliminary damage surveys made before the building was actually repaired.

The areas used for the high-rise building analysis were squares, 3.6 miles on a side, corresponding to the pages of the Thomas Brothers map of Los Angeles (see Figure 21). MIT performed the high-rise damage factor analysis, a substantial portion of which has been published separately.[13]

Because damage costs and replacement values were available directly for each high-rise building, a damage factor was calculated as follows:

$$DF_i = \frac{\text{Repair Cost}}{\text{Building Replacement Value}}$$

The mean damage factor was then calculated for each area. In the MIT report, the term mean damage ratio, MDR, is synonymous to the mean damage factor, m_{DF}, used in this report. That is:

$$MDR = m_{DF} = \frac{1}{n}\sum_{i=1}^{n} DF_i$$

where n is the number of high-rise buildings in the area considered. With this understanding, the term mean damage factor is used in this report.

The standard deviation damage factor is calculated from the formula:

$$\sigma_{DF} = \sqrt{\frac{1}{N}\left[\sum_{i=1}^{N} DF_i - m_{DF}{}^2\right]}$$

The formula used for calculating the coefficient of variation is:

$$V_{DF} = \frac{\sigma_{DF}}{m_{DF}}$$

Damage factor means, standard deviations, and coefficients of variation for each area are shown in Table 11, which includes only post-1947 buildings (because there were so few pre-1947 buildings). The mean damage factors were plotted and contoured as shown on the iso-*DF* map in Figure 22.

High-Rise Motion-Damage Relationships

Two EIS values were obtained for each zone in which damage to high-rise structures occurred. These two values were interpolated from the EIS maps shown in Figure 9 and Figure 12. These values correspond to an average of period bands IV, V, and VI and an average of bands V, VI, and VII, respectively.

Least-squares analyses were performed, in the log-log domain, on these data and the post-1947 high-rise damage data. Table 12 summarizes the parameters calculated from the high-rise motion-damage analysis. The analysis for the average of bands IV, V, and VI for mean damage factor is shown in Figure 23. A graph of the coefficient of variation of damage factor as a function of mean damage factor is presented in Figure 24.

The higher correlation between ground motion and damage factor occurs for the average of EIS bands IV, V, and VI. Note that the correlation coefficients between motion and damage are higher for the high-rise building data than for the low-rise building data.

CONCLUSIONS

Three ground motion parameters were tested for their correlation with low-rise damage. These were the average envelope pseudo acceleration (0.04-sec to 0.2-sec period range), the EIS rating average of period bands I and II, and the EIS rating average of period bands I, II, and III. Among the parameters considered, the latter was found to correlate best with the observed damage due to the San Fernando earthquake.

The low-rise motion-damage relationship was found to be:

$$\log(m_{DF}) = 8.86 \log(EI) - 7.94$$

with correlation coefficient, $\rho_{MD} = 0.614$

where EI is the first digit of the three-digit report (the average of bands I, II, and III).

The parameters tested for high-rise motion-damage correlation were the EIS rating average of bands IV, V, and VI and the EIS rating average of bands V, VI, and VII. These period bands encompass the general range of periods for high-rise buildings (about 0.4 sec to 4.0 sec). The first parameter gave the higher correlation coefficient. The high-rise motion-damage relationship was found to be:

$$\log(m_{DF}) = 10.8 \log(EI) - 10.3$$

with correlation coefficient, $\rho_{MD} = 0.817$

where EI is the second digit of the three-digit report (the average of bands IV, V, and VI).

The results obtained for low-rise motion-damage relationships agree reasonably well with previously derived results. However, a relatively low correlation coefficient was obtained for the low-rise motion-damage relationship.

This is demonstrated graphically by lack of correspondence between damage factor contours in Figure 14 and EIS parameters that are linearly related to low-rise damage (Figures 8 and 13). Better correlation might be realized by analyzing the relationship between low-rise damage factors and other EIS parameters (e.g., Figure 12, period bands V, VI, and VIII) to include non-linear response. It must also be considered that the damage factor map may reflect demographic bias, for example the clustering of older buildings with less resistant design and construction backgrounds.

The fact that the individual building damage costs could not be matched to individual building values produced a narrow range of values for the damage factor of each zip code zone. The error incurred by assuming that damage cost and building value are uncorrelated is small in comparison to other errors in the damage prediction process.

As shown by the behavior of the coefficient of variation of the mean, the uncertainty in predicting damage decreases as the level of ground motion increases.

The EIS iso-intensity maps presented in Figures 8 through 13 demonstrate the complexity of the relationship between ground response and local geology. The EIS intensity contours are generally elongated toward the south or southeast, especially for periods greater than 0.4 sec. However, this configuration may depend partly on the uneven distribution of ground motion data points. Such maps coupled with detailed knowledge of the underlying alluvium could constitute an approach to microzonation of the Los Angeles area. Measured success has been attained in correlating engineering intensity with building damage due to the San Fernando earthquake. The findings presented in this report indicate the viability of the engineering intensity approach and suggest that further theoretical study and analysis of the data are warranted.

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TABLES

TABLE 1

ENGINEERING INTENSITY SCALE BOUNDARY S_v VALUES (from Blume[1])

EIS Intensity Level	S_v Value (cm/sec)	S_v Value (in./sec)
9	greater than 300	greater than 118
8	100-300	39.4-118
7	60-100	23.6-39.4
6	30-60	11.8-23.6
5	10-30	3.94-11.8
4	4-10	1.57-3.94
3	1-4	0.394-1.57
2	0.1-1	0.039-0.394
1	0.01-0.1	0.0039-0.039
0	less than 0.01	less than 0.0039

TABLE 2

AVERAGING PROCESS TO OBTAIN THREE- AND ONE-DIGIT EIS REPORTS FOR ENVELOPE MOTION, PACOIMA DAM GROUND MOTION STATION

EIS Period Band	EIS Intensity Level	Three-Digit EIS Report	One-Digit EIS Report
I	5		
II	6	$\frac{5+6+8}{3} \approx 6$	
III	8		
IV	8		$\frac{6+8+7}{3} = 7$
V	8	$\frac{8+8+8}{3} = 8$	
VI	8		
VII	8		
VIII	7	$\frac{8+7+6}{3} = 7$	
IX	6		
Reported as:	568,888,876	687	7

TABLE 3

EIS INTENSITIES FOR GROUND MOTION STATIONS USED IN EIS ANALYSIS

Station Number	Nine-Digit EIS Report	Three-Digit Report	One-Digit Report	Station Number	Nine-Digit EIS Report	Three-Digit Report	One-Digit Report
1	568,888,876	687	7	32	355,677,555	475	5+
2	345,555,665	456	5	33	334,555,555	355	4+
3	355,555,565	455	5-	34	345,555,565	455	5-
4	355,667,765	466	5+	35	345,555,665	456	5
5	355,555,554	455	5-	36	355,566,665	466	5+
6	345,555,554	455	5-	37	234,444,553	344	4-
7	345,555,554	455	5-	38	355,555,564	455	5-
8	355,556,765	456	5	39	234,444,554	345	4
9	345,557,775	466	5+	40	345,555,565	455	5-
10	345,555,554	455	5-	41	234,444,554	345	4
11	344,556,665	456	5	42	345,566,664	465	5
12	345,555,554	455	5-	43	234,455,564	355	4+
13	344,555,665	456	5	44	345,455,554	455	5-
14	234,455,565	355	4+	45	233,454,555	345	4
15	345,556,665	456	5	46	233,445,565	345	4
16	345,555,665	456	5	47	234,454,443	344	4-
17	345,555,554	455	5-	48	234,444,565	345	4
18	345,566,665	466	5+	49	234,445,565	345	4
19	345,566,665	466	5+	50	345,566,665	466	5+
20	345,555,665	456	5	51	345,556,665	456	5
21	345,565,665	456	5	52	355,566,665	466	5+
22	245,444,443	444	4	53	344,556,664	455	5-
23	345,555,554	455	5-	54	345,556,555	455	5-
24	345,565,554	455	5-	55	355,444,444	444	4
25	345,555,665	456	5	56	356,656,775	566	6-
26	345,556,654	455	5-	57	345,555,554	455	5-
27	355,566,665	466	5+	58	345,555,665	456	5
28	345,555,565	455	5-	59	345,556,665	456	5
29	334,555,554	355	4+	60	345,555,665	456	5
30	355,565,665	456	5	61	345,555,675	456	5
31	234,444,554	345	4	62	234,556,665	356	5-

TABLE 4

LOCATION OF GROUND MOTION STATIONS UTILIZED IN EIS ANALYSIS

Station Number	Location of Station	Station Number	Location of Station
1	Pacoima Dam	32	Glendale, 633 E. Broadway
2	LA, 250 E. First St.	33	LA, 2011 Zonal Ave.
3	LA, 1901 Avenue of the Stars	34	LA, 1177 S. Beverly Drive
4	LA, 8244 Orion Blvd.	35	LA, 120 N. Robertson Blvd.
5	Pasadena, Cal Tech, Seismological Laboratory	36	LA, 646 S. Olive Ave.
6	Pasadena, Cal Tech, Athenaeum	37	Palos Verdes Estates, 2516 Via Tejon
7	Pasadena, Cal Tech, Millikan Library	38	Beverly Hills, 450 N. Roxbury Dr.
8	LA, 15250 Ventura Blvd.	39	Orange, 4000 W. Chapman Ave.
9	LA, 15107 Vanowen St.	40	LA, 1800 Century Park East
10	Pasadena, Jet Propulsion Laboratory	41	Fullerton, 2600 Nutwood Ave.
11	LA, 1150 S. Hill St.	42	LA, 15910 Ventura Blvd.
12	LA, 3838 Lankershim Blvd.	43	Long Beach State College
13	LA, 611 W. Sixth St.	44	LA, UCLA Reactor Laboratory
14	LA, 8639 Lincoln Blvd.	45	Costa Mesa, 666 W. 19th St.
15	LA, 3710 Wilshire Blvd.	46	Long Beach, 200 W. Broadway
16	LA, 4680 Wilshire Blvd.	47	San Dimas, Puddingstone Reservoir
17	LA, 7080 Hollywood Blvd.	48	Long Beach, Terminal Island
18	LA, 4867 Sunset Blvd.	49	LA, 9841 Airport Blvd.
19	LA, 3470 Wilshire Blvd.	50	LA, 808 S. Olive Ave.
20	LA, Water and Power Bldg.	51	LA, Hollywood Storage, P.E. Lot
21	LA, 445 Figueroa St.	52	LA, Hollywood Storage, Basement
22	Carbon Canyon Dam	53	LA, 2500 Wilshire Blvd.
23	Whittier Narrows Dam	54	LA, 1640 Marengo St.
24	LA, Griffith Park Observatory	55	Arcadia, Santa Anita Reservoir
25	LA, 616 S. Normandie Ave.	56	LA, 14724 Ventura Blvd.
26	Alhambra, 900 S. Fremont Ave.	57	Hollywood, 1760 N. Orchid Ave.
27	LA, 1625 W. Olympic Blvd.	58	Beverly Hills, 9100 Wilshire Blvd.
28	LA, 1880 Century Park East	59	LA, 800 W. First St.
29	LA, 435 N. Oakhurst Ave.	60	LA, 222 Figueroa St.
30	LA, 3407 W. Sixth St.	61	LA, 6200 Wilshire Blvd.
31	Santa Ana, Orange County Engr. Bldg.	62	LA, 3440 University Ave.

TABLE 5

AVERAGING PROCESS TO OBTAIN ENVELOPE S_a FOR PACOIMA DAM GROUND STATION

Period, T_i (sec)	S_a* Component S14°E	S_a Component S76°W	Envelope S_a S_{ae_i}
0.040	1.18g	1.13g	1.18g
0.042	1.20	1.13	1.20
0.044	1.22	1.12	1.22
0.046	1.28	1.12	1.28
0.048	1.31	1.13	1.31
0.050	1.36	1.18	1.36
0.055	1.46	1.27	1.46
0.060	1.55	1.43	1.55
0.065	1.40	1.78	1.78
0.070	1.56	1.77	1.77
0.075	1.68	2.13	2.13
0.080	1.76	1.93	1.93
0.085	1.90	1.67	1.90
0.090	1.73	1.96	1.96
0.095	1.72	2.01	2.01
0.100	1.68	1.82	1.82
0.110	1.80	1.63	1.80
0.120	1.61	1.66	1.66
0.130	2.13	1.74	2.13
0.140	2.28	2.19	2.28
0.150	1.95	1.99	1.99
0.160	1.86	1.82	1.86
0.170	1.78	1.93	1.93
0.180	1.63	1.93	1.93
0.190	1.89	1.90	1.90
0.200	2.22	1.70	2.22

Arithmetic average of the S_{ae} values,

$$S_{\overline{ae}} = \frac{1}{26} \sum_{i=1}^{26} S_{ae_i} = 1.75g.$$

*S_a values are based on a 5% damping ratio.

TABLE 6

AVERAGE ENVELOPE S_a BASED ON 5% DAMPING RATIO FOR GROUND MOTION STATIONS USED IN EIS ANALYSIS, AVERAGED BETWEEN 0.04 AND 0.2 SEC

Station No.*	$S_{\overline{ae}}$	Station No.*	$S_{\overline{ae}}$
1	1.752g	32	0.400g
2	0.196	33	0.130
3	0.359	34	0.187
4	0.346	35	0.164
5	0.321	36	0.376
6	0.173	37	0.0605
7	0.290	38	0.336
8	0.357	39	0.0414
9	0.197	40	0.164
10	0.282	41	0.0508
11	0.186	42	0.242
12	0.292	43	0.0548
13	0.168	44	0.177
14	0.0478	45	0.0474
15	0.227	46	0.0379
16	0.203	47	0.121
17	0.164	48	0.400
18	0.271	49	0.0597
19	0.211	50	0.232
20	0.270	51	0.215
21	0.209	52	0.430
22	0.132	53	0.198
23	0.207	54	0.229
24	0.295	55	0.379
25	0.209	56	0.454
26	0.236	57	0.304
27	0.358	58	0.252
28	0.213	59	0.196
29	0.133	60	0.200
30	0.383	61	0.220
31	0.0525	62	0.110

*The location of each station is presented in Table 4.

TABLE 7

DAMAGE FACTOR STATISTICS FOR EIS ANALYSIS

AREA ZIP CODE ZONES

Zip Code	Mean Damage Factor (m_{DF})			Coefficient of Variation of Mean ($V_{\overline{DF}}$)		
	$\rho'_{RV,DC} = -1$	$\rho'_{RV,DC} = 0$	$\rho'_{RV,DC} = 1$	$\rho'_{RV,DC} = -1$	$\rho'_{RV,DC} = 0$	$\rho'_{RV,DC} = 1$
90001	1.020E-02	8.827E-03	7.456E-03	.0509	.0582	.0682
90002	1.381E-02	1.157E-02	9.332E-03	.0410	.0481	.0585
90003	1.913E-02	1.573E-02	1.233E-02	.0345	.0410	.0510
90004	6.673E-03	4.593E-03	2.512E-03	.0757	.1090	.1972
90005	2.365E-02	2.026E-02	1.686E-02	.0823	.0927	.1071
90006	1.235E-02	1.041E-02	8.467E-03	.0857	.1003	.1216
90007	1.585E-02	1.339E-02	1.093E-02	.0765	.0889	.1070
90008	1.481E-02	1.291E-02	1.100E-02	.0316	.0355	.0407
90010	7.467E-04	7.178E-04	6.888E-04	.4952	.5149	.5363
90011	1.469E-02	1.256E-02	1.043E-02	.0410	.0472	.0561
90012	1.203E-02	9.987E-03	7.942E-03	.1565	.1861	.2309
90015	1.813E-02	1.372E-02	9.312E-03	.2259	.2935	.4249
90016	2.295E-02	2.012E-02	1.728E-02	.0288	.0321	.0363
90017	7.905E-02	7.015E-02	6.125E-02	.2408	.2548	.2716
90018	2.200E-02	1.894E-02	1.587E-02	.0347	.0394	.0459
90019	2.522E-02	2.186E-02	1.851E-02	.0267	.0298	.0339
90020	5.065E-03	4.587E-03	4.107E-03	.1413	.1551	.1720
90021	1.136E-02	1.038E-02	9.391E-03	.4114	.4482	.4927
90022	4.061E-04	3.533E-04	3.004E-04	.1745	.2005	.2356
90023	7.809E-04	6.454E-04	5.098E-04	.2199	.2658	.3362
90024	1.566E-03	1.391E-03	1.215E-03	.0994	.1117	.1275
90025	2.142E-03	1.915E-03	1.688E-03	.1187	.1324	.1498
90026	1.274E-02	1.056E-02	8.379E-03	.0465	.0554	.0688
90027	6.443E-03	5.410E-03	4.378E-03	.0538	.0633	.0773
90028	4.193E-02	3.525E-02	2.857E-02	.0736	.0820	.0940
90029	8.082E-03	7.063E-03	6.043E-03	.1007	.1142	.1322
90031	3.025E-03	2.528E-03	2.032E-03	.1138	.1356	.1682
90032	4.304E-03	3.727E-03	3.150E-03	.0705	.0811	.0956
90033	2.705E-03	2.415E-03	2.124E-03	.1342	.1500	.1701
90034	4.559E-03	3.830E-03	3.101E-03	.0590	.0697	.0853
90035	7.839E-03	6.822E-03	5.804E-03	.0474	.0537	.0622
90036	1.195E-02	1.042E-02	8.893E-03	.0492	.0553	.0635
90037	2.813E-02	2.355E-02	1.897E-02	.0328	.0379	.0454
90038	9.100E-03	8.092E-03	7.084E-03	.1026	.1141	.1288
90039	3.427E-03	2.891E-03	2.355E-03	.0768	.0906	.1108
90040	6.024E-04	5.117E-04	4.209E-04	.3793	.4463	.5421
90041	6.667E-03	5.198E-03	3.729E-03	.0578	.0734	.1015
90042	4.963E-03	4.119E-03	3.276E-03	.0633	.0759	.0950
90043	2.499E-02	2.145E-02	1.791E-02	.0181	.0203	.0233
90044	2.374E-02	2.039E-02	1.703E-02	.0212	.0240	.0278
90045	2.651E-04	2.292E-04	1.932E-04	.1780	.2059	.2441
90046	4.756E-03	3.730E-03	2.703E-03	.0648	.0818	.1119
90047	3.157E-02	2.742E-02	2.328E-02	.0158	.0174	.0197
90048	1.422E-02	1.250E-02	1.079E-02	.0438	.0486	.0550
90049	1.034E-03	9.463E-04	8.585E-04	.0950	.1037	.1142
90056	1.035E-03	9.491E-04	8.632E-04	.1843	.2007	.2204
90057	7.925E-03	7.098E-03	6.271E-03	.2239	.2481	.2788
90058	6.184E-03	5.366E-03	4.548E-03	.3296	.3770	.4414
90059	1.256E-02	1.050E-02	8.435E-03	.0409	.0481	.0588
90061	1.751E-02	1.499E-02	1.248E-02	.0416	.0476	.0559
90062	3.839E-02	3.131E-02	2.423E-02	.0267	.0310	.0379

