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Evaluation of Seismic Safety of Buildings

Report No. 10

STRONG-MOTION DURATION OF EARTHQUAKES

by

Erik H. Vanmarcke

and

Shih-sheng P. Lai

July 1977

Sponsored by
National Science Foundation
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and Technology
Grant ENV 76-19021

MIT

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Massachusetts Institute of Technology
Department of Civil Engineering
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Cambridge, Massachusetts 02139

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A simple procedure is proposed to estimate the strong-motion duration of earthquake motions. The proposed strong-motion duration is nearly proportional to the quantity I_o/a^2_{max}, in which a_{max} is the maximum ground acceleration and I_o is the integral of the squared accelerations. The proportionality factor is weakly dependen on the predominant period of the ground motion. The procedure has been applied to 140 horizontal components of strong earthquake ground motions. The results are tabulated and summarized in the form of histograms. The dependence of strong-motion duration on earthquake magnitude and epicentral distance is also examined.

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ABSTRACT

A simple procedure is proposed to estimate the strong-motion duration of earthquake ground motions. The proposed strong-motion duration is nearly proportional to the quantity I_0/a^2_{max}, in which a_{max} is the maximum ground acceleration and I_0 is the integral of the squared accelerations. The proportionality factor is weakly dependent on the predominant period of the ground motion. The procedure has been applied to 140 horizontal components of strong earthquake ground motions. The results are tabulated and summarized in the form of histograms. The dependence of strong-motion duration on earthquake-magnitude and epicentral distance is also examined.

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PREFACE

This is the tenth report prepared under the research project entitled "Evaluation of Seismic Safety of Buildings," supported by National Science Foundation Grant ATA 74-06935 and its continuation Grant ENV 76-19021.

The purpose of the supporting project is to evaluate the effectiveness of the total seismic design process, which consists of steps beginning with seismic risk analysis through dynamic analysis and the design of structural components. The project seeks to answer the question: "Given a set of procedures for these steps, what is the actual degree of protection against earthquake damage provided?" Alternative methods of analysis and design are being considered. Specifically, these alternatives are built around three methods of dynamic analysis: (1) time-history analysis, (2) response spectrum modal analysis, and (3) random vibration analysis.

The formal reports produced thus far are:

1. Arnold, Peter, Vanmarcke, Erik H., and Gazetas, George, "Frequency Content of Ground Motions during the 1971 San Fernando Earthquake," M.I.T. Department of Civil Engineering Research Report R76-3, Order No. 526, January 1976.
2. Gasparini, Dario, and Vanmarcke, Erik H., "Simulated Earthquake Motion Compatible with Prescribed Response Spectra," M.I.T. Department of Civil Engineering Research Report R76-4, Order No. 527, January 1976.
3. Vanmarcke, Erik H., Biggs, J.M., Frank, Robert, Gazetas, George, Arnold, Peter, Gasparini, Dario A., and Luyties, William, "Comparison of Seismic Analysis Procedures for Elastic Multi-degree Systems," M.I.T. Department of Civil Engineering Research Report R76-5, Order No. 528, January 1976.
4. Frank, Robert, Anagnostopoulos, Stavros, Biggs, J.M., and Vanmarcke, Erik H., "Variability of Inelastic Structural Response Due to Real and Artificial Ground Motions," M.I.T. Department of Civil Engineering Research Report R76-6, Order No. 529, January 1976.
5. Haviland, Richard, "A Study of the Uncertainties in the Fundamental Translational Periods and Damping Values for Real Buildings," Supervised by Professors J. M. Biggs and Erik H. Vanmarcke, M.I.T. Department of Civil Engineering Research Report R76-12, Order No. 531, February 1976.
6. Luyties, William H. III, Anagnostopoulos, Stavros, and Biggs, John M., "Studies on the Inelastic Dynamic Analysis and Design of Multi-Story Frames," M.I.T. Department of Civil Engineering Research Report R76-29, Order No. 548, July 1976.

7. Gazetas, George, "Random Vibration Analysis of Inelastic Multi-Degree-of-Freedom Systems Subjected to Earthquake Ground Motions," Supervised by Professor Erik H. Vanmarcke, M.I.T. Department of Civil Engineering Research Report R76-39, Order No. 556, August 1976.
8. Haviland, Richard W., Biggs, John M., and Anagnostopoulos, Stavros A., "Inelastic Response Spectrum Design Procedures for Steel Frames," M.I.T. Department of Civil Engineering Research Report R76-40, Order No. 557, September 1976.
9. Gasparini, Dario A., "On the Safety Provided by Alternate Seismic Design Methods," Supervised by Erik H. Vanmarcke and John M. Biggs, M.I.T. Department of Civil Engineering Research Report R77-22, Order No. 573, July 1977.

The project is supervised by Professors John M. Biggs and Erik H. Vanmarcke of the Civil Engineering Department. They have been assisted by Dr. Stavros Anagnostopoulos, a Research Associate in the Department. The research assistants on the project have been Peter Arnold, George Gazetas, Dario Gasparini, Robert Frank, William Luyties, Richard Haviland, Shih-sheng P. Lai, Ricardo Binder, and James Robinson.

STRONG-MOTION DURATION OF EARTHQUAKES

by Erik H. Vanmarcke[a] and Shih-sheng P. Lai[b]

INTRODUCTION

The duration of strong shaking during an earthquake plays an important role in many seismic engineering problems. The response of very lightly damped linear systems and of yielding or strength-degrading nonlinear systems depends significantly on the duration of shaking. Duration is also a key parameter affecting the likelihood of occurrence of the phenomena of low-cycle fatigue or soil liquefaction during earthquakes.

No single quantitative measure of the strong-motion duration is in common usage in earthquake engineering. Studies of the dependence of duration on magnitude (Housner, 1965) and on distance and magnitude (Esteva and Rosenblueth, 1964) are not based on quantitative definitions of duration. Two crude but simple measures of duration have been mentioned in the literature. The first defines duration as the time interval between the first and last peaks equal to or greater than a given level, usually 0.05 g, on the accelerogram (Page et al., 1975). The second definition is based on cumulative energy obtained by adding squared accelerations: duration is the time interval required to accumulate a prescribed fraction of the total energy, for example, 95 percent (Husid et al., 1969) or 90 percent (Trifunac and Brady, 1975). Bolt (1973) suggested that both these definitions could also be applied to sinusoidal components of the earthquake motion occurring within different narrow frequency bands.

In this paper, a new method is proposed for estimating the strong-motion duration of earthquakes, and it is applied to the horizontal components of each of 70 strong-motion records published by C.I.T.

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BACKGROUND

In this section, we examine briefly two well known and closely related functions which describe the frequency content of earthquake ground acceleration. These are helpful in clarifying the relationship between various measures of the severity of earthquake motion and in introducing the proposed approach to obtaining the duration of strong shaking.

The Fourier amplitude spectrum (F.a.s.) of the ground acceleration a(t) is the absolute value of the Fourier transform of a(t).

$$f(\omega) = \left| \int_{-\infty}^{\infty} a(t)\, e^{-i\omega t}\, dt \right| = \left| \int_{0}^{t_0} a(t)\, e^{-i\omega t}\, dt \right| \qquad (1)$$

in which ω = frequency of vibration (rad/sec.), $i = \sqrt{-1}$, and t_0 = length of the digitized accelerogram (in seconds). The squared Fourier amplitude spectrum $f^2(\omega)$, indicates how the total energy in the earthquake motion is distributed over the frequency axis. Its integral over all frequencies is directly related to the total motion "energy" I_0, or the so-called Arias Intensity (1970), as follows:

$$I_0 = \int_{0}^{t_0} a^2(t)\, dt = \int_{-\infty}^{\infty} a^2(t)\, dt = \frac{1}{2\pi} \int_{-\infty}^{\infty} f^2(\omega)\, d\omega = \frac{1}{\pi} \int_{0}^{\infty} f^2(\omega)\, d\omega \qquad (2)$$

The equality in the center of Eq. 2 is Parseval's relation, while the equality on the right side results from the fact that since a(t) is real, F.a.s. is an even function of frequency (i.e., $f(-\omega) = f(\omega)$).

A closely related function is the estimated spectral density function (s.d.f.) $G(\omega)$ which indicates how the ground motion power, or energy per unit time, is distributed over all frequencies. We have (Bendat, 1958):

$$G(\omega) = \frac{1}{s_0}\, \frac{1}{\pi}\, f^2(\omega) \qquad (3)$$

in which s_0 is the yet to be determined strong-motion duration. It must be stressed that the exact relationship between the two functions is rather delicate. $G(\omega)$ obtained by Eq. 3 is really an estimate of the true spectral density function. The latter is a statistical quantity describing the expected distribution of the earthquake power over frequency. Implied by Eq. 3 is an idealization of the earthquake as a segment of limited duration (s_0) of a random process with constant average frequency content.

