A PHYSICALLY BASED MODEL TO SIMULATE STRONG EARTHQUAKE RECORDS ON FIRM GROUND

by

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Synopsis

A stochastic model based on physical arguments is proposed to simulate strong earthquake records. This model permits generation of records of strong earthquakes with prescribed magnitude on firm ground at moderate and large distances and with any orientation relative to the causative fault. It is developed from analytical and statistical studies concerning parameters of the ground motion and source, such as the earthquake magnitude, the length of the rupture, the rupture propagation velocity, the relative position between the line source and the site of interest, the types, shapes, amplitudes and periods of waves, frequency-dependent attenuation, multiple wave reflection, the orientation of the records, etc.

1. Introduction

The previous models proposed for idealizing earthquake ground motions have consisted of stochastic processes that fail to take into account known physical features of the phenomenon. Certain parameters of such models have been evaluated by fitting the average response spectra or the autocorrelation function to the corresponding functions observed in real records. But these models have not introduced explicitly most of the relevant physical characteristics of earthquakes. These factors include magnitude, type of source, relative position between site and source, types of waves and their attenuation during transmission, multiple wave reflection, etc. These characteristics determine such earthquake parameters as maximum ground acceleration, duration of the motion, arrival times of the different types of waves, periods and amplitudes of waves, etc., which, at the same time, cause a time variation of both the frequency content and the intensity of the motion. The proper consideration of these two variations in a model for simulating seismic motions would permit more accurate study of their effects on the response of structures, particularly those structures with nonlinear behavior, whose periods of vibration change with the amplitude of oscillation. The object of this paper is to propose a model to simulate strong-motion-earthquake records on hard ground that takes into account, at least in an approximate manner, most of the pertinent physical characteristics of the earthquakes and that yields predictions of the time variation of both the intensity and frequency content of the motion.

2. Mathematical model for simulation of strong earthquake records

The model for simulation of strong-motion earthquake records proposed

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herein considers fault breakage as the cause of tectonic earthquake motions.

2.1 Formulation of the model

Let the plane ABCD in fig 1 be the plane of the causative fault of the earthquake to be simulated, and Δ be the perpendicular distance from the fault trace to the site of interest.

The energy released by the earthquake, W, can be computed as a function of the (Richter) magnitude of the earthquake(1), M, by the equation:

$$\log W = 11.4 + 1.4\, M;\ W \text{ in ergs} \qquad (1)$$

It will be assumed that this energy is radiated uniformly from a finite number of points placed uniformly along a line. Each of these points will be called an "elementary source"; an index "e" will be used to identify parameters associated to elementary sources. Each relatively small elementary source will be treated as a point source and Honda's theory(2) will be applied.

It is recognized that the location of the instrumental epicenter corresponds to the point of initial rupture of the fault(3). For this reason it will be assumed that the line containing the elementary sources is located at a depth equal to the epicenter's focal depth, H. The length of the fault L, will simply be taken equal to its expected value as computed by the equation(11,12)

$$E[L] = \begin{cases} \exp\left[1.43\,(M - 4.50)\right] & ; \quad M \le 7.4 \\ \exp\left[2.43\,(M - 5.65)\right] & ; \quad M > 7.4 \end{cases} \qquad (2)$$

as a function of the magnitude of the earthquake, M.

The total energy released by all elementary sources must be equal to that given by eq 1. Let N be the selected number of elementary sources; from eq 1

$$W = \exp\left[\,2.3\,(1.5\,M + 11.4)\,\right] = N W_e \qquad (3)$$

and therefore,

$$M_e = M - 0.29\ \ln N \qquad (4)$$

will be the value of the elementary magnitude. The number of elementary earthquakes to be used depends principally on the length of the fault and on the capacity of the digital computer. For the earthquakes simulated in this paper, N ranges between 25 and 50.

2.1.1 Pulse shape

The earthquake record will be formed by a random superposition of the shear and longitudinal waves arriving from each elementary source. The waves computed using Honda's(2) theory for a double-couple mechanism are heavily damped and, for practical use, can be considered as single full pulses. The initial shape of the displacement pulse to be used is given by

$$\ddot{x}(t) = A\omega^2 e^{-\eta\omega t}\left[(1-\eta^2/2)\sin 2\omega t + 2\eta(\cos 2\omega t - \cos\omega t) - (1-\eta^2)\sin\omega t\right]; \quad 0 \le t \le T \qquad (5)$$

A value of $\eta = 0.5$ will be used in this paper. This number is based on the values used in some previous models for earthquake simulations(5,6,7) which is considered to fit the observed autocorrelation functions(8).