TABLE 7 (continued)

Zip Code	Mean Damage Factor (m_{DF})			Coefficient of Variation of Mean ($V_{\overline{DF}}$)		
	$\rho'_{RV,DC}$ = -1	$\rho'_{RV,DC}$ = 0	$\rho'_{RV,DC}$ = 1	$\rho'_{RV,DC}$ = -1	$\rho'_{RV,DC}$ = 0	$\rho'_{RV,DC}$ = 1
90063	2.040E-03	1.720E-03	1.400E-03	.1090	.1290	.1581
90064	1.797E-03	1.547E-03	1.297E-03	.0787	.0911	.1084
90065	4.206E-03	3.604E-03	3.002E-03	.0587	.0681	.0814
90066	4.462E-04	3.902E-04	3.343E-04	.1345	.1537	.1793
90067	7.075E-02	4.326E-02	1.577E-02	.5122	.8314	2.2638
90068	5.513E-03	3.904E-03	2.296E-03	.0854	.1198	.2024
90069	3.395E-03	3.000E-03	2.604E-03	.0961	.1082	.1239
90201	2.031E-04	1.787E-04	1.543E-04	.3381	.3842	.4448
90210	1.709E-03	1.467E-03	1.226E-03	.1079	.1254	.1498
90211	8.502E-03	7.304E-03	6.106E-03	.0910	.1043	.1228
90212	5.873E-03	5.423E-03	4.973E-03	.0970	.1042	.1128
90220	2.030E-02	1.676E-02	1.323E-02	.0275	.0323	.0397
90221	7.511E-03	6.257E-03	5.003E-03	.0421	.0499	.0618
90222	1.302E-02	1.065E-02	8.285E-03	.0452	.0542	.0684
90230	1.039E-03	9.197E-04	8.005E-04	.1133	.1278	.1466
90240	1.661E-04	1.510E-04	1.359E-04	.3098	.3407	.3785
90241	9.300E-05	8.141E-05	6.983E-05	.4078	.4657	.5429
90242	1.421E-04	1.299E-04	1.177E-04	.3432	.3754	.4143
90245	3.395E-04	2.977E-04	2.558E-04	.2859	.3260	.3791
90247	8.781E-04	7.911E-04	7.042E-04	.1129	.1252	.1405
90248	9.807E-04	8.973E-04	8.139E-04	.1275	.1392	.1533
90249	1.349E-03	1.232E-03	1.115E-03	.1057	.1156	.1275
90250	3.484E-04	3.112E-04	2.739E-04	.1777	.1989	.2259
90254	7.540E-04	6.651E-04	5.762E-04	.2334	.2644	.3050
90255	3.960E-04	3.372E-04	2.785E-04	.2161	.2536	.3070
90260	4.040E-04	3.713E-04	3.385E-04	.2658	.2892	.3171
90262	4.699E-04	4.079E-04	3.459E-04	.1676	.1930	.2275
90265	4.653E-04	4.394E-04	4.134E-04	.2126	.2251	.2391
90266	3.553E-04	2.798E-04	2.043E-04	.2205	.2799	.3831
90270	1.410E-04	1.410E-04	1.410E-04	.8565	.8565	.8565
90272	4.199E-04	3.647E-04	3.095E-04	.1831	.2106	.2480
90274	3.747E-04	2.746E-04	1.745E-04	.2288	.3121	.4910
90277	3.725E-04	3.264E-04	2.803E-04	.2026	.2311	.2690
90278	1.781E-04	1.661E-04	1.540E-04	.3849	.4128	.4450
90280	2.530E-04	2.269E-04	2.008E-04	.2012	.2243	.2535
90290	9.230E-04	7.991E-04	6.752E-04	.2135	.2462	.2909
90291	1.310E-03	1.103E-03	8.956E-04	.1064	.1261	.1550
90301	1.023E-03	9.077E-04	7.926E-04	.1848	.2081	.2380
90302	2.123E-03	1.867E-03	1.610E-03	.1438	.1631	.1887
90303	7.200E-03	6.490E-03	5.780E-03	.0559	.0616	.0686
90304	2.506E-04	2.224E-04	1.942E-04	.5799	.6534	.7482
90305	1.605E-02	1.444E-02	1.283E-02	.0411	.0449	.0496
90401	3.365E-03	2.931E-03	2.498E-03	.4442	.5074	.5926
90402	4.569E-04	4.055E-04	3.541E-04	.1950	.2196	.2513
90403	1.727E-03	1.588E-03	1.449E-03	.1880	.2041	.2234
90404	3.759E-03	3.142E-03	2.525E-03	.1691	.2012	.2489
90405	6.774E-04	5.817E-04	4.861E-04	.1983	.2306	.2758
90501	1.075E-04	8.830E-05	6.911E-05	.4940	.6013	.7681
90502	2.727E-04	2.492E-04	2.258E-04	.3788	.4144	.4574
90503	1.803E-04	1.596E-04	1.384E-04	.2974	.3370	.3887
90504	2.522E-04	2.336E-04	2.149E-04	.2454	.2649	.2878

TABLE 7 (continued)

Zip Code	Mean Damage Factor (m_{DF})			Coefficient of Variation of Mean ($V_{\overline{DF}}$)		
	$\rho'_{RV,DC}$ = -1	$\rho'_{RV,DC}$ = 0	$\rho'_{RV,DC}$ = 1	$\rho'_{RV,DC}$ = -1	$\rho'_{RV,DC}$ = 0	$\rho'_{RV,DC}$ = 1
90505	4.397E-04	3.525E-04	2.654E-04	.2305	.2874	.3816
90601	1.367E-04	1.291E-04	1.216E-04	.4012	.4246	.4509
90602	1.817E-04	1.696E-04	1.576E-04	.3476	.3723	.4007
90603	1.389E-04	1.308E-04	1.227E-04	.3635	.3860	.4115
90604	1.843E-04	1.645E-04	1.446E-04	.2695	.3020	.3435
90605	2.412E-04	2.146E-04	1.881E-04	.2453	.2756	.3144
90606	1.547E-04	1.379E-04	1.211E-04	.3551	.3984	.4537
90620	4.358E-05	4.200E-05	4.042E-05	.5003	.5190	.5392
90630	1.281E-04	1.220E-04	1.159E-04	.3583	.3760	.3956
90631	1.794E-04	1.518E-04	1.243E-04	.2722	.3215	.3928
90638	1.209E-04	1.087E-04	9.645E-05	.3176	.3533	.3980
90640	2.807E-04	2.431E-04	2.055E-04	.2024	.2336	.2763
90650	7.697E-05	6.827E-05	5.957E-05	.2644	.2980	.3415
90660	1.753E-04	1.450E-04	1.148E-04	.2334	.2820	.3563
90670	1.882E-04	1.589E-04	1.297E-04	.4229	.5005	.6131
90680	1.110E-04	1.110E-04	1.110E-04	.8707	.8707	.8707
90701	1.295E-04	1.213E-04	1.131E-04	.3460	.3693	.3959
90706	6.723E-05	6.574E-05	6.426E-05	.4819	.4927	.5041
90710	3.712E-04	3.411E-04	3.109E-04	.2691	.2928	.3211
90712	9.604E-05	8.682E-05	7.760E-05	.3618	.4002	.4477
90713	2.421E-05	2.043E-05	1.664E-05	.6146	.7285	.8943
90715	1.657E-04	1.500E-04	1.343E-04	.4676	.5163	.5765
90717	3.956E-04	3.510E-04	3.064E-04	.3016	.3398	.3891
90720	2.322E-05	2.322E-05	2.322E-05	.9258	.9258	.9258
90723	1.449E-04	1.386E-04	1.324E-04	.4522	.4726	.4949
90731	4.318E-04	3.625E-04	2.933E-04	.1919	.2285	.2823
90732	2.149E-04	1.876E-04	1.604E-04	.2512	.2877	.3364
90740	1.682E-04	1.556E-04	1.429E-04	.3623	.3918	.4264
90744	3.772E-04	3.252E-04	2.732E-04	.2444	.2834	.3372
90745	2.270E-04	1.969E-04	1.669E-04	.2376	.2738	.3230
90746	5.041E-03	4.635E-03	4.230E-03	.0917	.0993	.1082
90802	2.701E-03	2.493E-03	2.285E-03	.5445	.5891	.6419
90803	2.463E-04	2.264E-04	2.065E-04	.2901	.3155	.3458
90804	1.272E-04	1.141E-04	1.010E-04	.5208	.5805	.6557
90805	1.705E-04	1.408E-04	1.111E-04	.2478	.3001	.3803
90806	7.412E-04	6.250E-04	5.089E-04	.1748	.2071	.2541
90807	1.467E-04	1.280E-04	1.093E-04	.3182	.3646	.4268
90808	1.223E-04	1.088E-04	9.519E-05	.2677	.3011	.3440
90810	7.291E-04	5.845E-04	4.399E-04	.1577	.1965	.2609
90813	2.485E-03	1.939E-03	1.394E-03	.1976	.2526	.3507
90814	3.007E-04	2.614E-04	2.221E-04	.3526	.4055	.4770
90815	2.902E-05	2.511E-05	2.120E-05	.4802	.5549	.6572
91001	3.849E-03	3.188E-03	2.527E-03	.0462	.0554	.0694
91006	2.055E-04	1.805E-04	1.555E-04	.1601	.1822	.2115
91010	3.508E-04	2.652E-04	1.797E-04	.2558	.3381	.4988
91011	5.495E-03	4.022E-03	2.549E-03	.0742	.1007	.1577
91016	6.125E-04	4.428E-04	2.731E-04	.2246	.3104	.5030
91020	1.040E-02	6.775E-03	3.147E-03	.1524	.2321	.4953
91024	4.292E-04	3.764E-04	3.236E-04	.2636	.3004	.3492
91030	2.438E-03	2.103E-03	1.768E-03	.0851	.0983	.1165
91040	5.738E-02	4.655E-02	3.572E-02	.0212	.0242	.0289

TABLE 7 (continued)

Zip Code	Mean Damage Factor (m_{DF}) $\rho'_{RV,DC}$ = -1	$\rho'_{RV,DC}$ = 0	$\rho'_{RV,DC}$ = 1	Coefficient of Variation of Mean ($V_{\overline{DF}}$) $\rho'_{RV,DC}$ = -1	$\rho'_{RV,DC}$ = 0	$\rho'_{RV,DC}$ = 1
91042	4.109E-02	3.393E-02	2.676E-02	.0243	.0281	.0337
91101	4.859E-02	3.989E-02	3.120E-02	.1443	.1612	.1857
91103	5.196E-03	4.024E-03	2.852E-03	.0553	.0706	.0984
91104	1.612E-03	1.354E-03	1.096E-03	.0956	.1136	.1401
91105	5.827E-03	3.873E-03	1.919E-03	.1130	.1689	.3387
91106	2.393E-03	1.921E-03	1.449E-03	.1087	.1348	.1779
91107	4.534E-04	3.744E-04	2.955E-04	.1506	.1822	.2307
91108	3.634E-04	3.343E-04	3.052E-04	.1884	.2047	.2241
91201	1.254E-02	1.077E-02	9.011E-03	.0486	.0556	.0653
91202	1.205E-02	1.030E-02	8.543E-03	.0424	.0487	.0575
91203	6.967E-03	5.881E-03	4.796E-03	.1556	.1831	.2230
91204	5.271E-03	4.393E-03	3.515E-03	.1583	.1885	.2338
91205	8.099E-03	6.900E-03	5.701E-03	.0824	.0959	.1150
91206	4.935E-03	4.383E-03	3.831E-03	.0700	.0783	.0890
91207	1.149E-02	1.007E-02	8.654E-03	.0512	.0572	.0652
91208	7.892E-03	6.937E-03	5.982E-03	.0554	.0624	.0715
91214	1.412E-02	1.167E-02	9.210E-03	.0303	.0360	.0446
91302	4.264E-03	3.850E-03	3.436E-03	.1172	.1290	.1436
91303	8.536E-03	7.564E-03	6.592E-03	.0778	.0870	.0989
91304	7.540E-03	6.482E-03	5.423E-03	.0324	.0373	.0441
91306	9.704E-03	8.411E-03	7.119E-03	.0384	.0439	.0512
91311	1.279E-02	1.071E-02	8.617E-03	.0410	.0480	.0584
91316	7.554E-03	6.325E-03	5.096E-03	.0314	.0370	.0451
91321	7.047E-02	5.920E-02	4.794E-02	.0251	.0271	.0296
91324	3.513E-02	3.075E-02	2.637E-02	.0127	.0137	.0150
91331	7.071E-02	6.080E-02	5.089E-02	.0116	.0125	.0136
91335	1.644E-02	1.443E-02	1.241E-02	.0237	.0265	.0302
91340	1.101E-01	9.095E-02	7.182E-02	.0119	.0126	.0133
91342	1.761E-01	1.431E-01	1.102E-01	.0093	.0090	.0073
91343	4.264E-02	3.817E-02	3.371E-02	.0152	.0160	.0171
91344	8.949E-02	7.666E-02	6.382E-02	.0094	.0094	.0091
91350	7.188E-02	6.430E-02	5.672E-02	.0146	.0150	.0153
91352	1.727E-02	1.323E-02	9.198E-03	.0345	.0440	.0619
91356	6.859E-03	5.851E-03	4.844E-03	.0461	.0533	.0635
91364	7.830E-03	6.729E-03	5.628E-03	.0257	.0295	.0348
91401	9.438E-03	7.962E-03	6.485E-03	.0333	.0389	.0470
91402	1.649E-02	1.427E-02	1.204E-02	.0341	.0386	.0448
91403	1.181E-02	9.441E-03	7.070E-03	.0284	.0348	.0454
91405	9.363E-03	8.023E-03	6.683E-03	.0498	.0574	.0680
91406	1.315E-02	1.142E-02	9.690E-03	.0305	.0346	.0401
91501	1.240E-02	1.021E-02	8.017E-03	.0595	.0709	.0886
91502	1.073E-02	7.386E-03	4.040E-03	.1245	.1788	.3229
91504	5.673E-03	4.756E-03	3.838E-03	.0675	.0800	.0983
91505	6.374E-03	5.631E-03	4.887E-03	.0492	.0553	.0634
91506	6.012E-03	5.275E-03	4.538E-03	.0620	.0701	.0810
91601	9.085E-03	7.810E-03	6.534E-03	.0578	.0665	.0786
91602	7.143E-03	6.147E-03	5.151E-03	.0712	.0819	.0967
91604	6.451E-03	5.655E-03	4.859E-03	.0413	.0466	.0537
91605	1.419E-02	1.171E-02	9.225E-03	.0358	.0426	.0531
91606	1.216E-02	1.019E-02	8.217E-03	.0434	.0511	.0624
91607	7.988E-03	7.132E-03	6.277E-03	.0493	.0547	.0616

TABLE 7 (continued)

Zip Code	Mean Damage Factor (m_{DF})			Coefficient of Variation of Mean ($V_{\overline{DF}}$)		
	$\rho'_{RV,DC} = -1$	$\rho'_{RV,DC} = 0$	$\rho'_{RV,DC} = 1$	$\rho'_{RV,DC} = -1$	$\rho'_{RV,DC} = 0$	$\rho'_{RV,DC} = 1$
91702	9.075E-05	7.575E-05	6.074E-05	.4593	.5502	.6860
91706	5.611E-05	4.896E-05	4.182E-05	.4790	.5488	.6426
91711	1.383E-04	1.178E-04	9.739E-05	.3662	.4296	.5197
91722	4.675E-05	3.764E-05	2.853E-05	.3684	.4576	.6037
91731	1.431E-04	1.351E-04	1.271E-04	.5610	.5942	.6316
91732	1.266E-04	1.063E-04	8.598E-05	.4633	.5519	.6823
91733	2.019E-04	1.812E-04	1.604E-04	.4053	.4516	.5100
91740	1.424E-04	1.365E-04	1.305E-04	.2874	.3000	.3137
91744	4.051E-04	3.422E-04	2.793E-04	.1412	.1671	.2046
91745	1.637E-04	1.513E-04	1.388E-04	.2084	.2255	.2458
91746	3.584E-04	3.121E-04	2.658E-04	.2271	.2607	.3060
91750	1.470E-05	1.470E-05	1.470E-05	.8101	.8101	.8101
91754	4.727E-04	4.097E-04	3.467E-04	.1408	.1624	.1918
91765	1.796E-04	1.701E-04	1.606E-04	.3715	.3922	.4153
91766	1.415E-04	1.193E-04	9.700E-05	.2786	.3305	.4063
91767	3.166E-04	2.712E-04	2.258E-04	.2007	.2342	.2812
91770	1.919E-04	1.617E-04	1.316E-04	.2694	.3194	.3925
91773	3.235E-05	3.235E-05	3.235E-05	.8183	.8183	.8183
91775	2.001E-04	1.710E-04	1.418E-04	.2784	.3257	.3925
91776	1.976E-04	1.769E-04	1.563E-04	.3358	.3749	.4244
91780	1.907E-04	1.761E-04	1.614E-04	.2867	.3105	.3386
91789	1.079E-05	1.079E-05	1.079E-05	.9162	.9162	.9162
91790	2.427E-04	2.042E-04	1.657E-04	.1902	.2259	.2782
91791	3.594E-04	2.983E-04	2.371E-04	.2107	.2538	.3191
91792	5.552E-04	5.380E-04	5.207E-04	.5163	.5328	.5503
91801	9.276E-04	8.229E-04	7.181E-04	.1315	.1481	.1695
91803	5.010E-04	4.354E-04	3.697E-04	.1907	.2193	.2581
92621	1.419E-04	1.091E-04	7.622E-05	.4590	.5971	.8543
92631	4.052E-05	4.052E-05	4.052E-05	.6223	.6223	.6223
92632	2.164E-04	1.728E-04	1.292E-04	.4515	.5654	.7562
92633	1.194E-04	1.107E-04	1.021E-04	.4076	.4394	.4765
92640	2.901E-05	2.901E-05	2.901E-05	.9086	.9086	.9086
92641	2.552E-04	2.196E-04	1.840E-04	.4363	.5069	.6049
92644	2.283E-04	2.188E-04	2.092E-04	.5107	.5329	.5571
92645	8.759E-05	8.722E-05	8.684E-05	.6713	.6742	.6771
92647	1.731E-04	1.572E-04	1.413E-04	.2610	.2875	.3198
92649	5.946E-04	4.550E-04	3.153E-04	.2568	.3354	.4837
92670	8.687E-05	8.183E-05	7.680E-05	.4396	.4667	.4972
92683	1.720E-04	1.588E-04	1.456E-04	.2710	.2934	.3200
92686	3.056E-04	2.848E-04	2.641E-04	.3061	.3284	.3541
92703	6.914E-05	6.577E-05	6.239E-05	.5697	.5989	.6313
92704	1.297E-04	1.150E-04	1.002E-04	.3549	.4003	.4592
92708	2.472E-04	2.301E-04	2.129E-04	.2710	.2912	.3147
92801	7.281E-05	7.249E-05	7.217E-05	.6314	.6342	.6370
92802	3.558E-05	3.558E-05	3.558E-05	.9001	.9001	.9001
92804	1.316E-04	1.229E-04	1.142E-04	.3585	.3838	.4130
92805	3.885E-05	3.682E-05	3.479E-05	.5944	.6272	.6637
92806	1.650E-04	1.407E-04	1.164E-04	.4649	.5453	.6592