A basic property of the s.d.f. is that the mean square acceleration σ_0^2 (which equals the variance, since the mean acceleration is zero) is obtained by integrating $G(\omega)$ over all frequencies.

$$\sigma_0^2 = \int_0^\infty G(\omega)\, d\omega \qquad (4)$$

in which σ_0 = r.m.s. (root-mean-square) strong-motion acceleration. Combining Eqs. 2, 3 and 4 yields the expected relationship

$$I_0 = s_0 \sigma_0^2 \qquad (5)$$

In words, the total ground motion intensity I_0 is distributed uniformly, at constant average power σ_0^2, over the strong-motion interval s_0.

STRONG-MOTION DURATION

The Arias Intensity I_0 and the maximum amplitudes of acceleration (a_{max}) and velocity (v_{max}) are well-known measures of the severity of an earthquake motion $a(t)$. Approximate procedures also exist for estimating the predominant frequency ω_0 of an accelerogram, e.g., counting the equivalent number of cycles in $a(t)$, or more crudely, evaluating the ratio a_{max}/v_{max}. The question at hand is how to determine quantitatively the strong-motion duration s_0 and the corresponding strong-motion r.m.s. acceleration σ_0. Eq. 5 suggests that large values of s_0 imply small r.m.s. values σ_0. For example, when s_0 equals t_0, we obtain $\sigma_0 = [I_0/t_0]^{\frac{1}{2}}$. For very small values of s_0, the r.m.s. acceleration can become as large as a_{max}, which happens when $s_0 = I_0/a^2_{max}$. These extreme choices for s_0 are undesirable because they imply values of σ_0 which are not related in a consistent manner to the maximum acceleration a_{max}. The solid line in Fig. 1 shows the peak factor a_{max}/σ_0 as a function of s_0 for the N - S Component of the El Centro, 1940 earthquake. Note that the ratio (a_{max}/σ_0) may be as high as 7.5 or as low as 1, depending on which value of s_0 is chosen. This observation is the key to the proposed method for evaluating strong-motion durations of earthquake records. The idea is that an approximate relationship must exist between σ_0 and a_{max}. The relationship is of course of a probabilistic nature. The theory of stationary Gaussian random functions provides a prediction of the most probable value of the peak factor a_{max}/σ_0 during a known time interval s_0 of steady strong shaking. Specifically, the value of a_{max}/σ_0, which is exceeded once on the average during the interval s_0 (or which has a probability e^{-1} of not being exceeded during s_0), is approximately[+]:

$$(a_{max}/\sigma_0) = \sqrt{2\,\ell n\,(2\,s_0/T_0)} \qquad s_0 \geq T_0 \qquad (6)$$

in which $T_0 = 2\pi/\omega_0$ = predominant period of the earthquake motion, and s_0/T_0 = number of cycles during the time interval s_0. The lower limit on s_0 insures that the peak factor will not be too low[+]; Eq. 6 is plotted in Fig. 1 for three different values of T_0: 0.2 sec., 0.3 sec. and 0.4 sec. Note the relative insensitivity of the peak factor (predicted by Eq. 6) to the choice of T_0

Assuming T_0 is known, Eqs. 5 and 6 can be viewed as a system of two equations and two unknowns, s_0 and σ_0. The solution for s_0 is implicit in the following equation:

$$s_0 = [2\,\ell n\,(2\,s_0/T_0)]\ \ (I_0/a^2_{max}) \qquad s_0 \geq T_0 \qquad (7)$$

The ratio (I_0/a^2_{max}) is available for all strong-motion earthquake records.

[+] Eq. 6 is derived on the basis of the assumption that the crossings of a specified, relatively high threshold occur as a Poisson arrival process. The formula is inappropriate for very low thresholds. The condition $a_{max} \geq 1.2\ \sigma_0$ implies $s_0 \geq T_0$, which is the bound set in Eq. 6.

The solution to Eq. 7 is plotted in Fig. 2. Note that the duration s_0 is nearly a linear function of I_0/a^2_{max} for a given value of T_0. For the El Centro, 1940 N - S component, the ratio I_0/a^2_{max} is 0.975, and T_0 is about 0.3 sec. From Fig. 2, it follows that s_0 is about 7.5 sec. The corresponding r.m.s. acceleration (obtained by using Eq. 5) is $\sigma_0 = 0.12$ g and the peak factor is $(a_{max}/\sigma_0) = 0.33\,g/0.12\,g \doteq 2.75$. The quantities s_0, σ_0 and a_{max} are shown in Fig. 3.

The main features of the strong-motion duration s_0 are that (i) the total motion energy I_0 is preserved, and (ii) a consistent relationship between a_{max} and the strong-motion r.m.s. acceleration σ_0 is guaranteed.

INTERPRETATION BASED ON MOVING AVERAGE POWER

The strong-motion duration may also be derived by using a procedure based on moving average power. The procedure yields essentially the same results as those just presented (Eq. 7), but it sheds a different light on the concept and the interpretation of strong-motion duration.

We start by examining the cumulative intensity function I(t) studied by Husid et al. (1969):

$$I(t) = \int_0^t a^2(u)\, d\, u \tag{8}$$

It is zero when $t = 0$ and reaches its maximum value $I_0 = I(t_0)$, the Arias Intensity, at the end of the record a(t). For some earthquake records, the function I(t) increases relatively slowly and smoothly, and has a "flat" average slope. In other cases, the strong shaking phase of the accelerogram is relatively short and intense, and the function I(t) will have a "steep" (average) slope during the time interval of strong shaking. The average slope of the function I(t) is the average moving power:

$$P_{\Delta t}(t_1) = \frac{1}{\Delta t}\int_{t_1}^{t_1+\Delta t} a^2(t)\,dt \qquad 0 \leq t \leq t_o - \Delta t \qquad (9)$$

in which Δt is the averaging interval. This function peaks where the motion is most intense. An example is shown in Fig. 4. Of course, the appearance of the average moving power will strongly depend on the choice of integration interval Δt. The larger Δt, the smoother the average moving power $P_{\Delta t}(t)$.

Let $\sigma^2_{\Delta t}$ denote the peak value of the moving average power. The corresponding "equivalent duration" $s_{\Delta t}$ is equal to the ratio of the Arias Intensity I_o to the peak average power $\sigma^2_{\Delta t}$.

$$s_{\Delta t} = I_o / \sigma^2_{\Delta t} \qquad (10)$$

As shown in Fig. 4, the effect is to distribute the total energy I_o uniformly at constant power $\sigma^2_{\Delta t}$. Finally, a peak factor is obtained:

$$a_{max} / \sigma_{\Delta t} = a_{max} / [I_o/s_{\Delta t}]^{\frac{1}{2}} \qquad (11)$$

For each integration interval Δt, we can compute the r.m.s. acceleration $\sigma_{\Delta t}$, the equivalent duration $s_{\Delta t}$, and the peak factor $(a_{max}/\sigma_{\Delta t})$. For very small integration intervals Δt, the r.m.s. acceleration $\sigma_{\Delta t}$ approaches the maximum acceleration a_{max}, and the peak factor approaches one. At the other extreme, when Δt equals the record length t_o, we have $\sigma_{\Delta t} = \sqrt{I_o/t_o}$.

For each value of Δt, a theoretical prediction can also be made for the peak factor, again based on the probable relationship between the standard deviation and the maximum value during segments of stationary Gaussian motions:

$$(a_{max} / \sigma_{\Delta t}) = \sqrt{2\ln 2(s_{\Delta t}/T_o)} \qquad (12)$$

T_0 is the predominant period, which is initially treated as constant in the procedure. (The initial value of T_0 is obtained by dividing the time t_0 by half the number of zero-crossings in the accelerogram).

The theoretical peak factor, plotted against Δt will vary more slowly than the peak factor computed by Eq. 11. The desired peak factor is the ordinate of the point where the two curves intersect. The corresponding values of $\sigma_{\Delta t}$ and $s_{\Delta t}$ may then be obtained from Eqs. 10 and 11.

Actually, T_0 depends on the choice of the time interval within which zero-crossings are counted. For some accelerograms, the predominant frequency is strongly influenced by the motion at the end of the record. Therefore, it seemed worthwhile to implement an iterative computational procedure in which only zero-crossings within the interval $s_{\Delta t}$ (centered at the time the peak acceleration occurs) are counted.

NUMERICAL RESULTS

The procedure just outlined has been applied to two horizontal components from each of 70 strong-motion records published by the California Institute of Technology. The records were selected by McGuire (1977) so as to be reasonably representative of a broad range of earthquake magnitudes, source-to-site distances, and site conditions. He also classified the records into two categories: "rock" (11 records) and "soil" (59 records)[+].

Table I lists the results for all 140 accelerograms which are labeled as in the C.I.T. computer files. In addition to the strong-motion durations and the corresponding peak factors, Table I lists the Richter magnitude (M), epicentral distance (R), M.M.I. Intensity, maximum acceleration Arias Intensity (I_0), the predominant period (T_0) and the soil/rock designation for each record.

[+] Magnitudes and epicentral distances are reported by McGuire and Barnhard (1977), and soil designations are given by McGuire (1977).