The initial shape of S and P waves will be considered to be the same, differing only in their periods and amplitudes; periods for longitudinal waves will be computed by using a random number generator, assuming a log-normal distribution with a coefficient of variation of 0.3 and mode, $\tilde{T}$, given by(9)

$$\tilde{T} = 2\pi E[v]/E[a] = 0.05 \quad e^{0.2M}R^{0.3} \qquad (6)$$

where

E = expectation
v = maximum ground velocity
a = maximum ground acceleration
R = instrumental focal distance

Periods for shear waves will be computed by multiplying P wave periods by a factor equal to 1.7 according with the observations reported by Gutenberg(10).

2.1.2 Attenuation of pulses

The Q-constant criterion (or "per-cyclic" damping) will be used herein to take into account the attenuation of the waves due to energy absorption in the media. In light of the estimate made by Press and Brace(11), that 80 per cent of the seismic energy is released at depths ranging between 0 and 60 km, the value of Q will be taken equal to 250, a value appropriate for that depth according to data compiled by Rascón and Cornell(12). The earthquakes to be simulated in this paper will have short focal depths (24 km).

The Q-constant criterion refers to harmonic waves. Therefore, if one wants to know the attenuation of a non-harmonic wave, after it has traveled a certain distance, it would be necessary to carry out a Fourier decomposition of each pulse. For many pulses this process is very time consuming, and therefore, (even though the value of η is relatively large) it will be assumed simply that the only frequency components of the pulse are ω and 2ω with initial relative amplitudes of 1 to 1/2.

The attenuation phenomenon causes a change in shape and in frequency content of the acceleration pulse with travel time and distance; an elongation of the apparent period of the pulse is noticed due to the faster attenuation per unit distance of the higher frequency components. This is in agreement with field observations(4) and with some theoretical results obtained by Sezawa(13) and Knopoff(14).

2.1.3 Duration of ground motion

If a constant velocity of rupture of the fault, v_r, is assumed, the duration

$$\delta t = d'/v_r$$

will be the time for the breakage of the fault section equal to the distance, d', between two elementary adjacent sources. The duration of generation of waves from each elementary earthquake, s_e, will be considered to be equal to

$$s_e = \bar{s} + \delta t \qquad (7)$$

where $\bar{s}$ is given by[1] $\bar{s} = 0.4\ e^{0.74M}$ using M_e instead of M. The value of the fault breakage velocity will be taken to be 3 km/sec, in accordance with compiled empirical and analytical results[12]. The implied total duration of the motion at the site of interest is

$$s = (\bar{\tau}_{1N} + s_e) - \tau_{11} \qquad (8)$$

where τ_{11} and $\bar{\tau}_{1N}$ are, respectively, the arrival times of the first longitudinal wave of the first elementary earthquake and of the first shear wave of the last elementary earthquake.

2.1.4 Superposition of waves

As stated above, the earthquake record will be formed by a random superposition of shear and longitudinal waves coming from each elementary source, the amplitude, A, of each wave being affected at any time, t, by three reduction factors corresponding to spherical spreading, multiple reflections and refractions, and attenuation, and by a randomly selected plus or minus sign to take into account possible changes in phase of the wave due to reflections and refractions.

These three reduction factors are given respectively by[12]

$$A(t)/A(0) = 1/r(t) \qquad (9)$$

$$A(t)/A(0) = e^{-kt};\ k = 0.5 \qquad (10)$$

$$A(t)/A(0) = e^{-(\pi/Q)\ (t/T)} \qquad (11)$$

where

r = traveled distance
T = $2\pi/\omega$ = wave period

Let τ_{ij} and $\bar{\tau}_{ij}$ be the arrival times of the i^{th} longitudinal and i^{th} shear wave, respectively, coming from the j^{th} elementary source. The acceleration P-pulse at the surface, to be used at a time t will have the form

$$\ddot{x}_{ij}(t\ ,\ \tau_{ij}) = (R_{1j}/R_{ij})\ A_{1j}\ \omega_j^2\ \exp\ [-\eta\omega_j\ (t - \tau_{ij})-(\tau_{ij} - \tau_{1j})(\omega_j/2Q + k)]$$
$$\{\exp\ [-(\tau_{ij} - \tau_{1j})\ \omega_j/2Q]\ \{(1 - \eta^2/2\ \sin\ 2\omega_j\ (t - \tau_{ij})$$
$$+ 2\eta\ [\cos\ 2\omega_j\ (t - \tau_{ij}) - \cos\ \omega_j\ (t - \tau_{ij})]\} \qquad (12)$$
$$- (1 - \eta^2)\ \sin\ \omega_j\ (t - \tau_{ij})\};\ \tau_{ij} \leq t \leq \tau_{ij} + 2\pi/\omega_j$$

where

R_{ij} = traveled distance
A_{1j} = amplitude of the first arriving P-wave coming from the j^{th} elementary source