TABLE 8

SAMPLE CALCULATION OF DAMAGE FACTOR STATISTICS

FOR ZIP CODE ZONE 90048

Building Damage Data		Building Value Data	
Number of damaged buildings (N_D)	398	Mean building value (m_{RV})	\$37,533
Mean damage cost for damaged buildings only ($m_{DC\|D}$)	\$2,425	Coefficient of variation of building value (V_{RV})	0.287
Coefficient of variation of damage cost for damaged buildings only ($V_{DC\|D}$)	0.516	Number of buildings (N_T)	2,226

Damage Factor Data	
Mean damage cost for all buildings (m_{DC})	\$434
Coefficient of variation of damage cost for all buildings (V_{DC})	2.467
Mean damage factor (m_{DF})	
$\rho'_{RV,DC} = -1$	.01422
$\rho'_{RV,DC} = 0$	.01250
$\rho'_{RV,DC} = +1$	.01079
Coefficient of variation of damage factor (V_{DF})	
$\rho'_{RV,DC} = -1$	2.066
$\rho'_{RV,DC} = 0$	2.295
$\rho'_{RV,DC} = +1$	2.593
Coefficient of variation of mean ($V_{\overline{DF}}$)	
$\rho'_{RV,DC} = 0$	0.0486

TABLE 9

RESULTS OF LEAST-SQUARES ANALYSIS BETWEEN GROUND MOTION STATISTICS AND LOW-RISE BUILDING DAMAGE FACTOR

Value-Damage Correlation Coefficient	Ground Motion Statistic Used		
	Average of EIS Bands I, II	Average of EIS Bands I, II, III	Average Envelope (S_a)
$\rho'_{RV,DC} = -1$	$m = 7.931$ $b = -6.982$ $\rho_{MD} = 0.5753$	$m = 9.015$ $b = -7.968$ $\rho_{MD} = 0.6160$	$m = 1.601$ $b = -1.604$ $\rho_{MD} = 0.6067$
$\rho'_{RV,DC} = 0$	$m = 7.781$ $b = -6.966$ $\rho_{MD} = 0.5728$	$m = 8.859$ $b = -7.942$ $\rho_{MD} = 0.6143$	$m = 1.570$ $b = -1.691$ $\rho_{MD} = 0.6034$
$\rho'_{RV,DC} = 1$	$m = 7.550$ $b = -6.923$ $\rho_{MD} = 0.5666$	$m = 8.628$ $b = -7.888$ $\rho_{MD} = 0.6099$	$m = 1.524$ $b = -1.805$ $\rho_{MD} = 0.5973$

TABLE 10

RESULTS OF LEAST-SQUARES ANALYSIS BETWEEN LOW-RISE BUILDING MEAN DAMAGE FACTOR AND COEFFICIENT OF VARIATION OF DAMAGE FACTOR

Value-Damage Correlation Coefficient	Analysis Results
$\rho'_{RV,DC} = -1$	$m = -0.4252$ $b = -2.078$ $\rho_{VM} = -0.8716$
$\rho'_{RV,DC} = 0$	$m = -0.4247$ $b = -2.046$ $\rho_{VM} = -0.8648$
$\rho'_{RV,DC} = 1$	$m = -0.4270$ $b = -2.014$ $\rho_{VM} = -0.8502$

TABLE 11

DAMAGE FACTOR MEAN, STANDARD DEVIATION, AND COEFFICIENT OF VARIATION FOR HIGH-RISE ANALYSIS AREAS (Post-1947 Buildings Only)

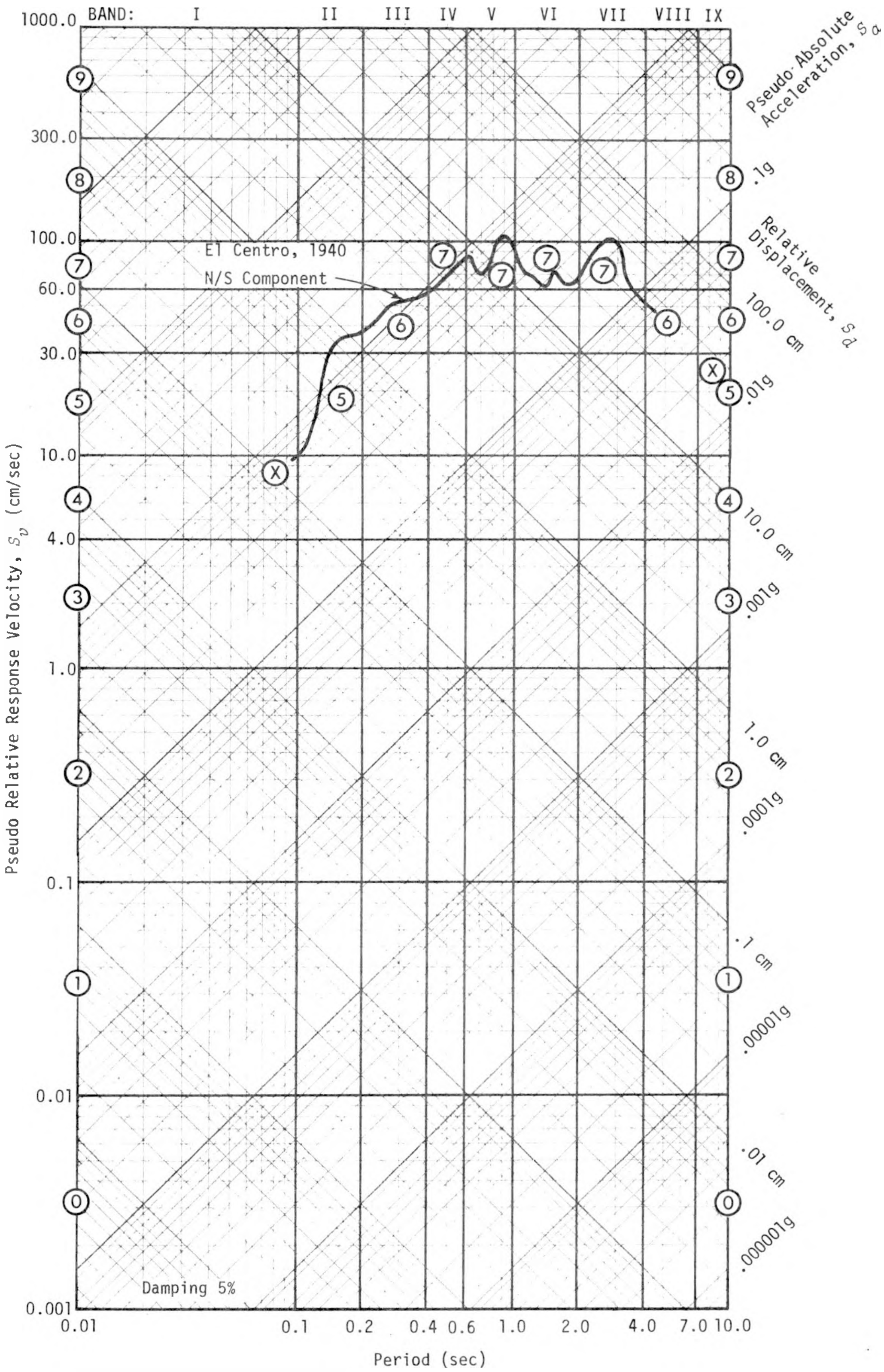
Area	Number of Buildings	m_{DF}	σ_{DF}	V_{DF}
2	2	0.504	0.246	0.488
7	4	0.011	0.0096	0.873
15	10	0.0292	0.0386	1.32
16	3	0.0016	0.0012	0.750
19	5	0.0393	0.0157	0.399
21	2	0.0	0.0	0.0
22	9	0.0066	0.0061	0.924
23	2	0.0052	0.0050	0.962
25	5	0.0368	0.0396	1.08
27	7	0.0015	0.0032	2.13
33	10	0.0006	0.0009	1.50
34	18	0.0061	0.0142	2.33
40	2	0.0013	0.0013	1.00
41	16	0.0009	0.0018	2.00
42	34	0.0016	0.0031	1.94
43	25	0.0037	0.0044	1.19
44	44	0.0048	0.0073	1.52
45	1	0.0377	0.0	0.0
49	9	0.0004	0.0007	1.75
56	13	0.0007	0.0011	1.57
63	1	0.0	0.0	0.0
68	2	0.0	0.0	0.0
70	2	0.0	0.0	0.0
73	1	0.0002	0.0	0.0
75	11	0.0	0.0	0.0
76	1	0.0	0.0	0.0
80	1	0.0	0.0	0.0
92	1	0.0	0.0	0.0
96	2	0.0	0.0	0.0

TABLE 12

RESULTS OF LEAST-SQUARES ANALYSIS BETWEEN GROUND MOTION STATISTICS AND HIGH-RISE BUILDING DAMAGE FACTOR

Ground Motion Statistic Used	
Average of EIS Bands IV, V, VI	Average of EIS Bands V, VI, VII
m = 10.83	m = 9.46
b = -10.25	b = -9.39
ρ_{MD} = 0.8165	ρ_{MD} = 0.6989

FIGURES



(N) = EIS intensity

FIGURE 1 ENGINEERING INTENSITY SCALE MATRIX WITH SUPERIMPOSED EXAMPLE SPECTRUM (from Blume[1])

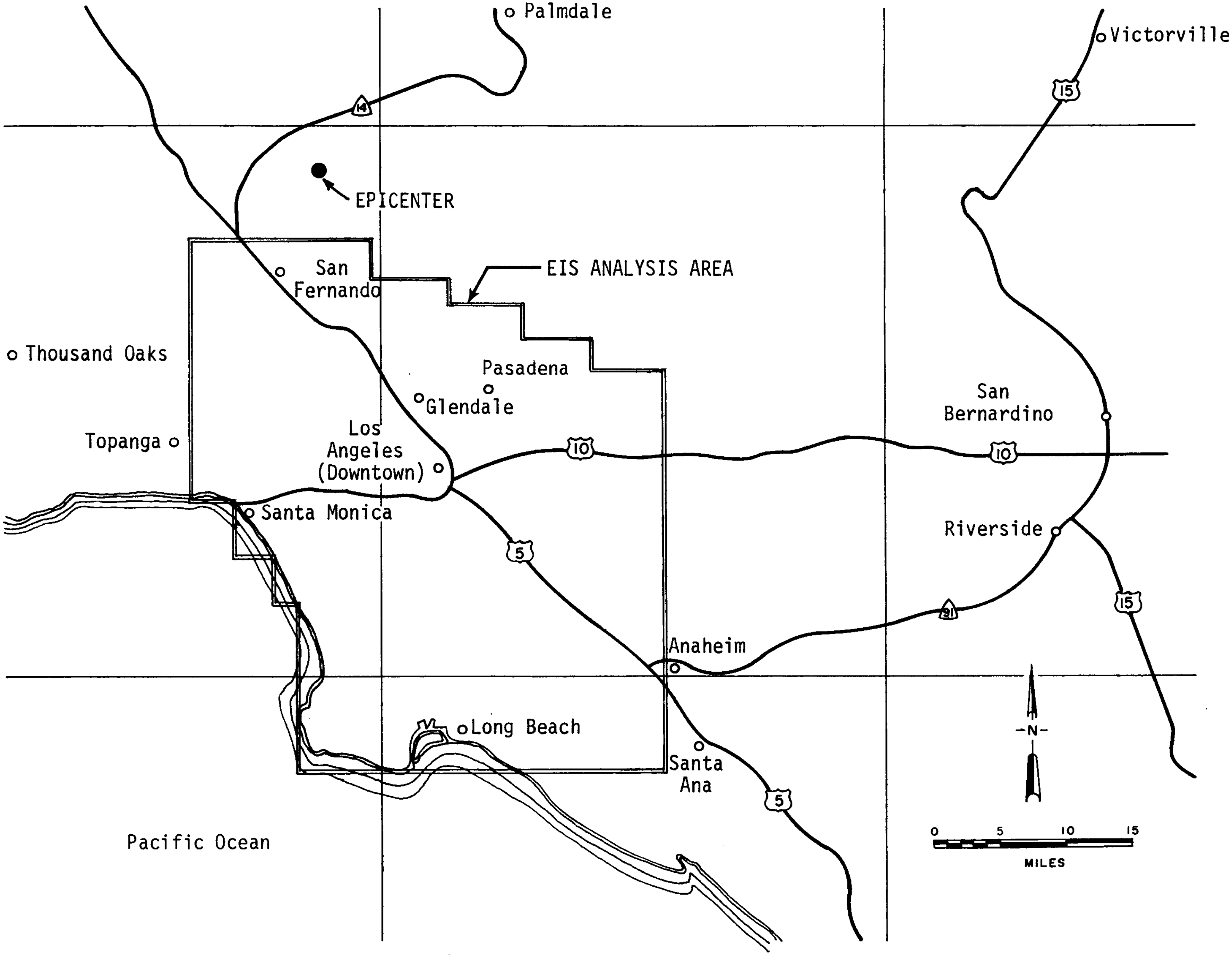


FIGURE 2 EIS ANALYSIS AREA

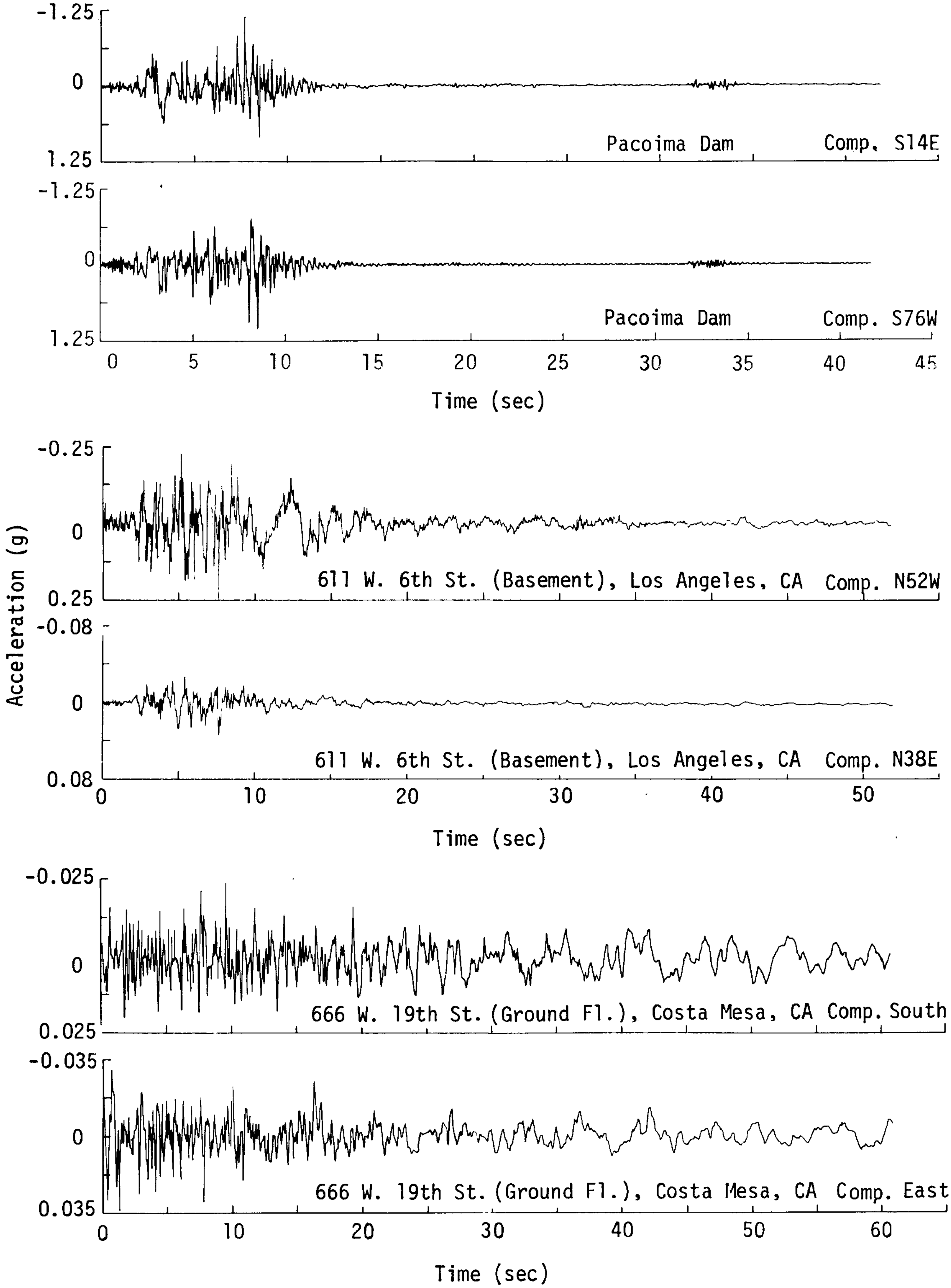


FIGURE 3 EXAMPLE RECORDED ACCELEROMETER TIME HISTORIES (Adapted from Reference 4)