Table II compares various durations for a subset of records. For each record, the time intervals based on the 5 to 95% energy fraction (as proposed by Trifunac and Brady, 1975), as well as those based on other energy fractions (10 to 90%; 20 to 80%; 25 to 75%; and 33 to 67%), and the proposed strong-motion duration, are listed side by side. Table II suggests strongly that the strong-motion durations cannot be related consistently to the time intervals corresponding by any specific fraction of total energy. By determining the energy fractions which correspond most closely to the strong-motion durations obtained for all 140 records, it was found that there are 16 records with a strong-motion duration shorter than the ".33 → .67%" time interval and 4 records with a duration exceeding the ".05 → .95%" time interval.

Histograms of the peak factors, the predominant periods, and the strong-motion durations are shown in Figs. 5, 6, and 7, respectively. The peak factors have a mean of 2.67 and a standard deviation of 0.381; for the predominant periods, the mean is 0.34 sec and the standard deviation 0.18 sec; the mean strong-motion duration is 9.27 sec and its standard deviation is 8.76 sec.

For earthquake records with strong-motion durations below 6 seconds (when the slope of I(t) is relatively "steep"), peak factors range between 2.2 and 2.6. For records with strong-motion durations exceeding 6 seconds (when the slope of I(t) is relatively "flat"), peak factors range from 2.6 to 3.2.

Table I contains the information needed to conduct a number of ground motion parameter studies which involve strong-motion duration. In particular, consider the relationship shown in Fig. 8 between strong-motion duration and earthquake magnitude for different ranges of epicentral distance. For comparison, two well-known prediction equations for strong-motion durations are also plotted in Fig. 6. The solid line (Fig. 8) is the linear relationship suggested by Housner (1965) for "the strong phase of ground shaking" (evaluated subjectively) against magnitude M:

$$s = 11\,M - 53 \qquad (13)$$

Esteva and Rosenblueth (1964) estimated the duration of an "equivalent ground motion with uniform intensity per unit time" as follows:

$$s = 0.02\,e^{0.74\,M} + 0.3\,R \qquad (14)$$

where R is the focal distance in kilometers. The durations predicted by Eq. 14 are plotted (as dotted lines) against magnitude for two values of R in Fig. 8.

CONCLUSIONS

A new and simple procedure is presented for estimating the strong-motion duration s_0 and the r.m.s. strong-motion acceleration σ_0 of earthquake ground motion records. The strong-motion duration is found to be nearly proportional to the quantity I_0/a_{max}^2, in which a_{max} is the maximum ground acceleration and I_0 is the Arias Intensity or the integral of the squared accelerations. The proportionality factor is equal to the square of the peak factor (the ratio of the maximum to the r.m.s. strong-motion acceleration); the latter averages about 2.65, and the proportionality factor about 7. A less important factor influencing the relationship between s_0 and I_0/a_{max}^2 is the predominant period of the strong phase of the accelerogram. The main features of the proposed procedure to obtain the strong-motion duration s_0 and the corresponding r.m.s. strong-motion acceleration σ_0 is that (i) it preserves the motion intensity I_0, i.e., $I_0 = \sigma_0^2 s_0$, and (ii) it guarantees a consistent and predictable relationship between a_{max} and σ_0, i.e., $(a_{max}/\sigma_0) = \sqrt{2\,\ell n\, 2(s_0/T_0)}$. This expression predicts the maximum acceleration which will occur <u>once</u> on the average during the strong-motion time interval s_0.

The proposed procedure could also be used to obtain equivalent durations for different frequency-filtered components of earthquake records as suggested by Bolt (1973). For example, one may wish to restrict attention to long-period ground motion components, or to components operating within a narrow band of frequencies in the neighborhood of the fundamental frequency of a structure of interest.

The proposed procedure has been applied to 140 horizontal components of strong earthquake ground motions. The results are tabulated and summarized in the form of histograms of strong-motion durations and peak factors. The dependence of strong-motion duration on earthquake magnitude and epicentral distance is also examined.

It is believed that the proposed definition of strong-motion duration fills a significant gap in earthquake engineering research. It will permit a more confident approach to a number of important seismic engineering problems in which strong-motion duration plays a key role. It is hoped that it will also be of service in the development of improved procedures for specifying design ground motions by permitting quantitative treatment of the correlation between duration and other ground motion parameters, as a function of earthquake source parameters and distance.

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REFERENCES

Arias, A. (1970). "A Measure of Earthquake Intensity" in *Seismic Design of Nuclear Power Plants*, R. Hansen, Editor, M.I.T. Press.

Bendat, J.S. (1958). *Principles and Applications of Random Noise Theory*, John Wiley and Sons, Inc., New York.

Bolt, B.A. (1973). "Duration of Strong Ground Motion," *5th World Conf. on Earthq. Eng.*, Vol. I, Rome, Italy.

C.I.T. Earthquake Engineering Research Laboratory (1971). "Strong-Motion Earthquake Accelerograms - Digitized and Plotted Data," Vol. II, Part A and subsequent Parts B through Y.

Esteva, L. and Rosenblueth E. (1964). "Spectra of Earthquakes at Moderate and Large Distances," *Soc. Mex. de Ing. Sismica*, Vol. II, No. 1, pp. 1-18, Mexico (in Spanish).

Housner, G.W., "Intensity of Ground Shaking Near the Causative Fault," *Proc. 3rd World Conf. Earthq. Eng.*, Vol. I, New Zealand.

Husid, R., Medina, H. and Rios, J. (1969). "Analysis de Terremotos Norteamericanos y Japoneses," *Revista del IDIEM*, 8, Chile.

McGuire, R.K. and Barnhard, J.A. (1977). "Magnitude, Distance and Intensity Data for C.I.T. Strong Motion Records," *U.S. Geological Survey Journal of Research*, No. 5, 3 pp.

McGuire, R.K. (1977). "Seismic Ground Motion Parameter Relations," prepared for presentation at ASCE National Convention, San Francisco, October.

Newmark, N.M. and Rosenblueth, E. (1971). "Fundamentals of Earthquake Engineering," Prentice-Hall, New Jersey.

Page, R.A., Boore, D.M., and Dietrich, J.H. (1975). "Estimation of Bedrock Motion at the Ground Surface," *USGS Professional Paper 941-A*, Edited by R.D. Boreherdt, p. A31.

Seed, H.B., Idriss, I.M. and Kiefer, F.W. (1969). "Characteristics of Rock Motions during Earthquakes," *J. Soil Mech. and Found. Div.*, Vol. 95, No. SM5.

Trifunac, M.D. and Brady, A.G. (1975). "A Study of the Duration of Strong Earthquake Ground Motion," *Bulletin of the Seismological Society of America*, Vol. 65, No. 3.

Vanmarcke, E.H. (1976). "Structural Response to Earthquakes," Chapter 8 in *Seismic Risk and Engineering Decisions*, C. Lomnitz and E. Rosenblueth, Editors, Elsevier Scientific Publ. Co., Amsterdam-Oxford-New York.