An equation similar to 12 can be constructed for S-wave by writing $\bar{\tau}_{ij}$, $\bar{R}_{ij}$, $\bar{\omega}_j$ and $\bar{A}_{1j}$ in place of τ_{ij}, R_{ij}, ω_j and A_{1j} respectively. (In general a bar will be used for the parameters associated with shear waves.)

There are not enough data of A_{1j} and $\bar{A}_{1j}$ to permit fitting of probability distribution; therefore, considering that the amplitude of a wave is affected along its trajectory by a large number of perhaps additive random factors, a normal distribution will be used with parameters given by(12)

$$E\left[A_{11}\right] = \exp\left[2.35\ (M - 1.35)\right]$$
$$E\left[\bar{A}_{11}\right] = \exp\left[1.67\ (M + 1.21)\right] \qquad (13)$$
$$\sigma\left[A_{11}\right] = \exp\left[1.85\ (M + 0.06)\right]$$
$$\sigma\left[\bar{A}_{11}\right] = \exp\left[0.91\ (M + 7.19)\right]$$

in which σ denotes standard deviation. The method for obtaining these parameters for $j \neq 1$ will be given below.

It will be assumed that each type of pulse coming from the j^{th} elementary source arrives at the site of interest following a Poisson process with mean rate, ν_j, (mean number of pulses per unit time).

$$\nu_j(t-\tau_{1j}) = \nu_{oj} + H(t - \tau_{1j}-\delta t)\ [e^{\mu(t-\tau_{1j}-\delta t)} - 1];$$
$$t \geq \tau_{1j} \qquad (14)$$

where ν_{oj} is the initial rate, μ is a constant(12) and H(.) is the Heaviside step function. The values of ν_{oj} will be considered to be the same for all j's and both for shear and longitudinal waves, i.e.,

$$\nu_{oj} = \bar{\nu}_{oj} = \nu_o\ ;\ j = 1, 2, \ldots, N \qquad (15)$$

Eq. 14 implies that the mean rate is assumed to be constant during the time interval δt, the time required to rupture a fault length equal to the distance between two adjacent elementary sources. After this interval an increasing rate function is used because, due to the polarization of waves when reflected and refracted at soil interfaces, the number of waves increases with time.

2.1.5 Variance of the Stochastic Process

It has been assumed that individual waves arrive at the site of interest following a Poisson process with non-constant mean rate. The resultant stochastic process will then be a non-homogeneous-multiple-filtered Poisson process(8) with an influence function for each type of wave from each elementary source given by

$$w = w(t - \tau,\ \tau\ ,\ A_{1j}) \tag{16}$$

The whole process will consist of the sum of pairs of independent stochastic processes associated with each elementary source; one for longitudinal and one for shear waves. The variance of the process will therefore be equal to the sum of the variances of each elementary process.

The variance of an elementary process associated with P-waves, given the value of ωj, will have the form

$$\mathrm{Var}\ [\ddot{x}_{(r,\theta,\phi),j}(t\ ,\tau_{ij})]$$

$$= E[\ A_{1j}^2] \int_{\tau_{1j}+t-T_j}^{\tau_{1j}+t} w^2(t-\tau,\tau)\ \Phi^2_{(r,\theta,\phi)}(\theta_j,\phi_j)\ \ d\tau \tag{17}$$

where

$\ddot{x}_{(r,\ \theta,\ \phi),\ j}(t,\ \tau_{1j})$ = acceleration pulses in the directions defined by the spherical coordinates, r, θ and ϕ.

$$\Phi_r = \sin 2\ \theta_j\ \cos\ \phi_j$$

$$\Phi_\theta = \cos 2\ \theta_j\ \cos\ \phi_j \tag{18}$$

$$\Phi_\phi = \cos\ \theta_j\ \sin\ \phi_j$$

Since the mean value of the process is zero, eq 17 will give the value of $E\ [\ddot{x}^2(r,\theta,\phi),j(t,\ \tau_{1j})]$. The zero mean follows from the fact that the values of A_{1j} and $\bar{A}_{1j}$ can be positive or negative with equal probability.