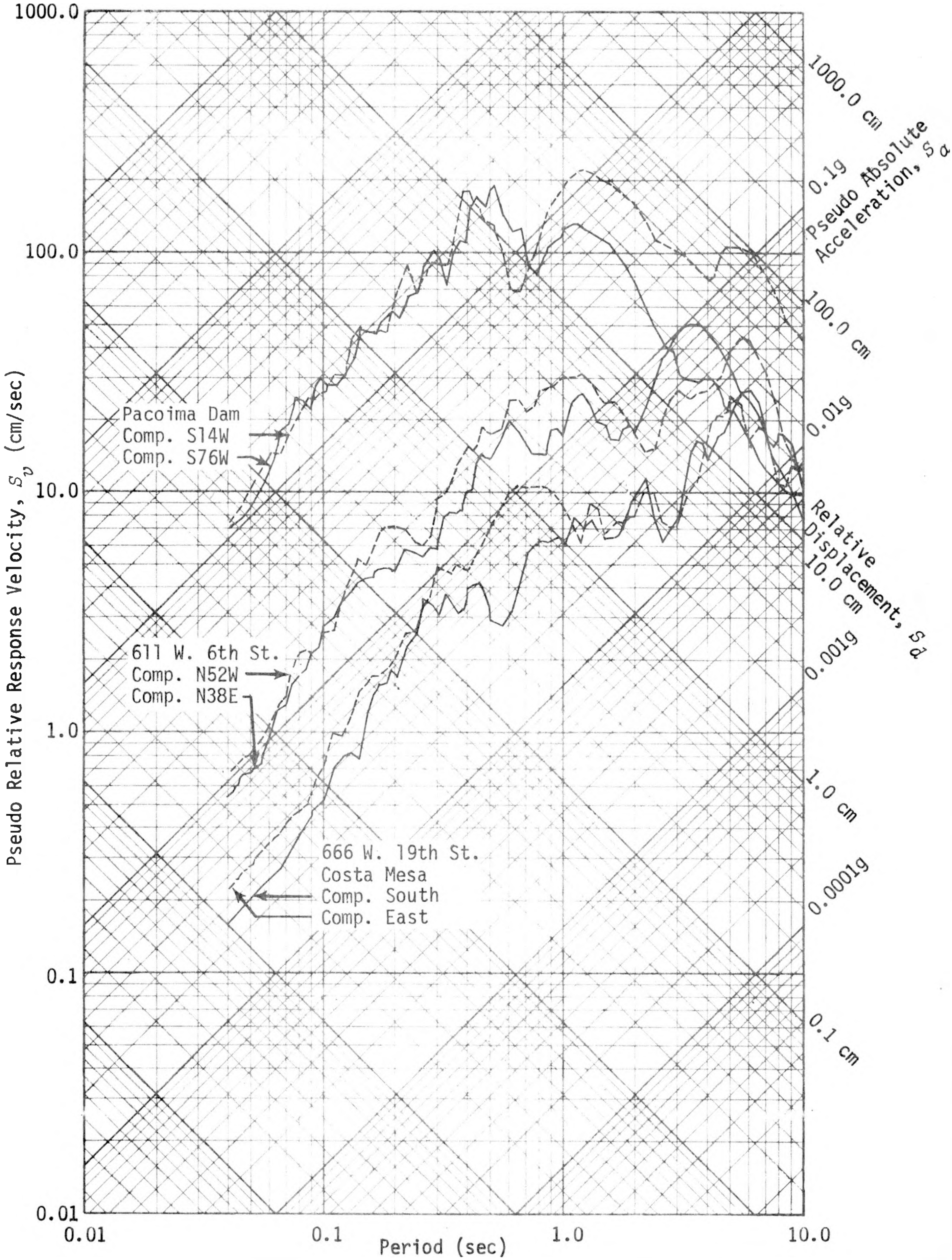


FIGURE 4 RESPONSE SPECTRA FROM ACCELEROGRAMS IN FIGURE 3, HORIZONTAL COMPONENTS, BASED ON 5% DAMPING RATIO

URS/BLUME

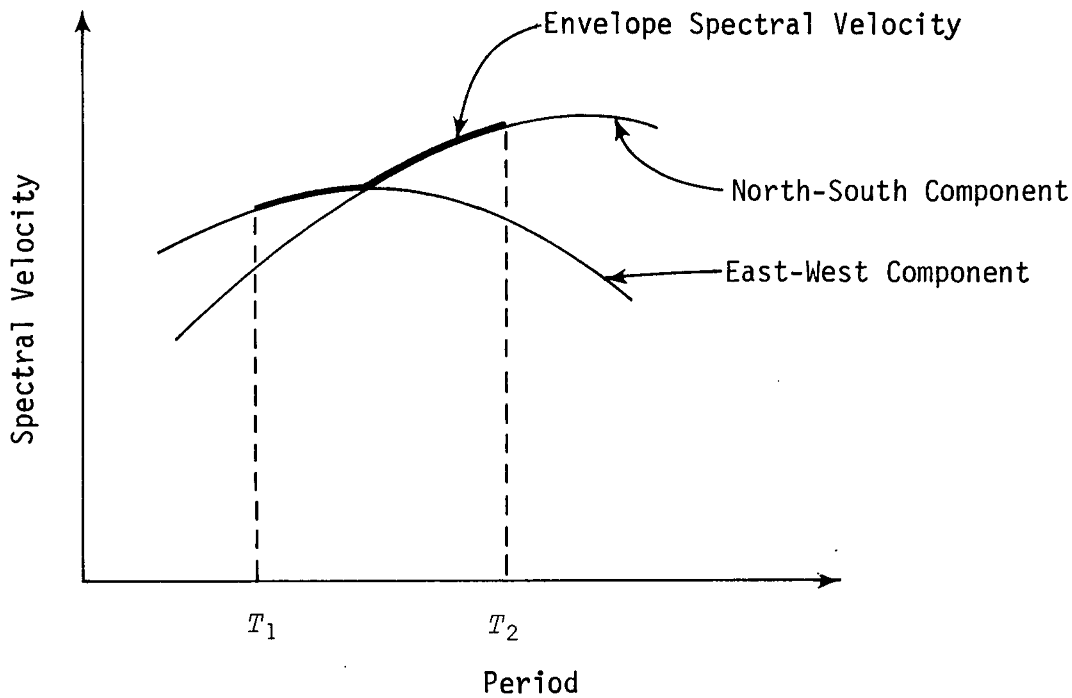


FIGURE 5 GRAPHIC EXPLANATION OF IDEALIZED ENVELOPE SPECTRAL VELOCITY

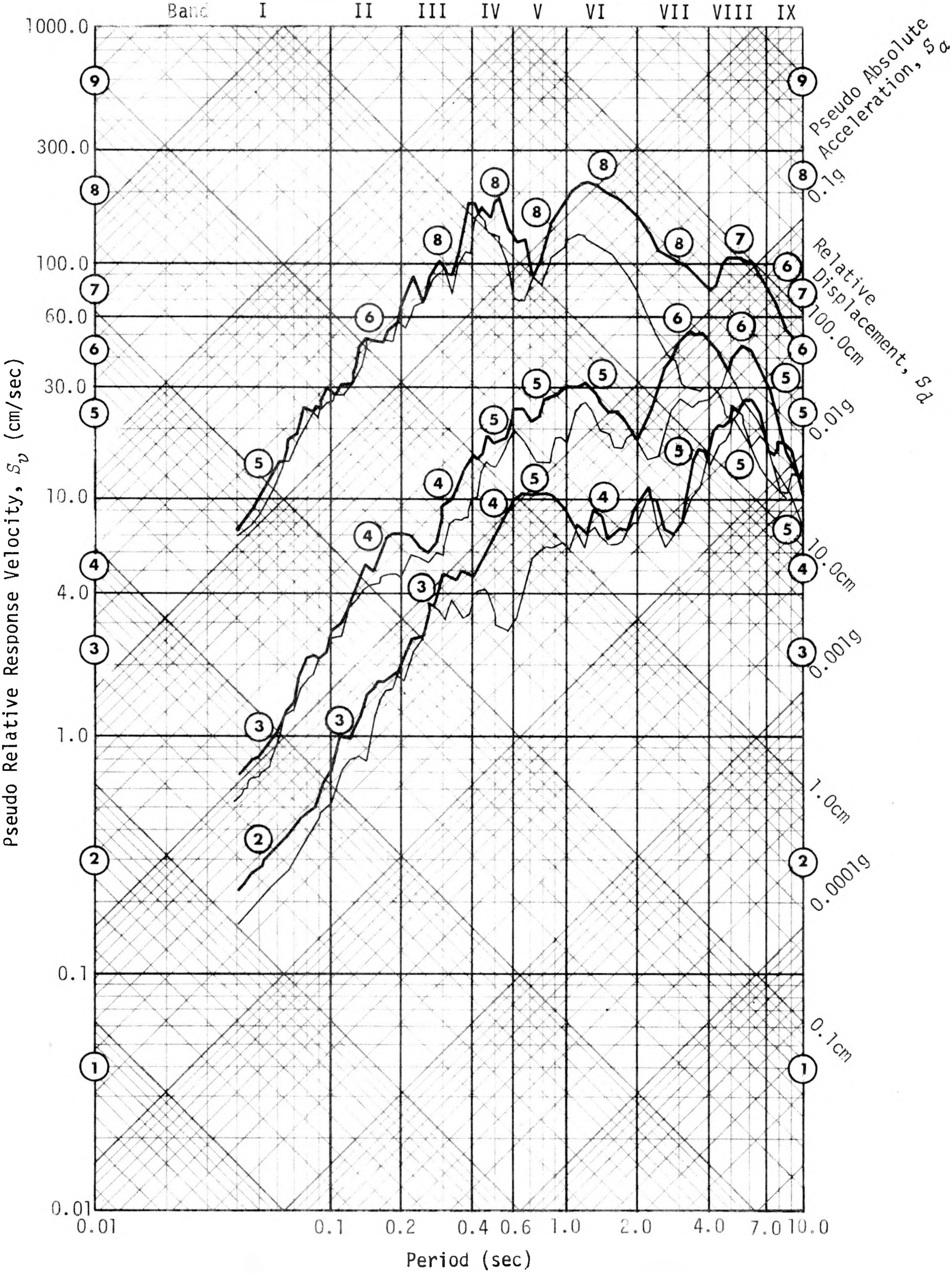


FIGURE 6 ENGINEERING INTENSITY SCALE MATRIX SUPERIMPOSED ON EXAMPLE ENVELOPE RESPONSE SPECTRA

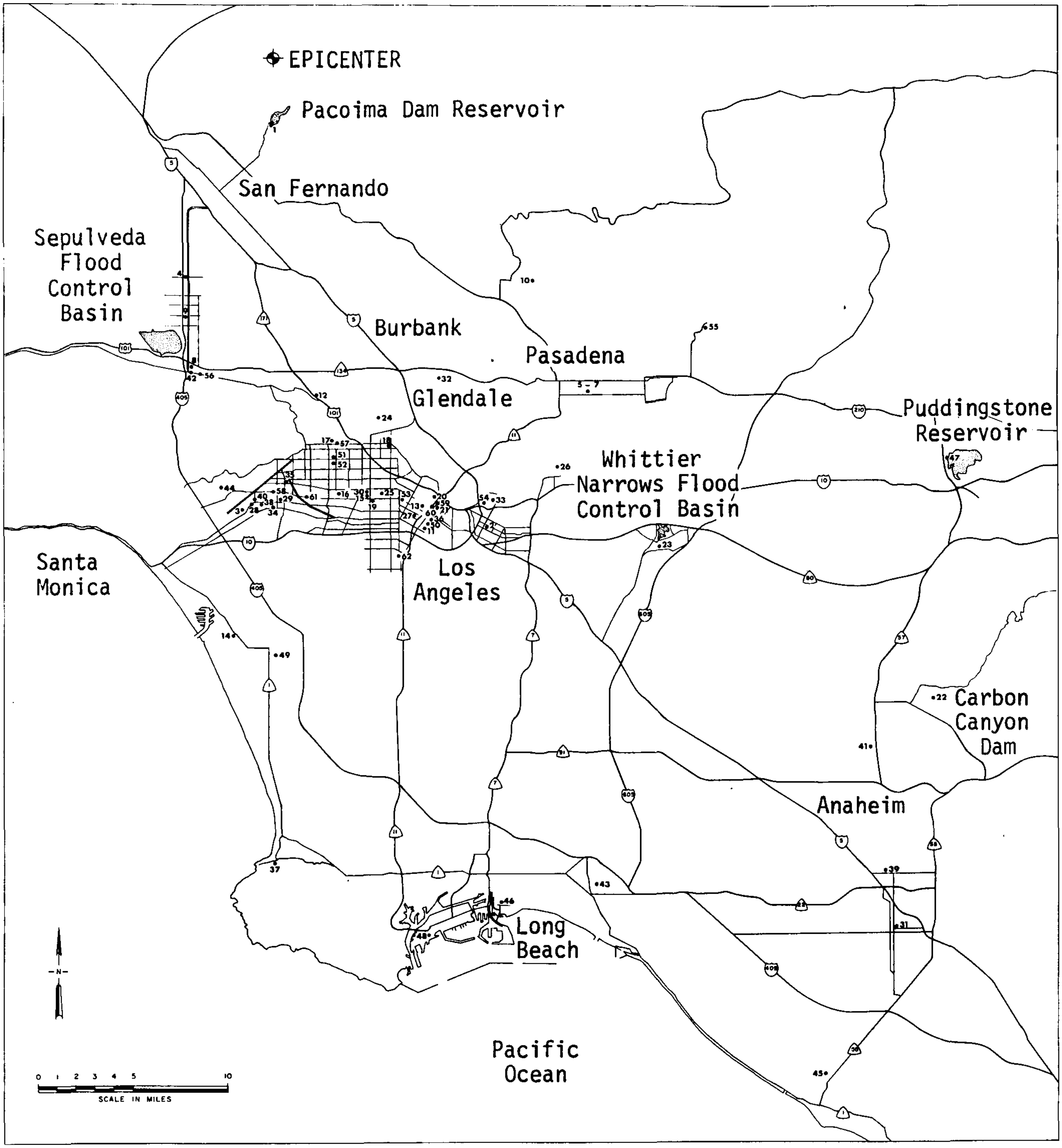


FIGURE 7 LOCATION OF STATIONS USED IN ENGINEERING INTENSITY SCALE GROUND MOTION ANALYSIS

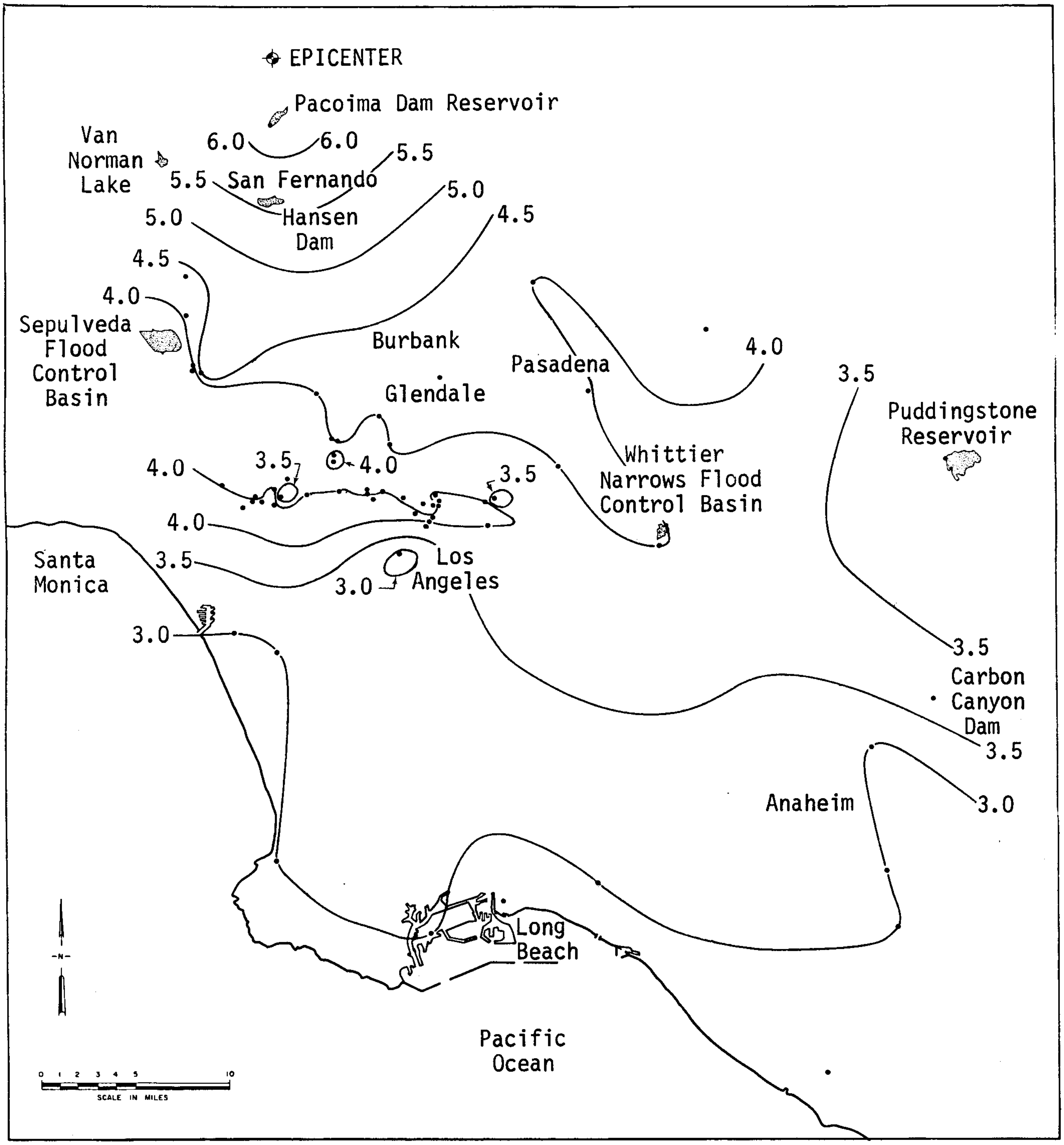


FIGURE 8 ISO-ENGINEERING INTENSITY SCALE PLOT, AVERAGE OF PERIOD BANDS I, II, AND III