LIST OF FIGURE CAPTIONS

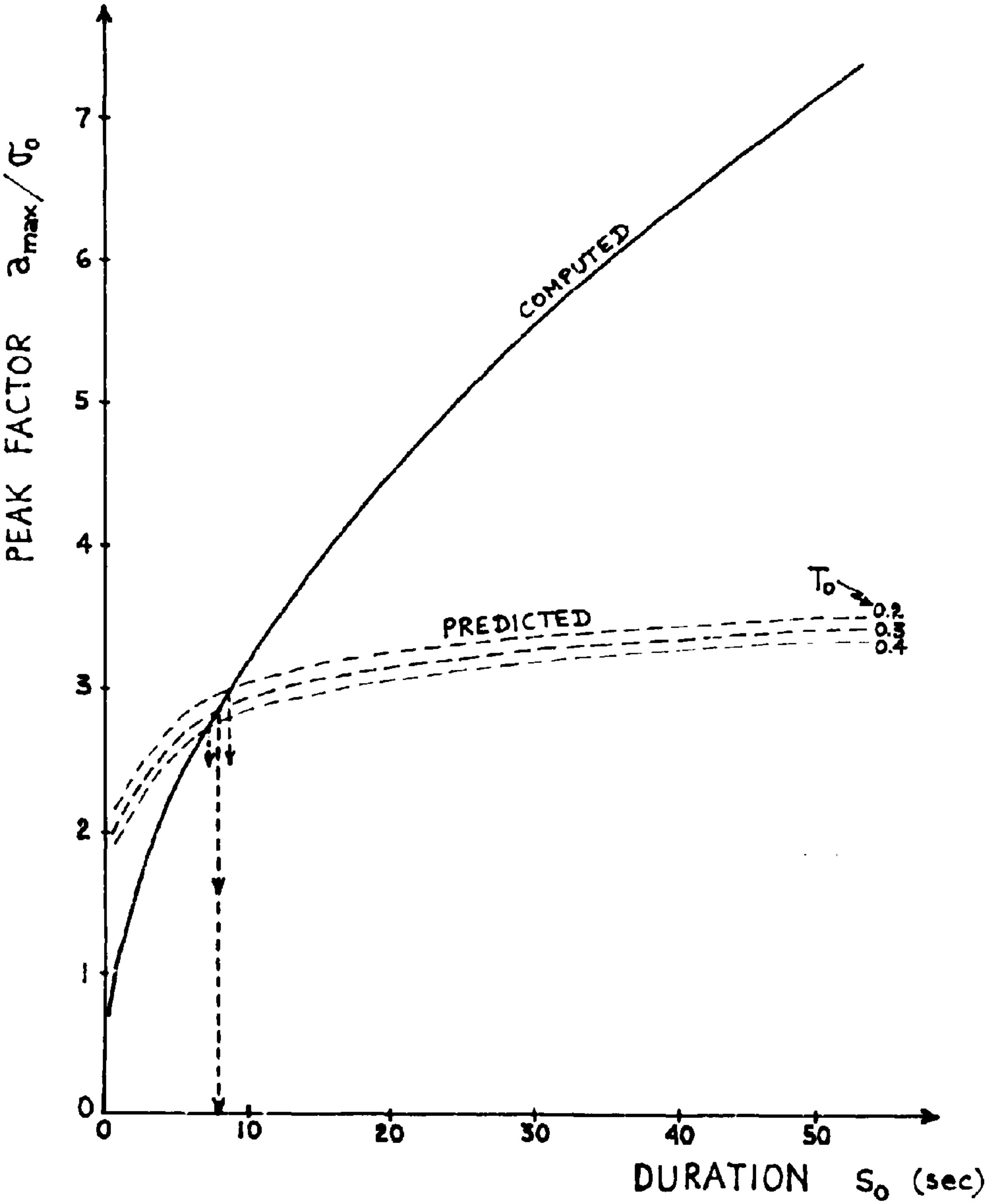
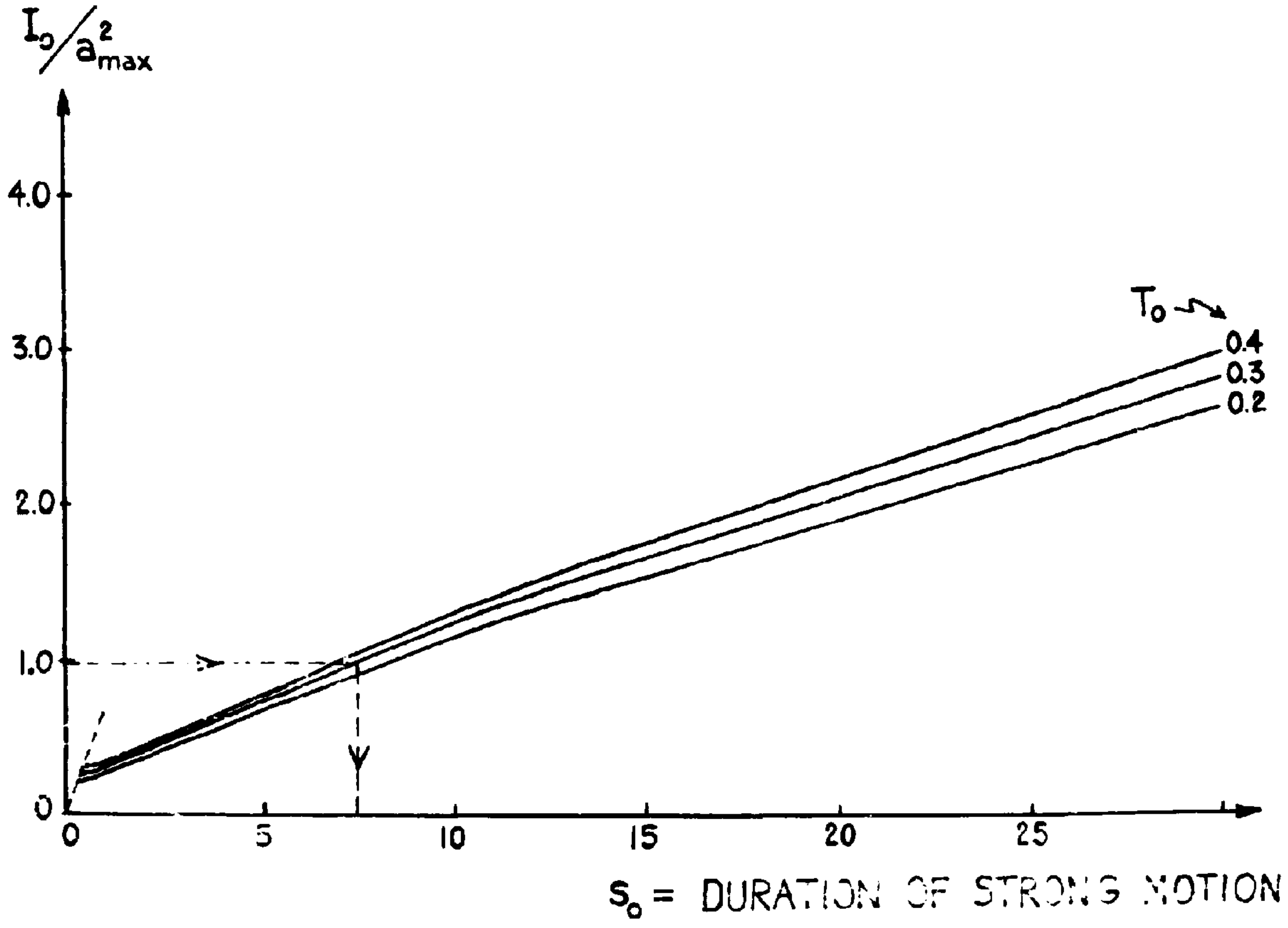

PEAK FACTOR a_{max}/σ_0
0
1
2
3
4
5
6
7
0
10
20
30
40
50
DURATION S_0 (sec)
COMPUTED
PREDICTED
T_0
0.2
0.3
0.4

Figure 1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3.0
2.0
1.0
0
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5
10
15
20
25
T_o
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0.3
0.2
S_o = DURATION OF STRONG MOTION

Figure 2

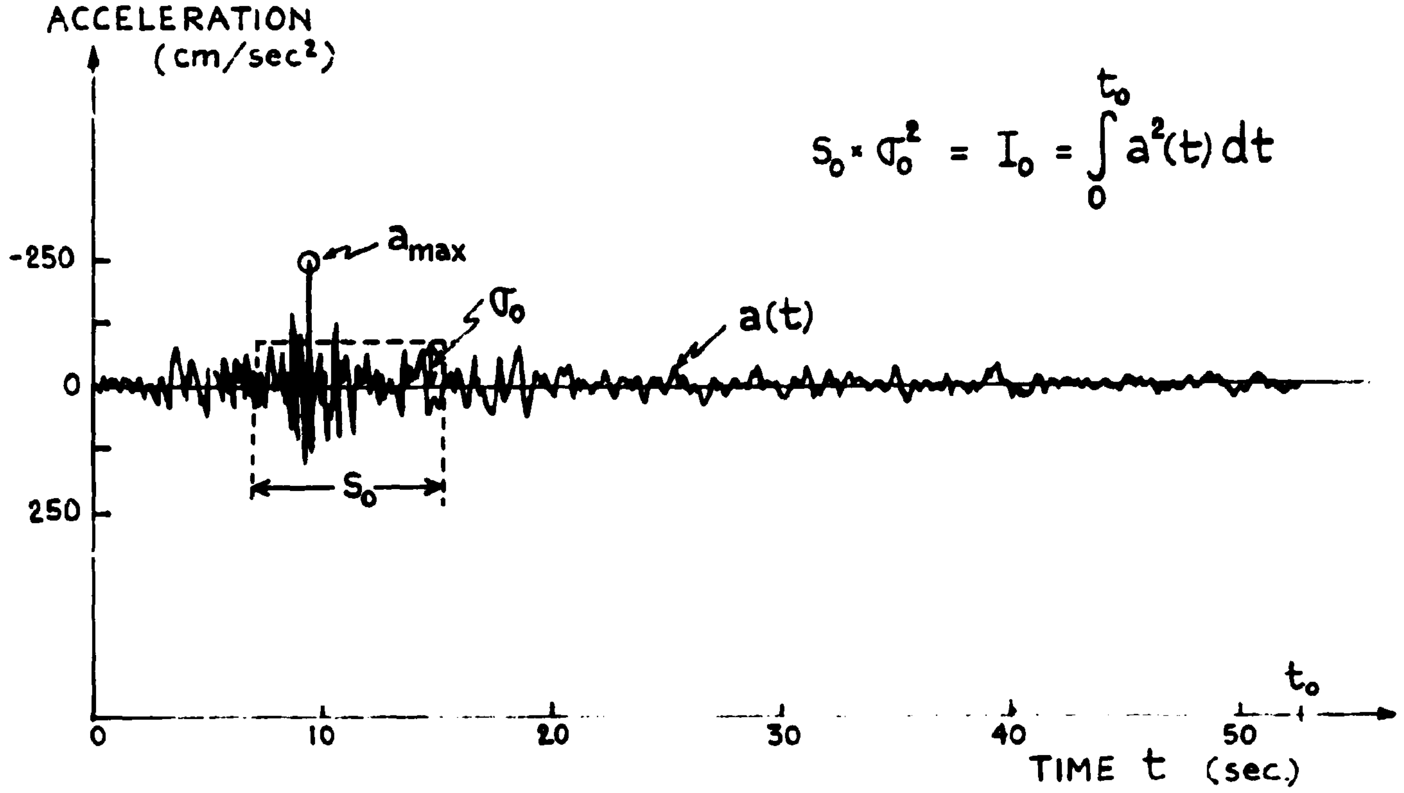
ACCELERATION
(cm/sec²)
-250
0
250
$S_0 \times \sigma_0^2 = I_0 = \int_0^{t_0} a^2(t)\,dt$
a_{max}
σ_0
a(t)
S_0
t_0
0
10
20
30
40
50
TIME t (sec.)

Figure 3

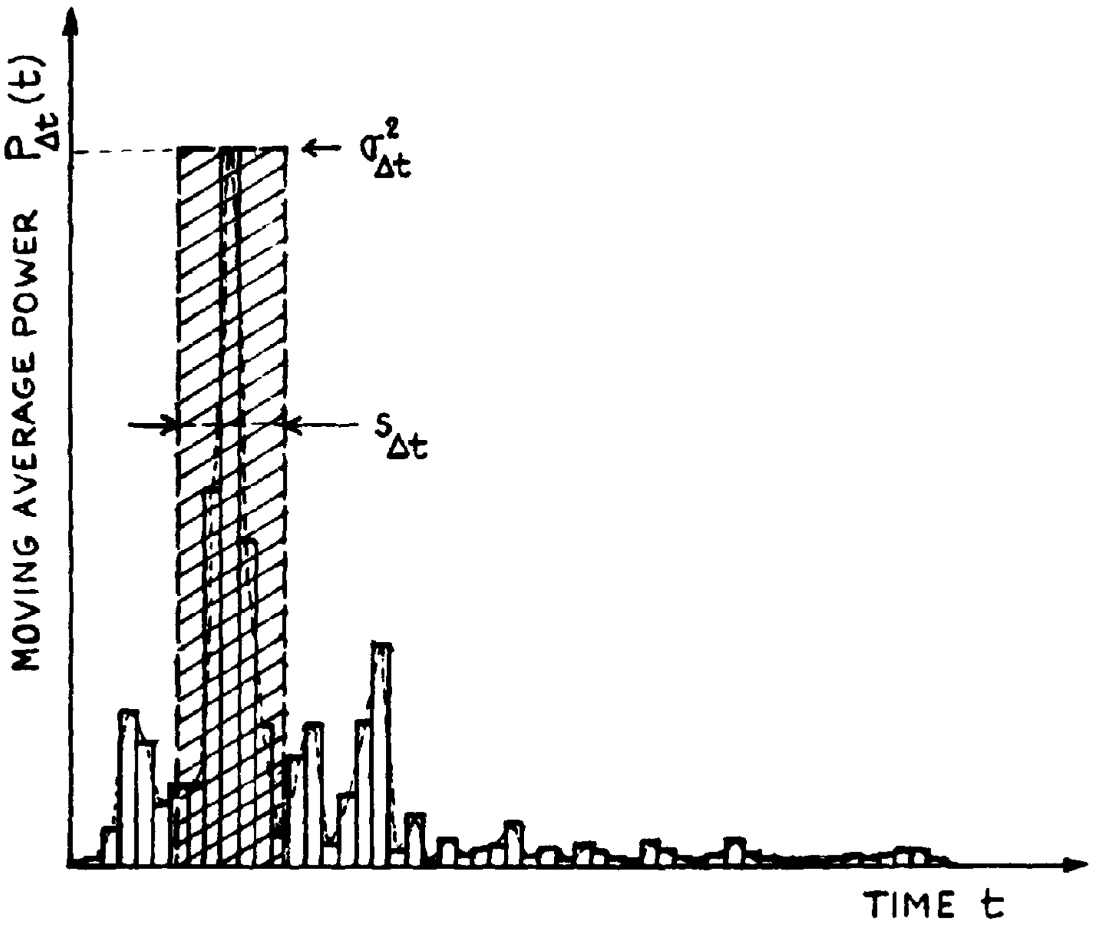
MOVING AVERAGE POWER $P_{\Delta t}(t)$
$\sigma^2_{\Delta t}$
$s_{\Delta t}$
TIME t

Figure 4

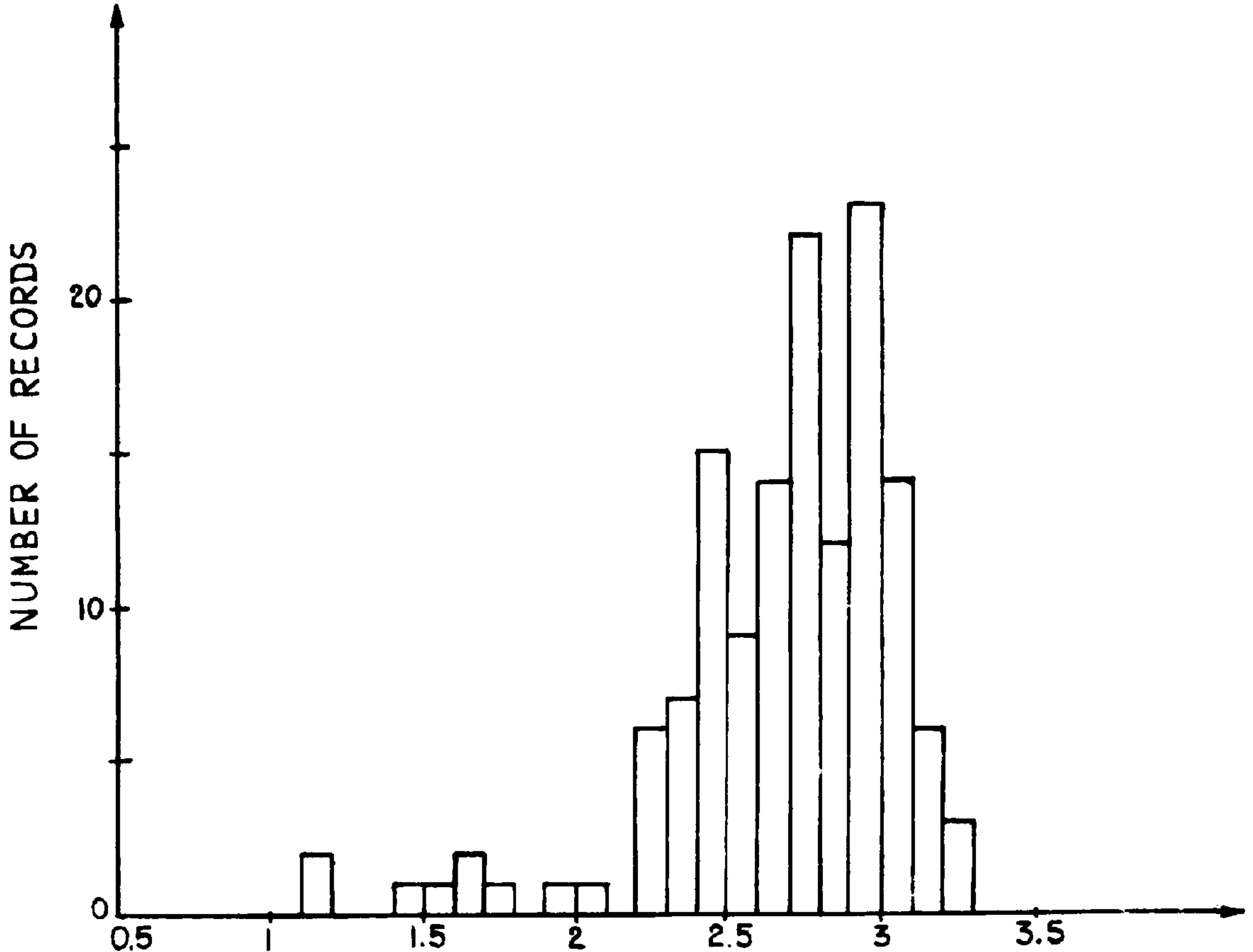
NUMBER OF RECORDS
0
10
20
0.5
1
1.5
2
2.5
3
3.5
PEAK FACTOR a_{max}/σ_o