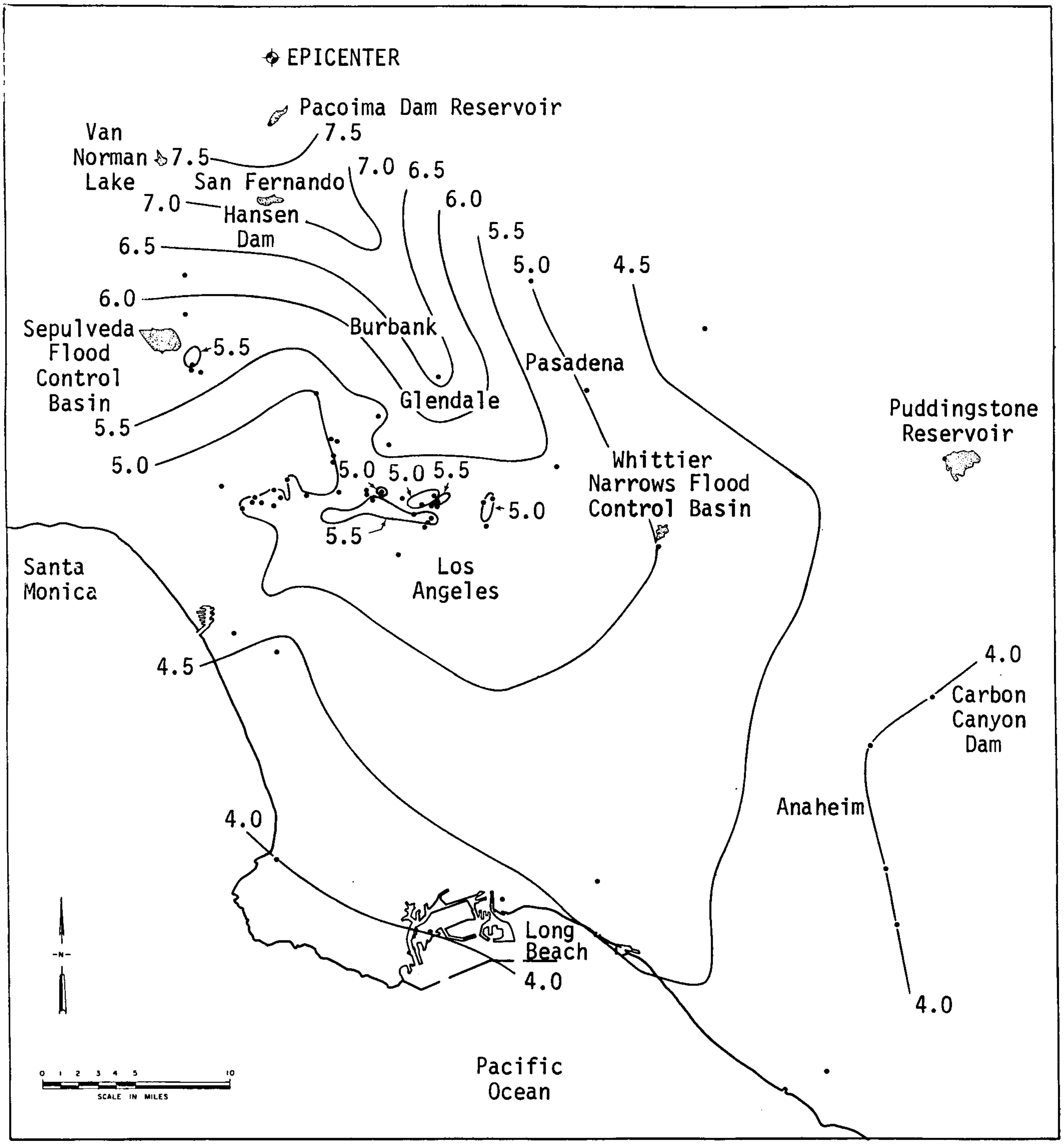


FIGURE 9 ISO-ENGINEERING INTENSITY SCALE PLOT, AVERAGE OF PERIOD BANDS IV, V, AND VI

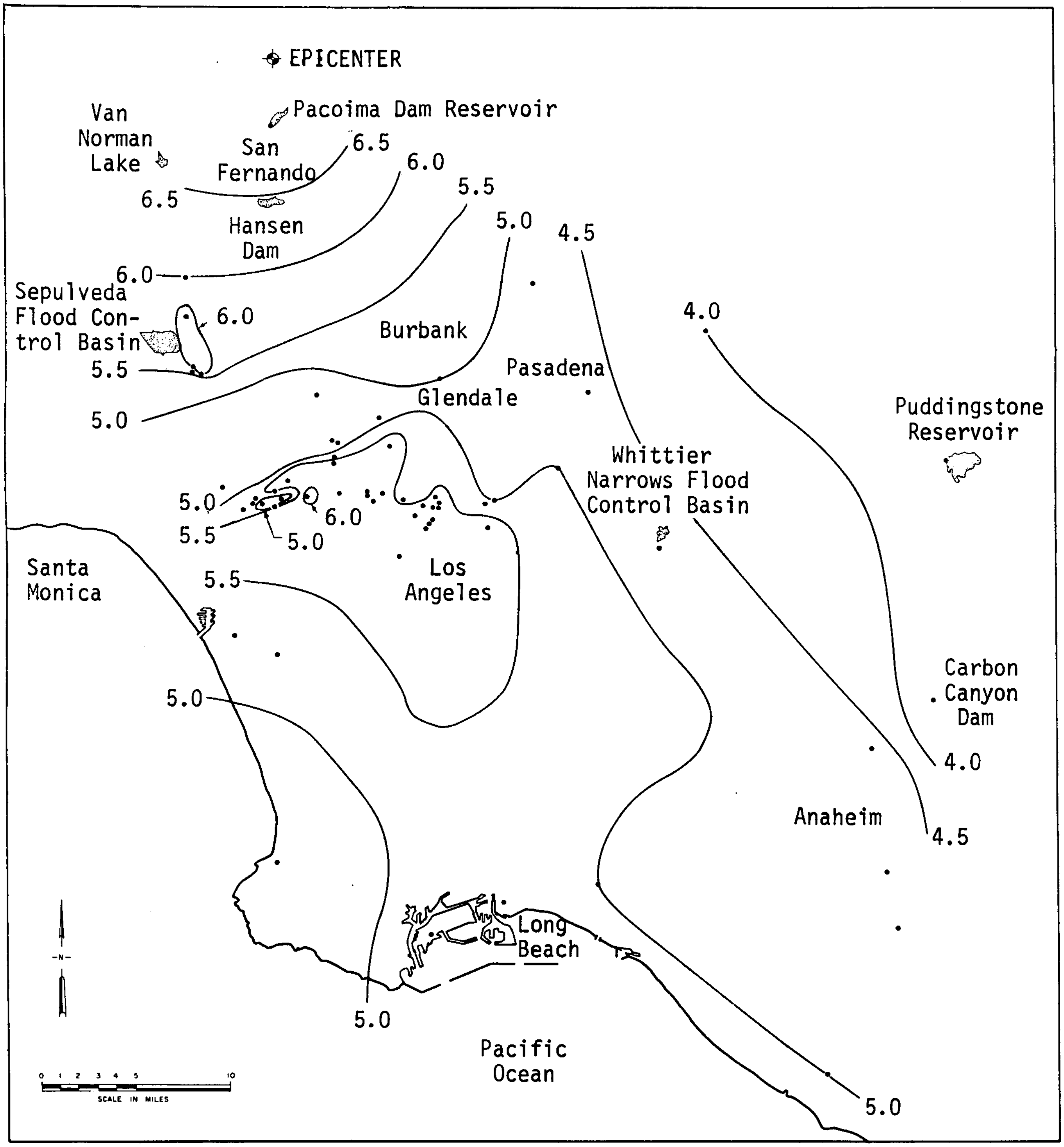


FIGURE 10 ISO-ENGINEERING INTENSITY SCALE PLOT,
AVERAGE OF PERIOD BANDS VII, VIII, AND IX

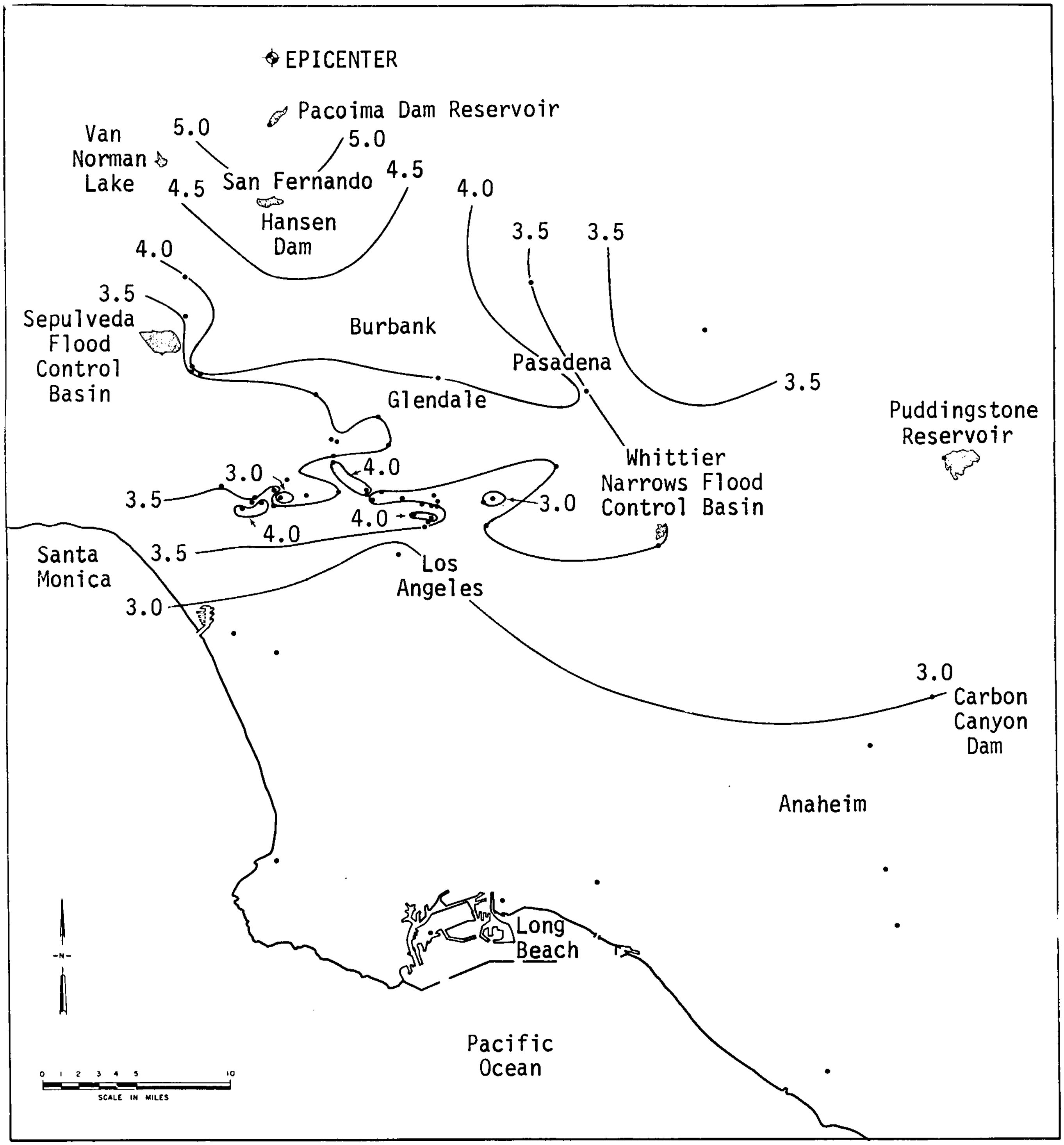


FIGURE 11 ISO-ENGINEERING INTENSITY SCALE PLOT, AVERAGE OF PERIOD BANDS I and II

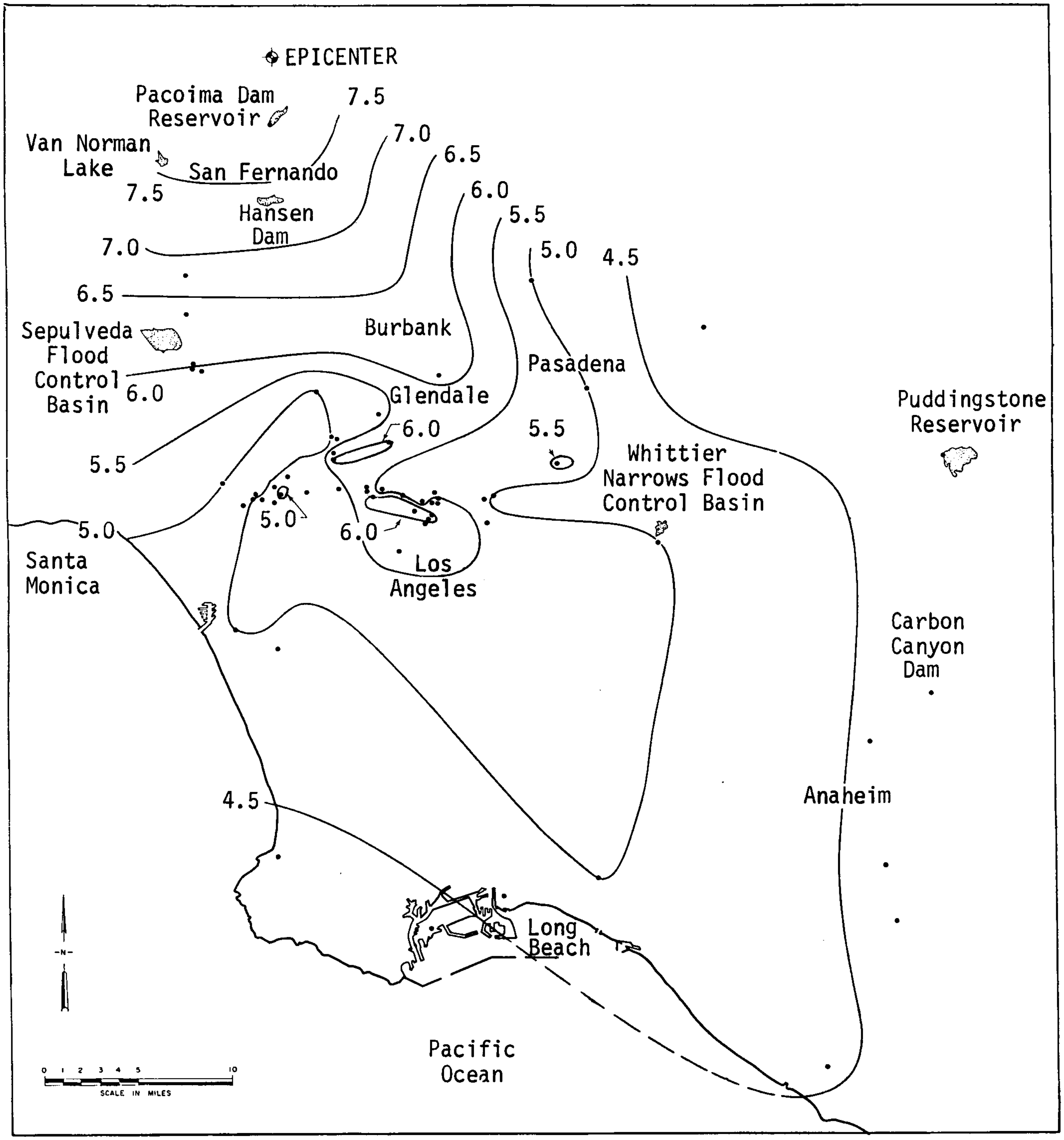


FIGURE 12 ISO-ENGINEERING INTENSITY SCALE PLOT, AVERAGE OF PERIOD BANDS V, VI, AND VII

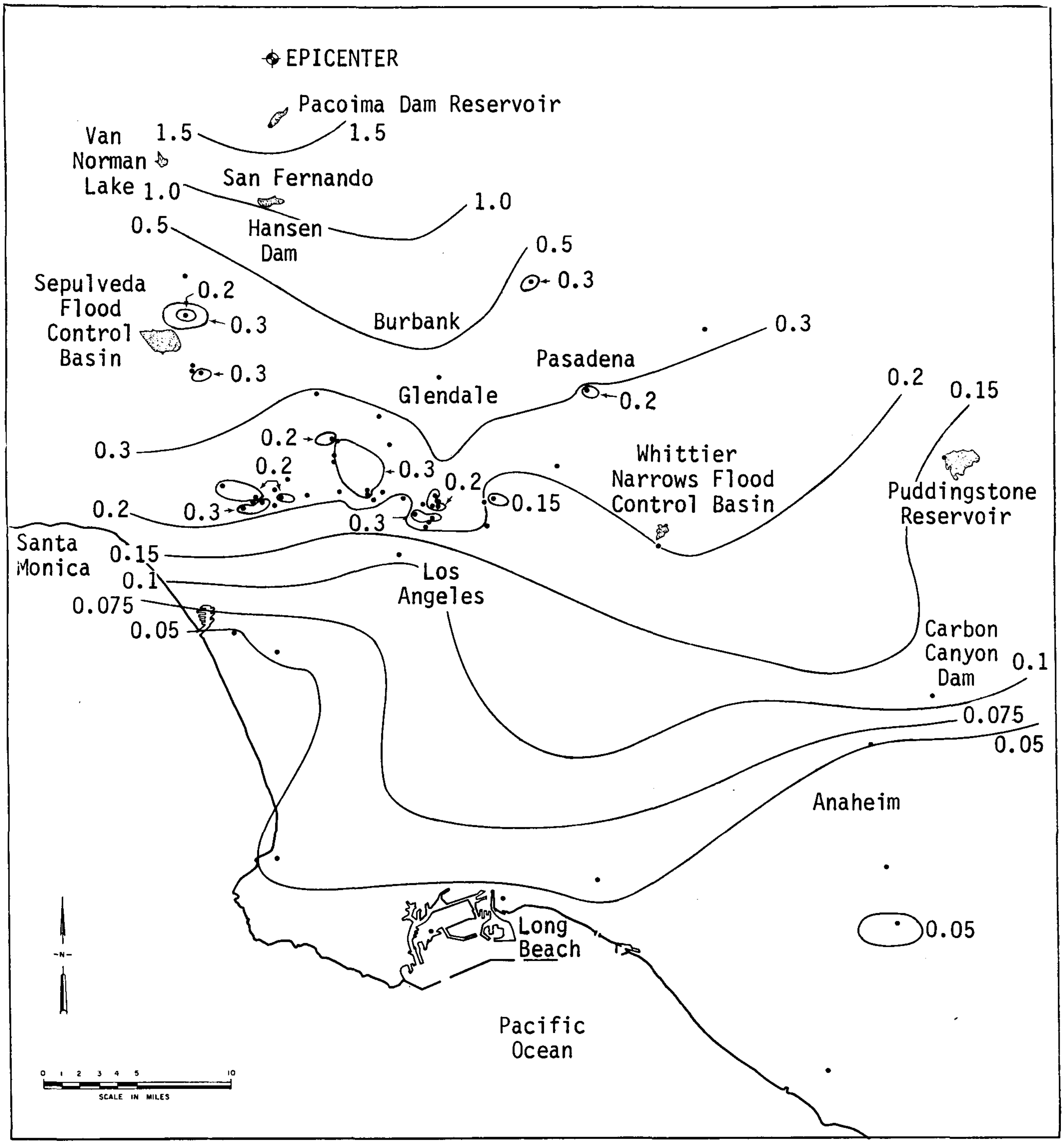


FIGURE 13 ISO-SPECTRAL ACCELERATION CONTOUR LINES, ENVELOPE S_a AVERAGED BETWEEN 0.04 SEC AND 0.2 SEC

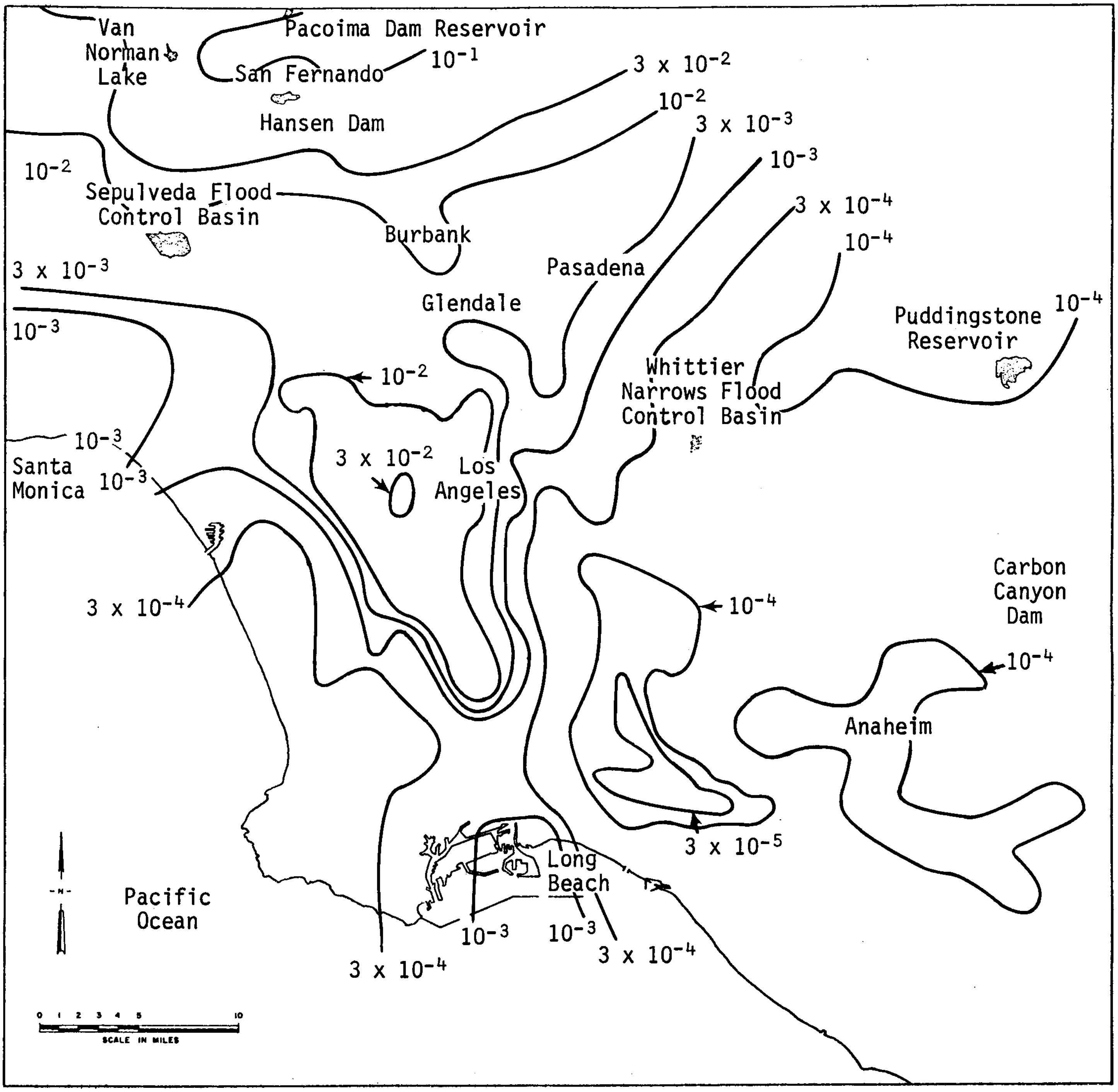


FIGURE 14 LOW-RISE ISO-DAMAGE FACTOR CONTOUR LINES

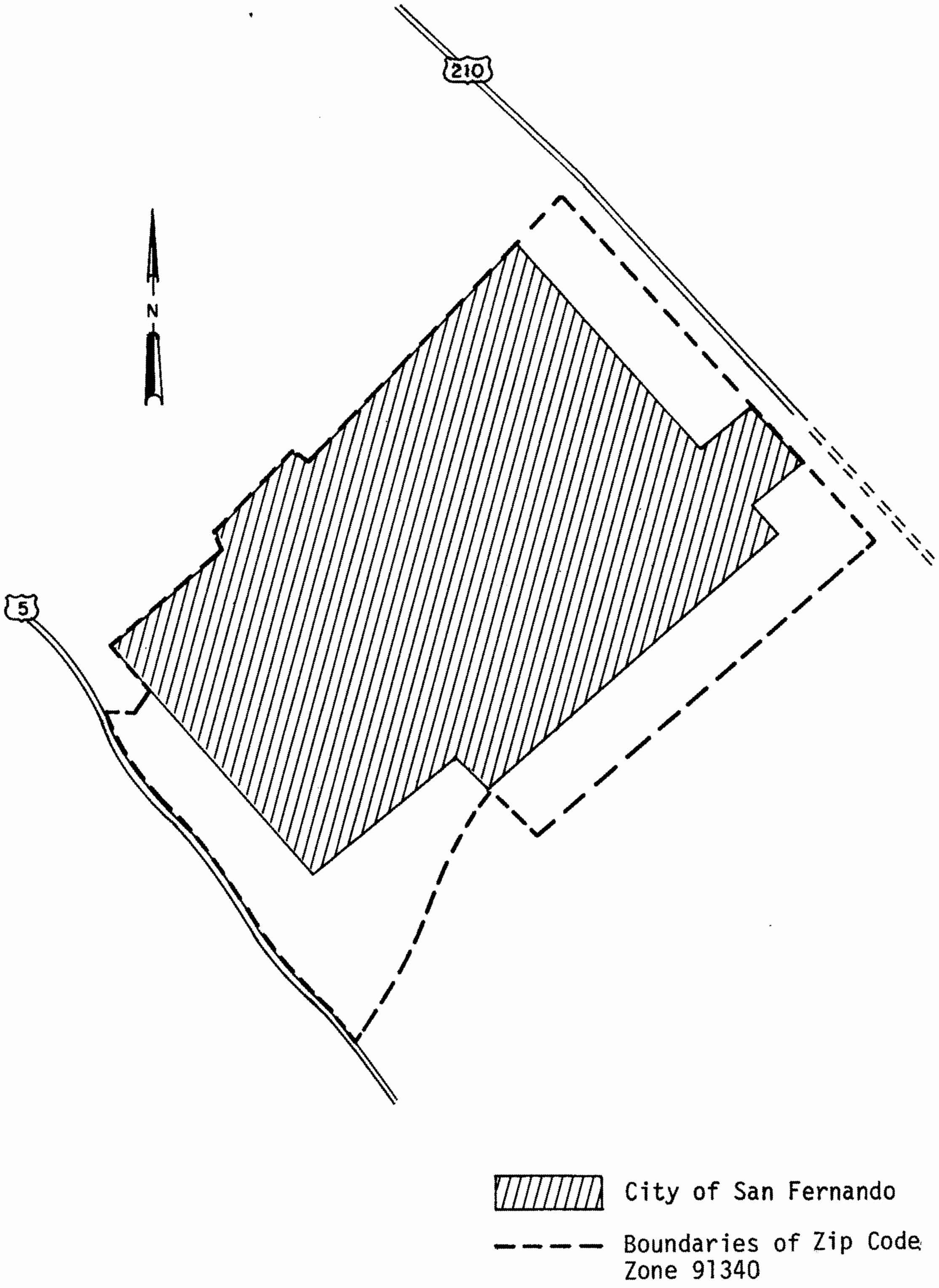


FIGURE 15 CITY LIMITS OF SAN FERNANDO COMPARED WITH ZIP CODE ZONE 91340

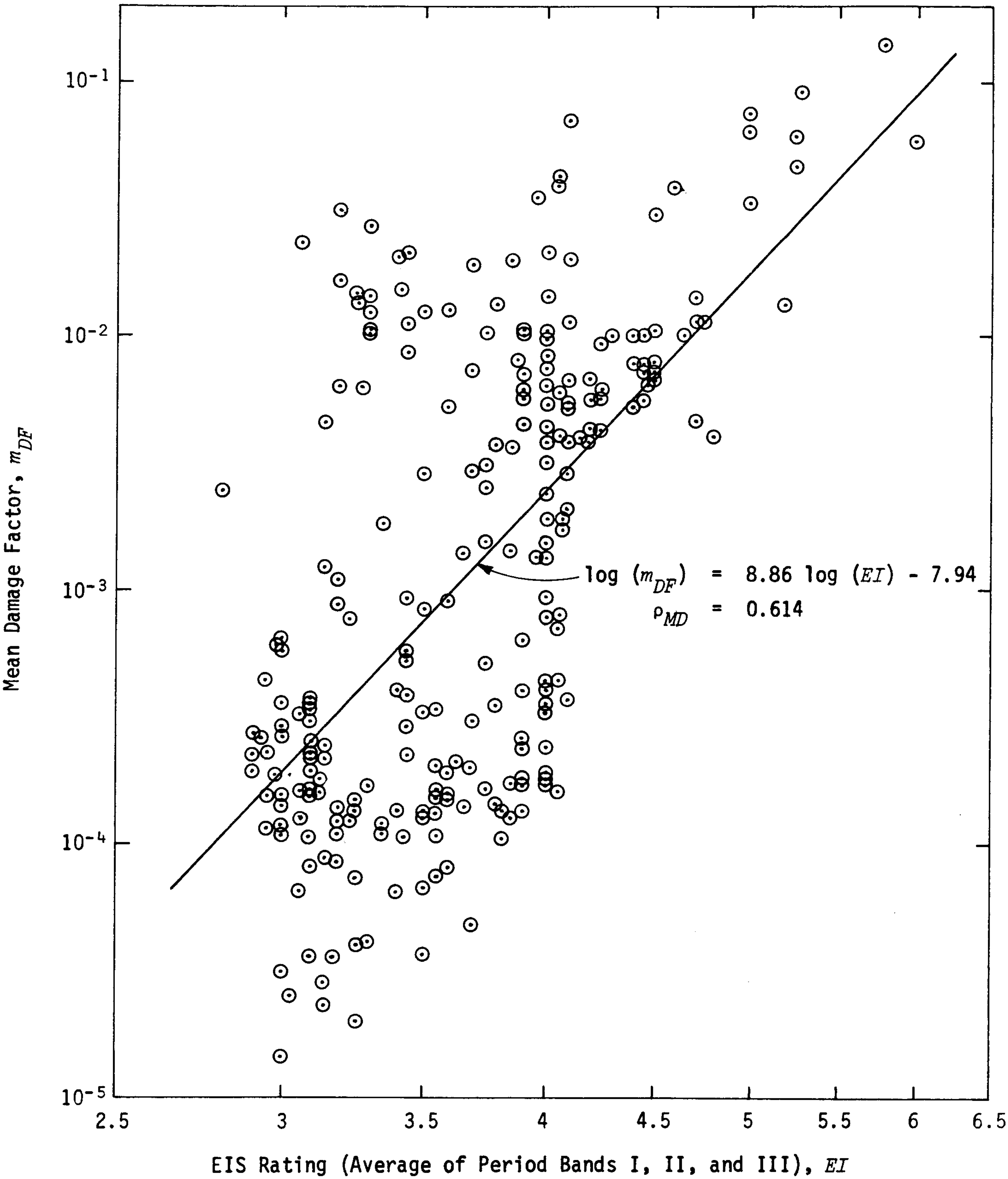


FIGURE 16 PLOT OF LOW-RISE MEAN DAMAGE FACTOR VERSUS GROUND MOTION ($\rho'_{RV,DC} = 0$)

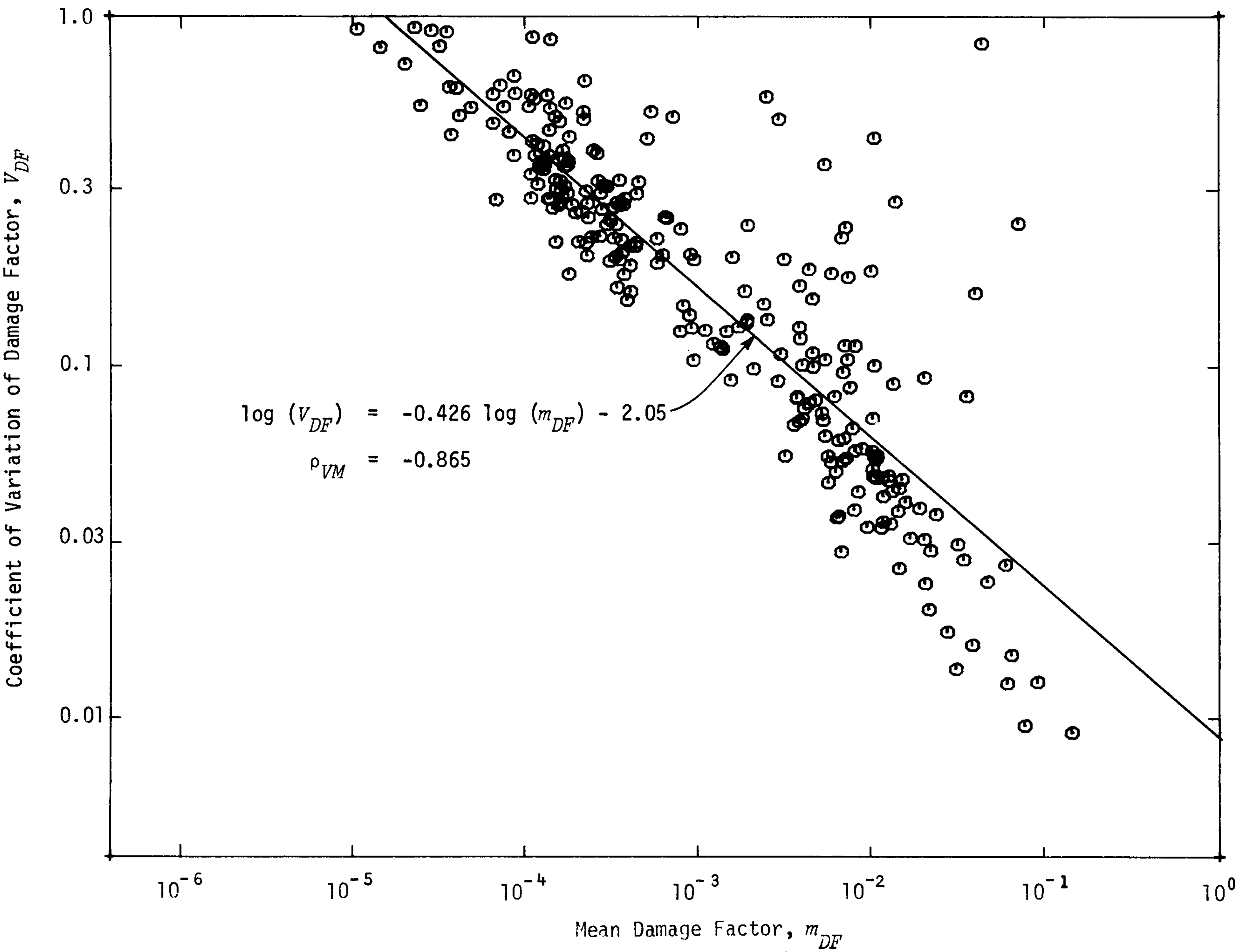


FIGURE 17 PLOT OF LOW-RISE COEFFICIENT OF VARIATION OF DAMAGE FACTOR VERSUS MEAN DAMAGE FACTOR ($\rho'_{RV,DC} = 0$)

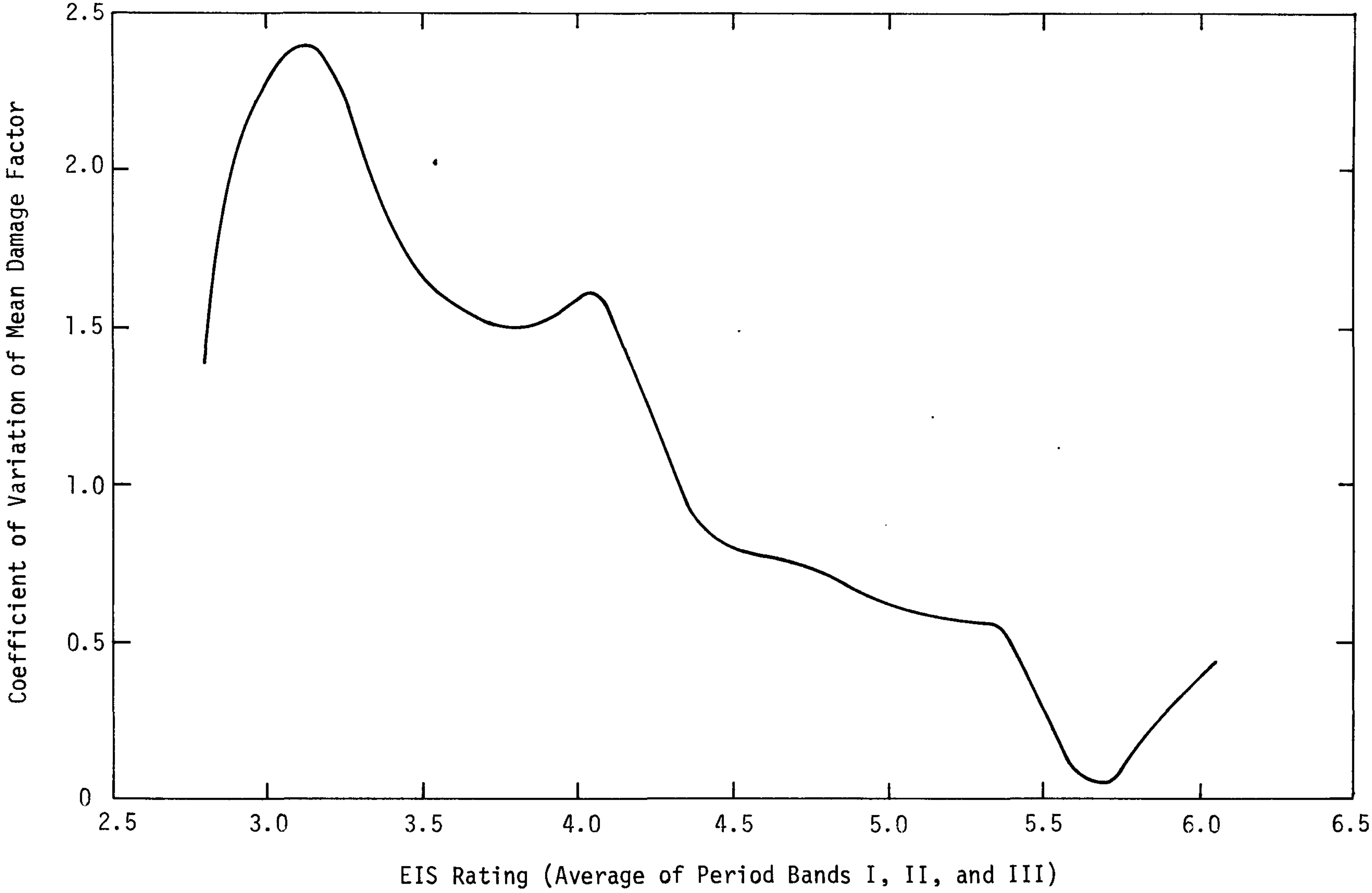


FIGURE 18 LOW-RISE COEFFICIENT OF VARIATION OF MEAN DAMAGE FACTOR VERSUS GROUND MOTION ($\rho'_{RV,DC} = 0$)