Figure 5

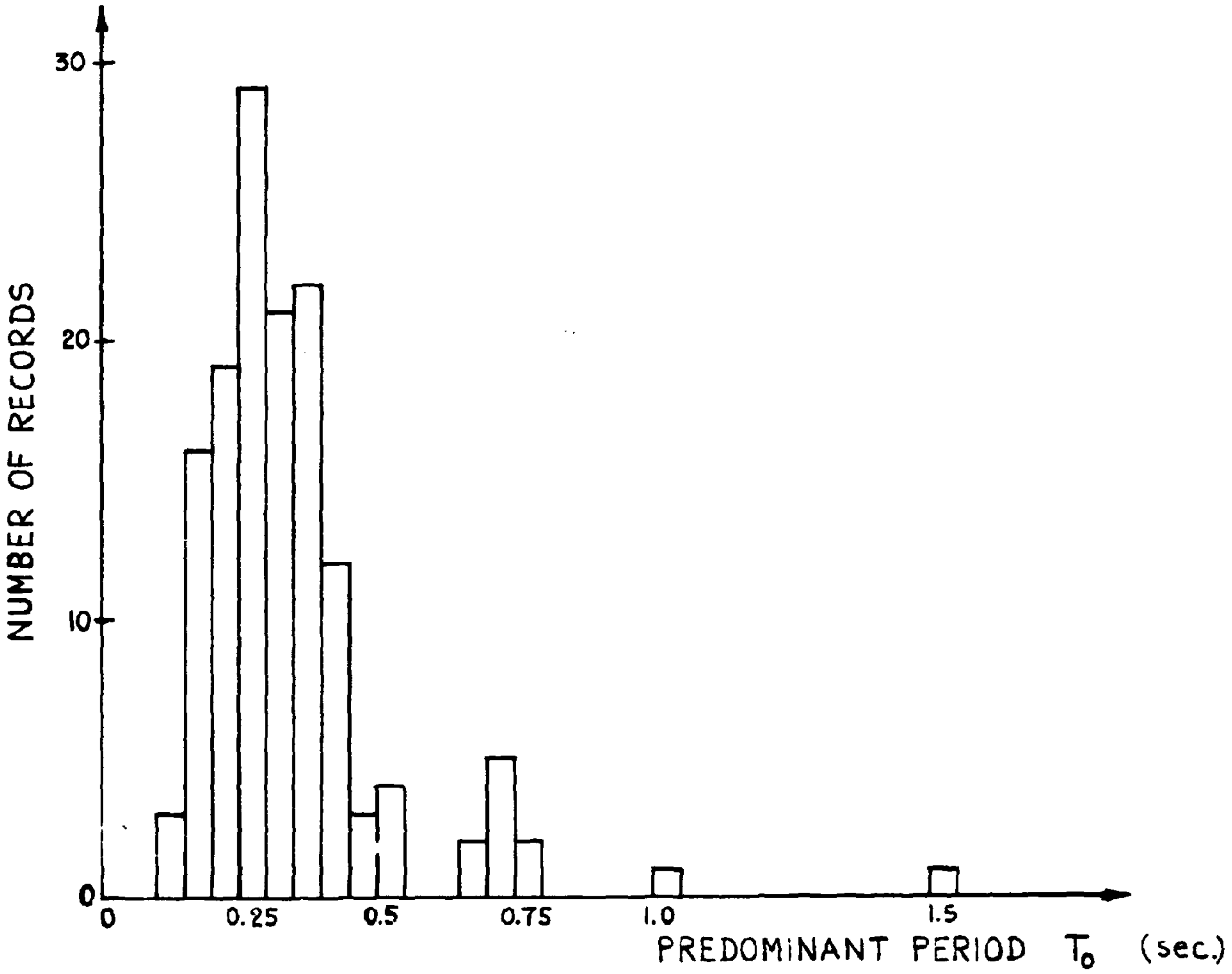
NUMBER OF RECORDS
30
20
10
0
0
0.25
0.5
0.75
1.0
1.5
PREDOMINANT PERIOD T_o (sec.)

Figure 6

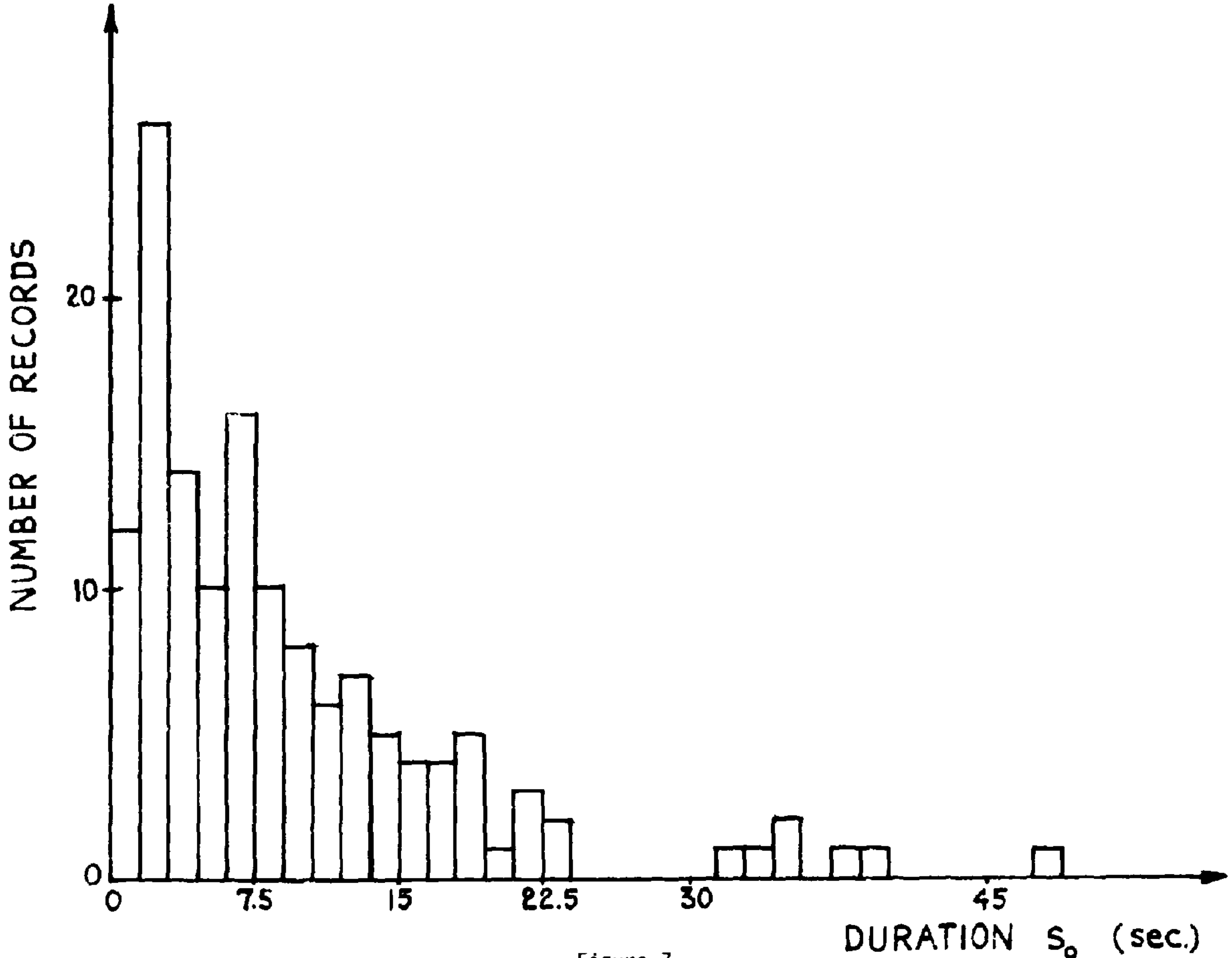

Figure 7

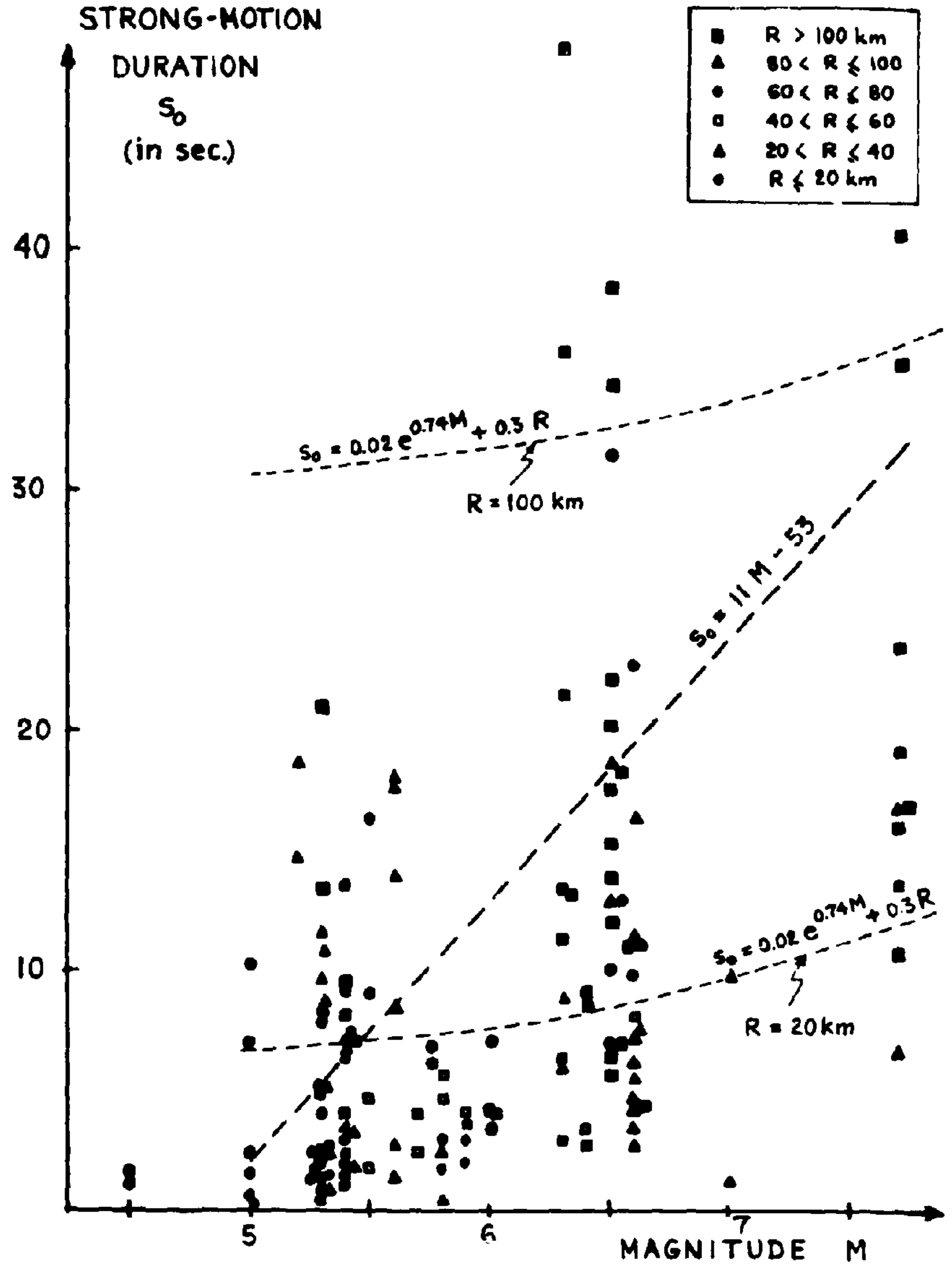
STRONG-MOTION
DURATION
S_0
(in sec.)
R > 100 km
80 < R ≤ 100
60 < R ≤ 80
40 < R ≤ 60
20 < R ≤ 40
R ≤ 20 km
40
30
20
10
$S_0 = 0.02\, e^{0.74M} + 0.3\, R$
R = 100 km
$S_0 = 11\, M - 53$
$S_0 = 0.02\, e^{0.74M} + 0.3\, R$
R = 20km
5
6
7
MAGNITUDE M