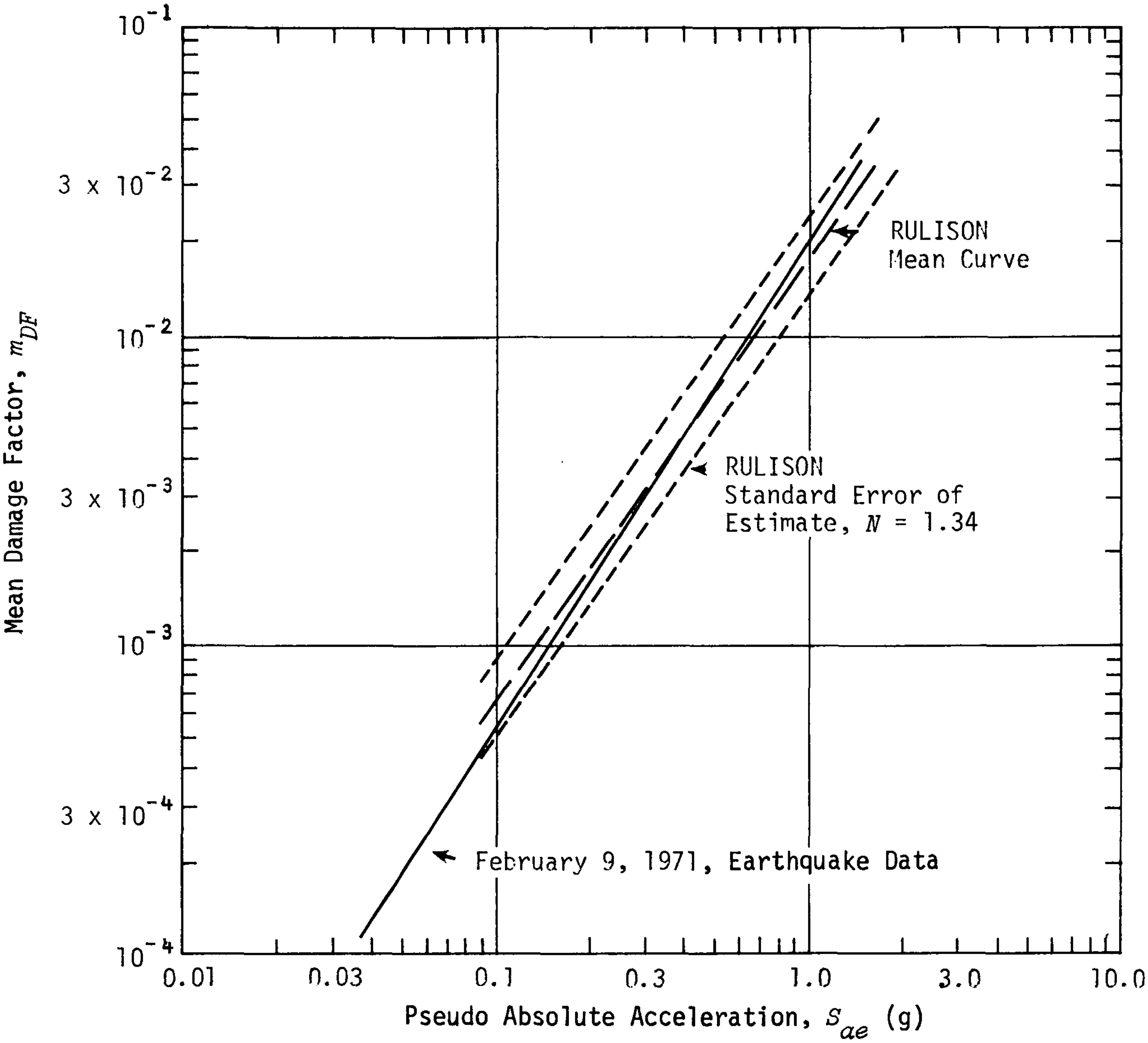


FIGURE 19 COMPARISON OF LOW-RISE RELATIONSHIPS BETWEEN S_{ae} AND MEAN DAMAGE FACTOR. RULISON DATA[7] COMPARED TO FEBRUARY 9, 1971, SAN FERNANDO EARTHQUAKE DATA ($\rho'_{RV,DC} = 0$)

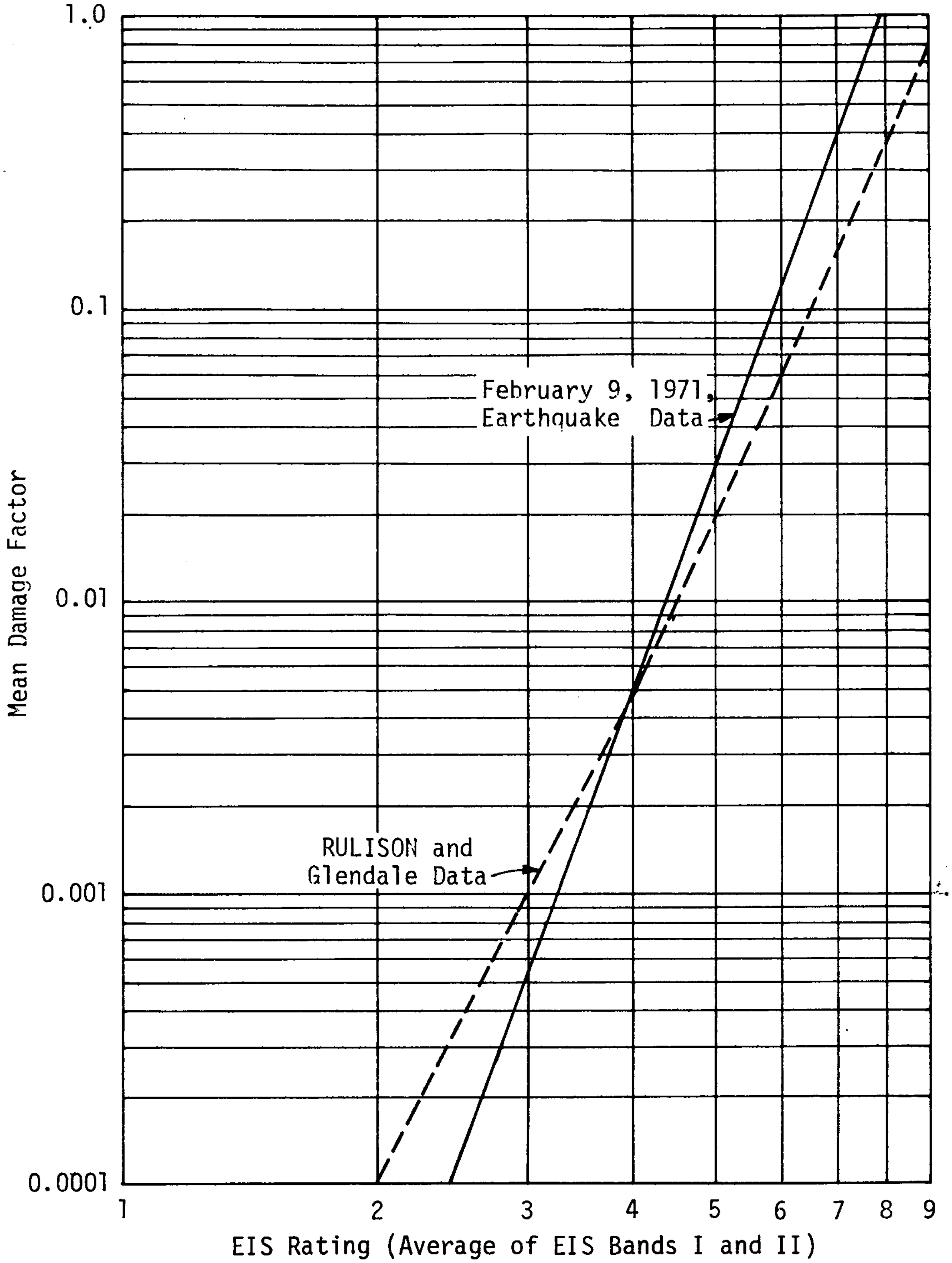


FIGURE 20 COMPARISON OF LOW-RISE RELATIONSHIPS BETWEEN AVERAGE OF EIS BANDS I AND II AND MEAN DAMAGE FACTOR, RULISON/GLENDALE DATA[11] COMPARED TO FEBRUARY 9, 1971, EARTHQUAKE DATA ($\rho'_{RV,DC} = 0$)

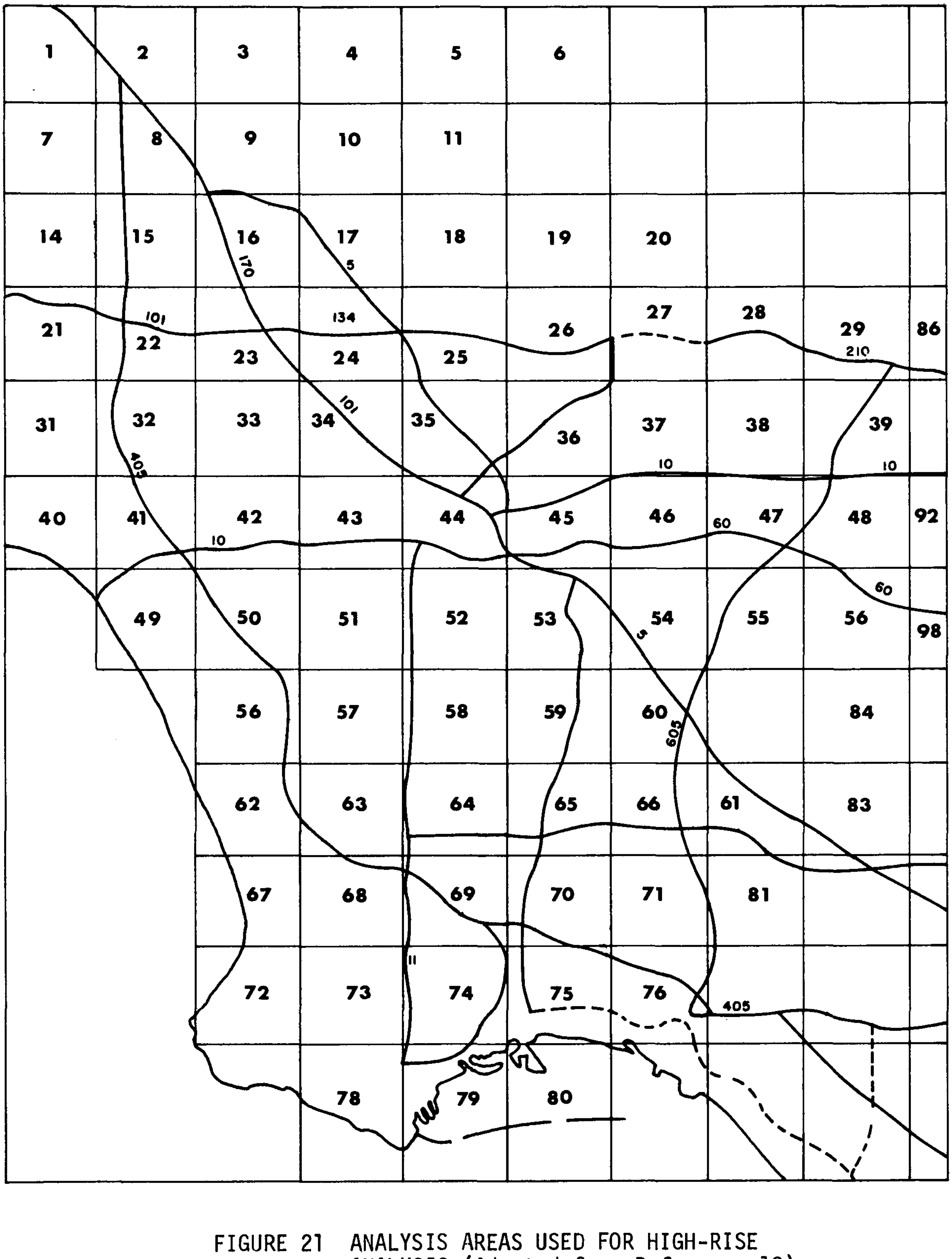


FIGURE 21 ANALYSIS AREAS USED FOR HIGH-RISE ANALYSIS (Adapted from Reference 13)