Figure 8

TABLES

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_0 $\left(10^4 \frac{cm^2}{sec^3}\right)$	T_0 (sec)	PEAK FACTOR	s_0 DURATION	SITE s = soil r = rock
A002-1 A002-2	Northwest California	S44W N46W	5.0	53	5	0.104 0.112	0.5616 0.7047	0.18 0.24	2.76 2.65	4.11 4.12	s s
A003-1 A003-2	Kern County	S00E S90W	7.7	127	7	0.047 0.053	0.4068 0.7132	0.44 0.52	2.92 3.00	16.00 23.59	s s
A004-1 A004-2	Kern County	N21E S69E	7.7	43	7	0.156 0.179	3.4020 3.6887	0.26 0.24	3.05 3.00	13.66 10.72	s s
A005-1 A005-2	Kern County	N42E S48E	7.7	89	7	0.090 0.131	1.485 1.802	0.43 0.66	2.95 2.45	16.80 6.62	s s
A006-1 A006-2	Kern County	S00W N90E	7.7	119	7	0.055 0.044	0.5191 0.6473	0.40 0.40	3.03 3.21	19.32 35.41	s s
A007-1 A007-2	Kern County	S00W N90E	7.7	119	7	0.059 0.042	0.6343 0.6372	0.35 0.37	3.03 3.28	17.09 40.08	s s
A008-1 A008-2	Eureka	S00W N90E	6.6	24	7	0.168 0.258	2.1154 4.4298	0.32 0.42	2.66 2.45	5.47 4.23	s s
A009-1 A009-2	Eureka	N44E N46W	6.6	40	7	0.159 0.201	3.4131 2.3542	0.39 0.37	2.86 2.42	11.53 3.52	s s
A010-1 A010-2	San Jose	N31W N59E	5.8	10	7	0.102 0.108	0.4675 0.3323	0.25 0.19	2.52 2.43	2.97 1.78	s s
A014-1 A014-2	San Francisco	N09W N81E	5.3	15	6	0.043 0.046	0.1012 0.8769	0.21 0.27	2.70 2.40	4.07 2.42	s s
A015-1 A015-2	San Francisco	N10E S80E	5.3	12	6	0.083 0.105	0.1751 0.3114	0.21 0.16	2.27 2.54	1.34 2.02	r r

TABLE I

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_0 $\left(10^4 \frac{cm^2}{sec^3}\right)$	T_0 (sec)	PEAK FACTOR	s_0 DURATION	SITE s = soil r = rock
A016-1	San Francisco	S09E	5.3	14	6	0.085	0.3302	0.29	2.42	2.76	s
A016-2		S81W				0.056	0.2122	0.26	2.72	5.16	s
A017-1	San Francisco	N26E	5.3	24	6	0.040	0.0600	0.21	2.51	2.48	s
A017-2		S64E				0.024	0.0360	0.22	2.74	4.82	s
A018-1	Hollister	S01W	5.6	21	7	0.065	0.8371	0.47	2.94	18.05	s
A018-2		N89W				0.179	1.6319	0.42	2.27	2.72	s
A019-1	Borrego Mountain	S00W	6.5	64	6	0.130	1.5104	0.34	2.73	7.07	s
A019-2		S90W				0.057	0.9603	0.34	3.23	31.55	s
A020-1	Borrego Mountain	S00W	6.5	96	6	0.030	0.1375	0.42	2.87	12.90	s
A020-2		S90W				0.029	0.1818	0.52	2.92	18.73	s
B021-1	Long Beach	S08W	6.3	53	6	0.133	1.4159	0.30	2.74	6.44	s
B021-2		N82W				0.154	1.1565	0.31	2.43	2.91	s
B023-1	Southern California	N00E	5.4	38	5	0.033	0.0617	0.35	2.45	3.53	s
B023-2		N90W				0.027	0.0649	0.35	2.70	6.76	s
B024-1	Lower California	S00W	6.5	64	6	0.160	3.4234	0.23	3.08	13.30	s
B024-2		S90W				0.183	3.8876	0.30	2.91	10.19	s
B026-1	1st N.W. California	N45E	5.5	55	6	0.144	0.6262	0.27	2.27	1.74	s
B026-2		S45E				0.089	0.4604	0.20	2.76	4.64	s
B027-1	2nd N.W. California	N45E	6.6	104	6	0.062	0.2566	0.32	2.57	4.34	s
B027-2		S45E				0.039	0.2004	0.36	2.88	11.23	s
B030-1	Northern California	N44E	5.4	43	6	0.054	0.3256	0.27	2.93	9.67	s
B030-2		S46E				0.068	0.3296	0.23	2.67	4.01	s

TABLE I (Continued)

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_o $\left(10^4 \frac{cm^2}{sec^3}\right)$	T_o (sec)	PEAK FACTOR	s_o DURATION	SITE s = soil r = rock
B031-1	Wheeler Ridge	N21E	5.9	43	6	0.065	0.2434	0.34	2.47	3.64	s
B031-2		S69E				0.068	0.2653	0.26	2.63	4.12	s
B034-1	Parkfield	N05W	5.3	5	6	0.355	3.8963	0.26	2.26	1.66	s
B034-2		N85E				0.434	5.3081	0.38	1.80	0.95	s
B035-1	Parkfield	N50E	5.3	9	6	0.237	1.9147	0.16	2.59	2.37	s
B035-2		N40W				0.275	2.3601	0.18	2.49	1.99	s
B036-1	Parkfield	N50E	5.3	38	6	0.053	0.3357	0.19	3.12	12.60	s
B036-2		N40W				0.064	0.3855	0.16	3.09	9.55	s
B037-1	Parkfield	N65W	5.3	6	6	0.269	1.9059	0.21	2.27	1.39	r
B037-2		S25W				0.347	2.8140	0.33	1.66	0.65	r
B038-1	Parkfield	N36W	5.3	77	6	0.014	0.0195	0.23	2.92	8.27	r
B038-2		S54W				0.012	0.0123	0.23	2.92	8.07	r
B039-1	2nd Northern California	S11E	5.8	51	5	0.021	0.0300	0.34	2.58	4.77	s
B039-2		N79E				0.020	0.0314	0.38	2.60	5.58	s
B040-1	Borrego Mountain	N33E	6.5	134	5	0.041	0.1508	0.30	2.77	7.01	r
B040-2		N57W				0.046	0.1737	0.33	2.65	5.65	r
C048-1	San Fernando	N00W	6.6	20		0.255	7.9804	0.41	2.78	9.93	s
C048-2		S90W				0.134	4.2129	0.41	3.07	22.88	s
D056-1	San Fernando	N21E	6.6	29		0.135	4.3301	0.28	2.43	2.71	r
D056-2		N69W				0.271	6.1760	0.25	2.85	7.07	r
E071-1	San Fernando	S00W	6.6	89		0.027	0.0425	0.16	2.86	4.77	s
E071-2		N90E				0.026	0.0451	0.16	2.94	6.14	s

TABLE I (Continued)