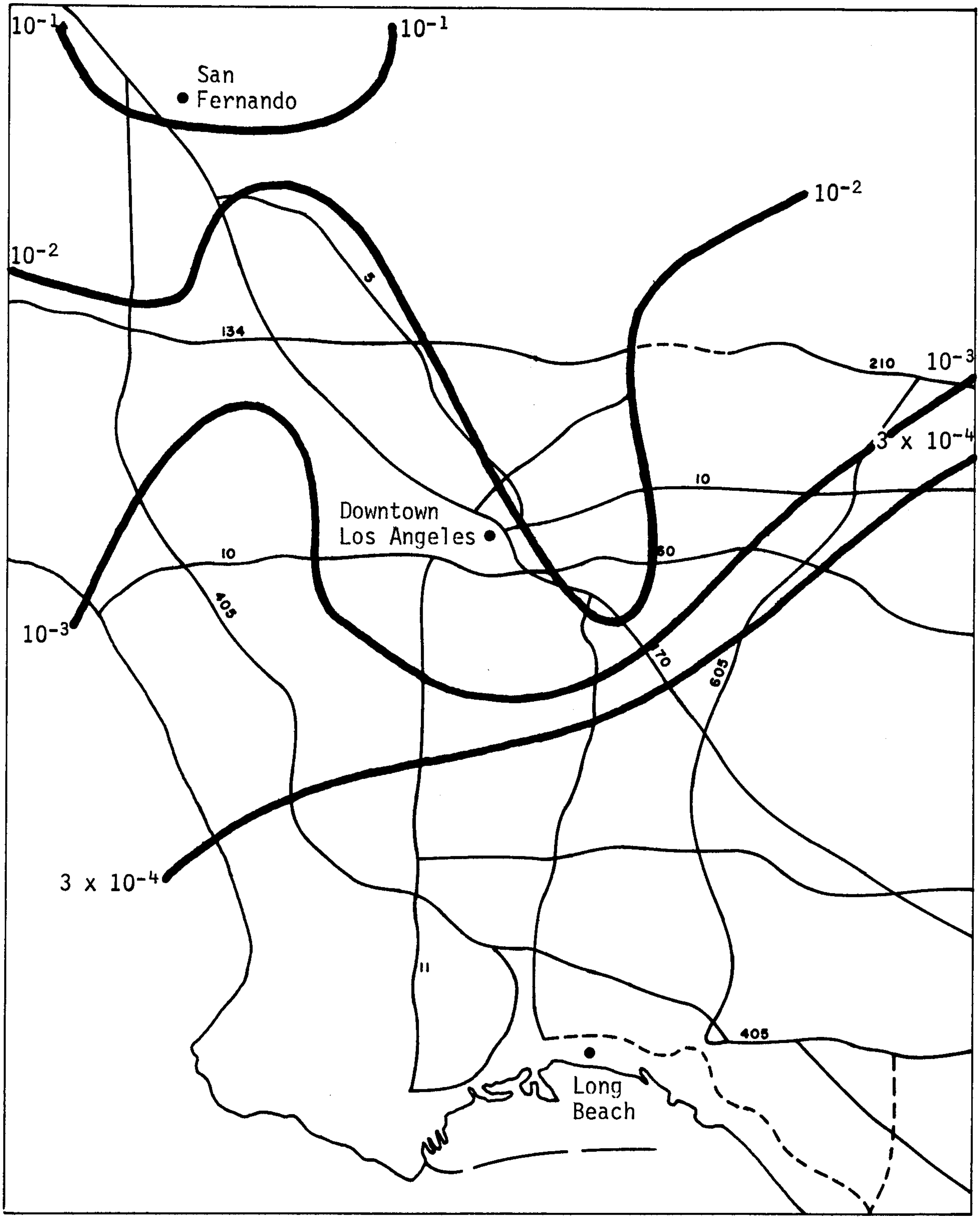


FIGURE 22 HIGH-RISE ISO-DAMAGE FACTOR CONTOUR LINES

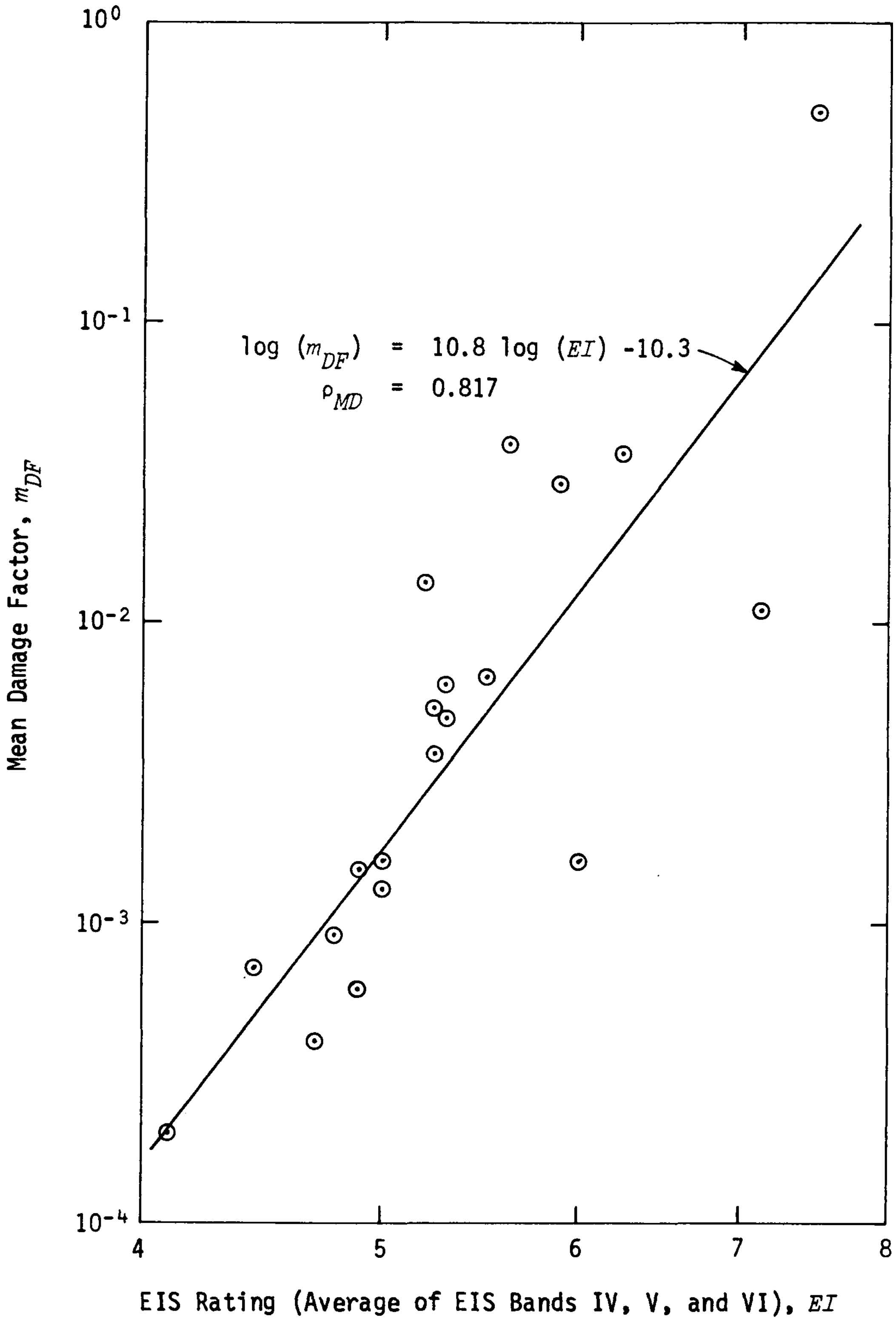


FIGURE 23 PLOT OF HIGH-RISE (Post-1947 Buildings) MEAN DAMAGE FACTOR VERSUS AVERAGE OF EIS BANDS IV, V, AND VI

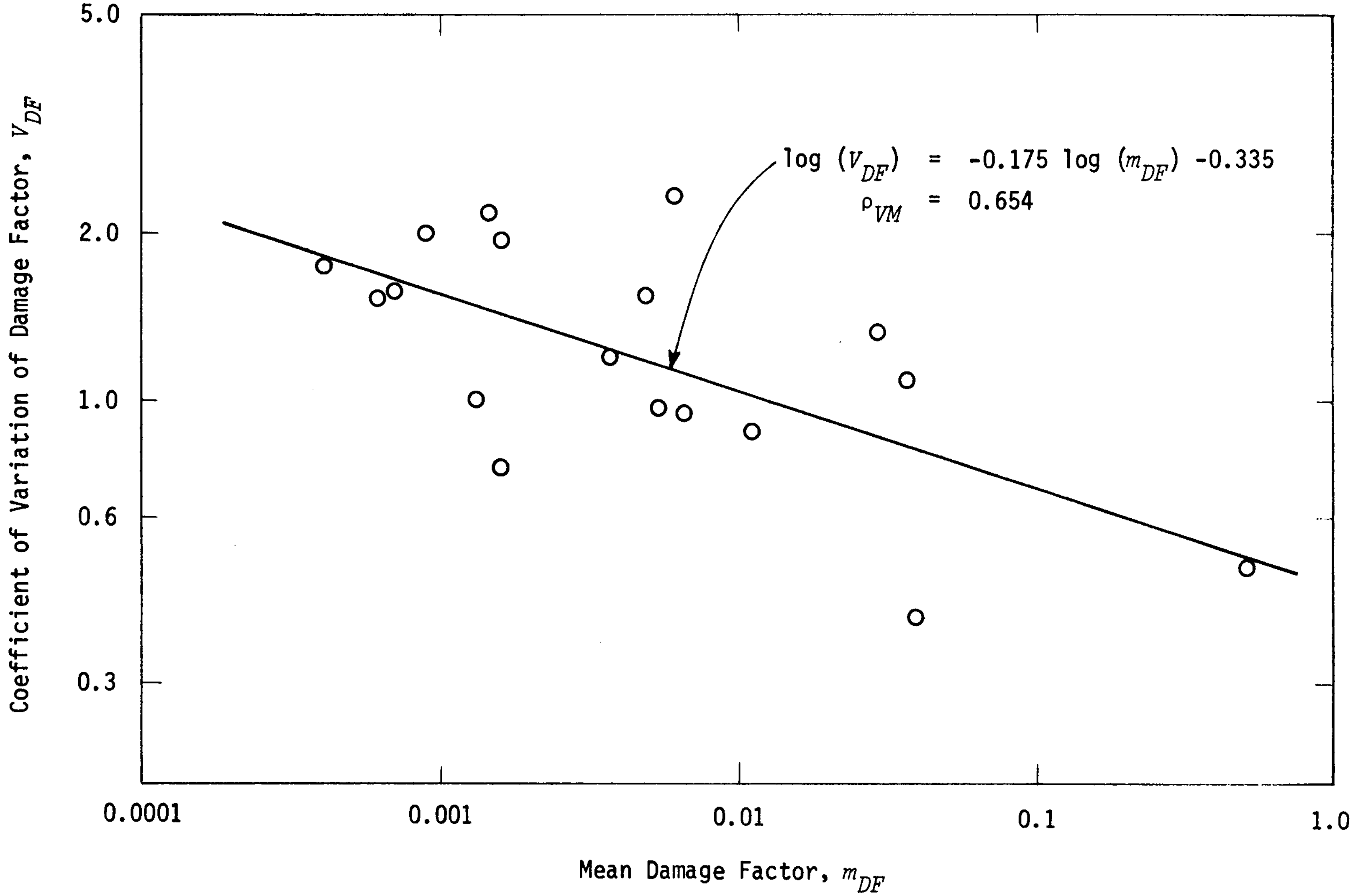


FIGURE 24 PLOT OF HIGH-RISE (Post-1947 Buildings) COEFFICIENT OF VARIATION OF DAMAGE FACTOR VERSUS MEAN DAMAGE FACTOR

APPENDIX A

NOMENCLATURE

NOMENCLATURE

b	y-intercept, in the log-log domain
Cov(w, z)	Covariance of w and z
DC	Damage cost
DF, DF_i	Damage factor, damage factor of ith building
$E[\,]$	Expectancy operator, for only damaged buildings
EI	Engineering intensity scale value
$f(x, y)$	Function of x and y
LV_i	Loan value (repair cost) of ith damaged building
m	Slope of best-fit line, in the log-log domain
m_{DC}	Mean damage cost for all buildings
$m_{DC\|D}$	Mean damage cost for only damaged buildings
m_{DF}	Estimated mean damage factor
m_{RV}	Mean building replacement value
m'_{RV}	Mean replacement value for only damaged buildings
m_w	Mean value of w
m_x	Mean value of x
m_y	Mean value of y
m_z	Mean value of z
MDR	Mean damage ratio
n	Number of buildings
N_D	Number of damaged buildings
N_T	Total number of buildings
RV	Replacement value
S_a	Pseudo absolute acceleration, spectral acceleration
$S_{\overline{ae}}$	Average envelope spectral acceleration within the period band

S_d	Relative displacement
S_v	Spectral velocity, pseudo relative response velocity
T	Period of building
V_{DC}	Coefficient of variation of repair cost for all buildings
$V_{DC\|D}$	Coefficient of variation of repair cost for damaged buildings only
V_{DF}	Coefficient of variation of damage factor
$V_{\overline{DF}}$	Coefficient of variation of mean damage factor
V_{RV}	Coefficient of variation of replacement value
Var[]	Variance operator
x	Ground motion intensity
y	Damage factor statistic
μ_{DF}	True mean damage factor
ρ_{MD}	Correlation coefficient between damage factor statistic and ground motion statistic
$\rho_{RV,DC}$	Correlation coefficient between building replacement value and building damage cost
$\rho'_{RV,DC}$	Correlation coefficient between building replacement value and building damage cost for damaged buildings only
ρ_{VM}	Correlation coefficient between coefficient of variation of damage factor and mean damage factor
ρ_{xy}	Correlation coefficient between x and y
σ_{DC}	Standard deviation damage cost
$\sigma_{DC\|D}$	Standard deviation repair cost for damaged buildings only
σ_{DF}	Standard deviation damage factor
σ_{RV}	Standard deviation replacement value
σ'_{RV}	Standard deviation replacement value for damaged buildings only
σ_x	Standard deviation of x

σ_y	Standard deviation of y
$\sigma_{\log x}$	Standard deviation of $\log x$
$\sigma_{\log y}$	Standard deviation of $\log y$
$\left.\frac{\partial}{\partial x}\right\|_{m_x,\, m_y}$	Partial derivative operator with respect to x evaluated at m_x and m_y
$\left.\frac{\partial^2}{\partial x^2}\right\|_{m_x,\, m_y}$	Second partial derivative operator with respect to x evaluated at m_x and m_y
$\left.\frac{\partial^2}{\partial x \partial y}\right\|_{m_x,\, m_y}$	Mixed partial derivative operator evaluated at m_x and m_y
$\left.\frac{\partial}{\partial y}\right\|_{m_x,\, m_y}$	Partial derivative operator with respect to y evaluated at m_x and m_y
$\left.\frac{\partial^2}{\partial y^2}\right\|_{m_x,\, m_y}$	Second partial derivative operator with respect to y evaluated at m_x and m_y

APPENDIX B

DERIVATIONS: STATISTICAL FORMULAS

DERIVATIONS: STATISTICAL FORMULAS

This appendix presents the derivation of three relationships:

A. The relationship between mean damage factor, m_{DF}, mean damage cost, m_{DC}, and mean replacement value, m_{RV}, including higher-order terms involving the coefficient of variation damage cost, V_{DC}, the coefficient of variation replacement value, V_{RV}, and the correlation coefficient between building replacement value and building damage cost, $\rho_{RV,DC}$.

B. The relationship yielding the coefficient of variation of damage factor from the terms V_{DC}, V_{RV}, and $\rho_{RV,DC}$.

C. The limitation on the value of the correlation coefficient, $\rho_{RV,DC}$.

A. The second order Taylor series approximation to the expected value of a function $f(x, y)$ is given in Reference 12 as:

$$E[f(x, y)] = f(m_x, m_y) + \frac{1}{2}\left.\frac{\partial^2 f}{\partial x^2}\right|_{m_x,\, m_y}\sigma_x^2 + \frac{1}{2}\left.\frac{\partial^2 f}{\partial y^2}\right|_{m_x,\, m_y}\sigma_y^2 + \left.\frac{\partial^2 f}{\partial x \partial y}\right|_{m_x,\, m_y}\rho_{xy}\sigma_x\sigma_y$$

In the case we are studying,

$$f(x, y) = x/y$$

where:

$f(x, y)$ = the damage factor

x = the damage cost

y = the replacement value

The following statements may then be written:

$$E[f(x, y)] = m_{DF}$$

$$f(m_x, m_y) = \frac{m_x}{m_y} = \frac{m_{DC}}{m_{RV}}$$

$$\left.\frac{\partial^2 f}{\partial x^2}\right|_{m_x,\ m_y} = 0$$

$$\left.\frac{\partial^2 f}{\partial y^2}\right|_{m_x,\ m_y} = \frac{2m_x}{m_y^3} = \frac{2m_{DC}}{m_{RV}^3}$$

$$\left.\frac{\partial^2 f}{\partial x \partial y}\right|_{m_x,\ m_y} = -\frac{1}{m_y^2} = -\frac{1}{m_{RV}^2}$$

Substitution into the expression for $E[f(x, y)]$ yields:

$$m_{DF} = \frac{m_{DC}}{m_{RV}} + \left(\frac{m_{DC}}{m_{RV}^3}\right)\sigma_{RV}^2 - \left(\frac{1}{m_{RV}^2}\right)\rho_{RV,DC}\sigma_{DC}\sigma_{RV}$$

By use of the two relationships

$$V_{RV} = \sigma_{RV}/m_{RV}$$

$$V_{DC} = \sigma_{DC}/m_{DC}$$

the final equation for the mean damage factor is obtained:

$$m_{DF} = \frac{m_{DC}}{m_{RV}}\left[1 + V_{RV}^2 - \rho_{RV,DC}V_{DC}V_{RV}\right]$$

B. To obtain the coefficient of variation, the first-order approximation for the variance of a function $f(x, y)$ is used:

$$\mathrm{Var}[f(x, y)] = \left(\left.\frac{\partial f}{\partial x}\right|_{m_x,\ m_y}\right)^2 \sigma_x^2 + \left(\left.\frac{\partial f}{\partial y}\right|_{m_x,\ m_y}\right)^2 \sigma_y^2$$

$$+ 2\left.\frac{\partial f}{\partial y}\right|_{m_x,\ m_y}\left.\frac{\partial f}{\partial x}\right|_{m_x,\ m_y}\rho_{xy}\sigma_x\sigma_y$$

The following equations are then needed:

$$\mathrm{Var}[f(x, y)] = \sigma_{DF}^2$$

$$\left.\frac{\partial f}{\partial x}\right|_{m_x, m_y} = \frac{1}{m_y} = \frac{1}{m_{RV}}$$

$$\left.\frac{\partial f}{\partial y}\right|_{m_x, m_y} = -\frac{m_x}{m_y^2} = -\frac{m_{DC}}{m_{RV}^2}$$

The equation for the variance becomes:

$$\sigma_{DF}^2 = \left(\frac{1}{m_{RV}^2}\right)\sigma_{DC}^2 + \left(\frac{m_{DC}^2}{m_{RV}^4}\right)\sigma_{RV}^2 + 2\left(\frac{1}{m_{RV}}\right)\left(-\frac{m_{DC}}{m_{RV}^2}\right)\rho_{VD}\sigma_{DC}\sigma_{RV}$$

Substitution of the expressions for the coefficients of variation gives:

$$V_{DF}^2 m_{DF}^2 = \frac{m_{DC}^2}{m_{RV}^2}\left[V_{DC}^2 + V_{RV}^2 - 2\rho_{RV,DC}V_{DC}V_{RV}\right]$$

Dividing by m_{DF}^2 and then substituting the former expression for m_{DF} yields:

$$V_{DF}^2 = \frac{V_{DC}^2 + V_{RV}^2 - 2\rho_{RV,DC}V_{DC}V_{RV}}{\left(1 + V_{RV}^2 - \rho_{RV,DC}V_{DC}V_{RV}\right)^2}$$

Therefore, the coefficient of variation is given by:

$$V_{DF} = \frac{\sqrt{V_{DC}^2 + V_{RV}^2 - 2\rho_{RV,DC}V_{DC}V_{RV}}}{1 + V_{RV}^2 - \rho_{RV,DC}V_{DC}V_{RV}}$$

C. The following assumptions are made to obtain the limitation on the correlation coefficient, $\rho_{RV,DC}$:

1. The mean replacement value of all buildings, m_{RV}, is the same as the mean replacement value of damaged buildings only, m'_{RV}.
2. The standard deviation of building replacement value for all buildings, σ_{RV}, is the same as the standard deviation of the building replacement value for damaged buildings only, σ'_{RV}.

The ratio of the motion-damage correlation coefficient for all buildings, $\rho_{RV,DC}$, to the correlation coefficient for damaged buildings only, $\rho'_{RV,DC}$, is given by:

$$\frac{\rho_{RV,DC}}{\rho'_{RV,DC}} = \frac{E[RV \times DC] - m_{RV}m_{DC}}{\sigma_{RV}\sigma_{DC}} \times \frac{\sigma'_{RV}\sigma_{DC|D}}{E'[RV \times DC] - m'_{RV}m_{DC|D}}$$

where:

$E[RV \times DC]$ = the mean value of the product of the replacement cost and the damage cost, for all buildings

$E'[RV \times DC]$ = the mean value of the product of the replacement cost and the damage cost, for damaged buildings only

Because the damage cost for undamaged buildings is zero,

$$E[RV \times DC] = \frac{N_D}{N_T} E'[RV \times DC]$$

where:

N_D = the number of damaged building

N_T = the total number of buildings

The following relationships also hold:

$$m_{DC} = \frac{N_D}{N_T} m_{DC|D}$$

$$\sigma_{DC} = V_{DC} m_{DC} = \frac{N_D}{N_T} V_{DC} m_{DC|D}$$

$$\sigma_{DC|D} = V_{DC|D} m_{DC|D}$$

The ratio now becomes:

$$\frac{\rho_{RV,DC}}{\rho'_{RV,DC}} = \frac{\frac{N_D}{N_T} E'[RV \times DC] - m_{RV}\left(\frac{N_D}{N_T} m_{DC}\right)}{\sigma_{RV}\left(\frac{N_D}{N_T} V_{DC} m_{DC|D}\right)} \times \frac{\sigma'_{RV}\left(V_{EC|D} m_{DC|D}\right)}{E'[RV \times DC] - m'_{RV} m_{DC|D}}$$

$$\frac{\rho_{RV,DC}}{\rho'_{RV,DC}} = \frac{V_{DC|D}}{V_{DC}}$$

Since $-1 \leq \rho'_{RV,DC} \leq 1$, the final equation becomes:

$$|\rho_{RV,DC}| \leq \frac{V_{DC|D}}{V_{DC}}$$