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_o $\left(10^4 \frac{cm^2}{sec^3}\right)$	T_o (sec)	PEAK FACTOR	s_o DURATION	SITE s = soil r = rock
F086-1	San Fernando	N83E	6.6	46		0.107	1.1561	0.35	2.77	8.09	s
F086-2		S07W				0.082	0.8030	0.27	2.96	11.09	s
G114-1	San Fernando	S60E	6.6	33		0.113	2.0904	0.26	3.11	16.42	s
G114-2		S30W				0.139	1.5509	0.18	2.98	7.51	s
T286-1	Borrego Valley	North	6.5	48	7	0.060	0.6205	0.27	3.12	17.63	s
T286-2		East				0.047	0.4517	0.28	3.15	20.24	s
T287-1	Imperial Valley	North	5.6	30	6	0.031	0.1415	0.30	3.01	13.90	s
T287-2		East				0.028	0.1523	0.39	3.00	17.72	s
T288-1	Imperial Valley	North	5.5	11	6	0.007	0.0060	0.38	2.78	8.99	s
T288-2		East				0.036	0.2194	0.29	3.08	16.26	s
T289-1	Lower California	North	6.3	150	4	0.025	0.0889	0.33	2.96	13.28	s
T289-2		East				0.028	0.1031	0.40	2.85	11.37	s
T290-1	Imp. County Foreshock	North	7	22	6	0.031	0.0233	0.17	2.36	1.37	s
T290-2		East				0.016	0.0277	0.20	3.04	9.95	s
T293-1	Gulf of California	North	6.3	147	6	0.014	0.0907	0.73	3.13	48.70	s
T293-2		East				0.015	0.0799	0.51	3.14	35.85	s
U298-1	Humboldt Bay	N45W	5.75	80	5	0.039	0.1332	0.33	2.73	6.86	s
U298-2		S45W				0.037	0.1005	0.25	2.79	6.10	s
U299-1	Santa Barbara	N45E	5.9	16	8	0.238	2.0100	0.27	2.33	2.03	s
U299-2		S45E				0.176	1.5176	0.37	2.33	2.80	s
U300-1	Northern California	N45W	6.4	50	6	0.121	0.6519	0.29	2.43	2.79	s
U300-2		S45W				0.116	0.6519	0.27	2.54	3.33	s

TABLE I (Continued)

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_o $\left(10^4 \frac{cm^2}{sec^3}\right)$	T_o (sec)	PEAK FACTOR	s_o DURATION	SITE s = soil r = rock
U301-1 U301-2	Northern California	N89W S01W	5.3	21	7	0.197 0.122	1.0933 1.1072	0.39 0.38	1.66 2.57	0.78 5.08	s s
U305-1 U305-2	Central California	N89W S01W	5.3	27	5	0.053 0.050	0.2983 0.3082	0.32 0.32	2.83 2.91	8.70 10.82	s s
U307-1 U307-2	Central California	N89W S01W	5.0	6	6	0.057 0.036	0.2963 0.1514	0.35 0.31	2.73 2.90	7.12 10.25	s s
U308-1 U308-2	Northern California	N46W S44W	5.7	59	6	0.059 0.075	0.2011 0.2351	0.26 0.30	2.62 2.38	4.00 2.54	s s
U309-1 U309-2	Central Cal. Aftershock	N89W S01W	5.6	21	7	0.172 0.076	1.0012 0.6454	0.37 0.43	1.98 2.71	1.43 8.46	s s
U311-1 U311-2	Parkfield	N21E S69E	5.3	131	4	0.008 0.011	0.0184 0.0234	1.00 0.76	2.73 2.67	21.04 13.49	s s
U312-1 U312-2	Ferndale	N46W S44W	5.8	32	6	0.105 0.237	0.4672 0.6584	0.27 0.20	2.46 1.48	2.66 0.30	s s
U313-1 U313-2	Northern California	N89W S01W	5.2	39	5	0.013 0.017	0.0357 0.0448	0.43 0.41	2.99 2.92	18.60 14.74	s s
V314-1 V314-2	Long Beach	N39E N51W	6.3	59	7	0.064 0.097	1.0251 1.4550	0.72 0.39	2.86 2.91	21.62 13.48	r r
V315-1 V315-2	Long Beach	South West	6.3	27	7-9	0.196 0.159	2.9709 2.5643	0.30 0.26	2.71 2.90	5.81 8.88	s s
V316-1 V316-2	Torrance Gardena	North East	5.4	6	6	0.040 0.055	0.1376 0.2399	0.35 1.54	2.69 1.17	6.47 1.52	s s

TABLE I (Continued)

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_0 $\left(10^4 \frac{cm^2}{sec^3}\right)$	T_0 (sec)	PEAK FACTOR	s_0 DURATION	SITE s = soil r = rock
V317-1 V317-2	Torrance Gardena	S50E S40W	5.4	6	6	0.015 0.011	0.0215 0.0201	0.38 0.38	2.69 2.92	7.07 13.64	s s
V319-1 V319-2	Southern California	N36W S54W	6	77	6	0.054 0.036	0.1532 0.1183	0.31 0.34	2.49 2.73	3.40 7.05	r r
V329-1 V329-2	Southern California	South West	5	6	6	0.167 0.089	0.6101 0.1506	0.43 0.48	1.51 1.19	0.67 0.49	s s
V330-1 V330-2	Northern California	N79E S11E	5	19	6	0.046 0.048	0.0872 0.0782	0.29 0.38	2.36 2.05	2.31 1.52	s s
V331-1 V331-2	Southern California	South East	4.5	18	5	0.041 0.037	0.0465 0.0283	0.19 0.15	2.39 2.39	1.63 1.27	r r
V332-1 V332-2	Northern California	South East	6.25-6.5	151	6	0.015 0.013	0.0235 0.0189	0.37 0.46	2.78 2.71	8.59 9.07	s s
W334-1 W334-2	Lytle Creek	S65E S25W	5.4	13	6	0.142 0.198	0.8279 0.9002	0.25 0.18	2.43 2.30	2.42 1.26	r r
W335-1 W335-2	Lytle Creek	S85E S05W	5.4	19	5-6	0.071 0.056	0.1854 0.0950	0.12 0.13	2.80 2.66	2.98 2.26	r r
W336-1 W336-2	Lytle Creek	S54E S36W	5.4	22	5-6	0.057 0.071	0.1412 0.1466	0.16 0.16	2.74 2.53	3.36 1.90	r r
W339-1 W339-2	Lytle Creek	South East	5.4	18	6	0.041 0.036	0.1452 0.1328	0.25 0.25	2.85 2.93	7.32 9.12	s s
W342-1 W342-2	Lytle Creek	North East	5.4	56	5	0.020 0.019	0.0364 0.0287	0.24 0.20	2.91 2.92	8.18 7.05	s s

TABLE I (Continued)

C.I.T. NO.	EARTHQUAKE	COMP.	M	R (km)	MMI	a_{max} (g)	I_o $\left[10^4 \frac{cm^2}{sec^3}\right]$	T_o (sec)	PEAK FACTOR	s_o DURATION	SITE s = soil r = rock
Y370-1	Borrego Mountain	South	6.5	144	6	0.022	0.0762	0.31	3.04	15.41	s
Y370-2		East				0.029	0.0704	0.31	2.74	6.57	s
Y371-1	Borrego Mountain	S04E	6.5	174	5	0.013	0.0660	0.73	3.01	34.50	s
Y371-2		S86W				0.012	0.0560	0.65	3.09	38.51	s
Y373-1	Borrego Mountain	S82E	6.5	205	6	0.008	0.0095	0.75	2.63	12.01	s
Y373-2		S08W				0.007	0.0087	0.55	2.80	13.95	s
Y379-1	Borrego Mountain	N83W	6.5	214	5	0.019	0.0905	0.72	2.87	22.21	s
Y379-2		S07W				0.019	0.0813	0.73	2.80	18.62	s

TABLE I *(Continued)*

C.I.T. No.	DURATIONS CORRESPONDING TO FRACTION OF I_0					PROPOSED STRONG-MOTION DURATION s_0
	5 - 95%	10 - 90%	20 - 80%	25 - 75%	33 - 67%	
B037-1	5.48	3.08	0.70	0.32	0.18	1.39
B035-1	13.72	8.68	4.56	3.76	2.10	2.37
A016-1	27.48	5.54	1.92	1.16	0.84	2.76
B021-2	18.20	11.44	6.78	5.44	3.92	2.91
A008-1	13.00	6.08	2.66	2.04	1.42	5.47
G114-2	18.94	15.80	9.86	8.58	6.40	7.51
A004-2	28.82	20.10	10.26	8.16	4.72	10.72
T288-2	38.14	34.46	23.66	20.00	7.64	16.26
Y379-1	49.64	42.26	27.40	25.28	15.58	22.21
A003-2	26.84	20.04	13.38	10.00	7.32	23.59
A019-2	39.82	32.06	19.28	14.62	19.94	31.55
A007-2	32.08	27.14	18.32	14.12	7.54	40.08

TABLE II

Comparison of Durations Corresponding to Various Fractions of Total Energy and the Proposed Strong-Motion Duration s_0 for 12 Strong-Motion Earthquake Records.