After evaluating the integrals appearing in eq 17 one arrives at

$$E[\ddot{x}^2_{(r,\theta,\phi),j}(t,\tau_{1j})] = \Phi^2_{(r,\theta,\phi)}(\theta_j,\ \phi_j)\ \omega_j^3\ E[A_{1j}^2]\ e^{-\lambda_j(t-\ \tau_{1j})}$$

$$(R_{1j}/R_{ij})^2\ \nu_o F(t-\ \tau_{1j}) \tag{19}$$

where

$$\lambda_j = (\ \omega_j/Q) - \mu + 2k \tag{20}$$

F = function of t − τ_{1j}(12)

The expected square values of the process in the X or Y directions are

$$E[a^2_{(x,y)}(t)] = \sum_{j=1}^{N_p} E[A^2_{1j}]\ \omega_j^3\ (R_{1j}/R_{ij})^2 \nu_o\ e^{-\lambda_j(t-\tau_{1j})}$$

$$\times F(t-\tau_{1j})\ \delta_{p,(x,y),j} \tag{21}$$

$$+ \sum_{j=1}^{N_s} E[\overline{A}^2_{1j}]\ \overline{\omega}_j^3\ (R_{1j}/\overline{R}_{ij})^2\ \nu_o\ e^{-\overline{\lambda}_j(t-\overline{\tau}_{1j})}$$

$$\times \overline{F}\ (t-\overline{\tau}_{1j})\ \delta_{s,(x,y),j}$$

where

N_s, N_p = number of trains of S and P waves, respectively, which are non-zero at the instant t,

and, for the case of vertical faults, (fig 1),

$$\delta_{p,x,j} = 2\,\Delta\ d_j^2/R_j^3$$

$$\delta_{s,x,j} = (\Delta/R_j)\ [(H/\rho_j)^2 + (d_j/\rho_j)^2\ (1 - 2\rho_j^2\ /R_j^2)]$$

$$\delta_{p,y,j} = 2\ \Delta^2 d_j/R_j^3$$

$$\delta_{s,y,j} = (d_j/R_j)\ (2\rho_j^2\ /\ R_j^2 - 1) \tag{22}$$

$$\delta_{p,z,j} = 2H\,\Delta\, d_j/R_j^3$$

$$\delta_{s,z,j} = (H\,\Delta\, d_j/\rho_j R_j)\ [(1-2\rho_j^2\ /R_j^2)\ /\rho_j - 1/R_j]$$

where

d_j = distance from the j^{th} elementary source to the projection of the site of interest on the line containing all the elementary sources

R_j = focal distance to the j^{th} elementary source

$\rho_j^2 = d_j^2 + H^2$

In eq 21 we do not know, at this point, the values of the parameters μ, ν_o, $E[A^2_{1j}]$ and $E[\overline{A}^2_{1j}]$ for $j \neq 1$.

2.1.6 Computation of μ

The value of the arrival rate exponent, μ , is computed by making the variance of the last train of shear waves, at the time s, be a predefined fraction, ϕ, of its maximum mean square value. In this way the contribution of waves arriving at a time after s will be neglected and, therefore, only the strong part of the record will be simulated. In this paper, $\phi = 0.1$ will be used[12].

2.1.7 Computation of $E\left[A_{1j}^2\right]$ and $E\left[\bar{A}_{1j}^2\right]$

The values of $E\left[A_{1j}^2\right]$ and $E\left[\bar{A}_{1j}^2\right]$ for $j \neq 1$ are computed in such a way that the mean energy density per cycle at each elementary source be the same for all P and S waves respectively. Owing to this assumption and because the mean rate of waves for each elementary source is assumed to be the same, the total expected energy released by each elementary source will also be identical. Detailed analytical results are given by Rascón and Cornell[12].

2.1.8 Computation of the Initial Rate Value of Waves, ν_0

Determination of ν_0 requires a relationship between the expected peak acceleration and a representative root mean square value. Several theories exist for estimating the probability distributions of the peaks and of the first passage times of a stationary random process[15,16]. To the authors' knowledge there is no way to relate the ensemble root mean square value of a non-stationary process to the expected peak of the process. The equation

$$E\left[a\right] / \sigma = \sqrt{2} \sqrt{\ln (2s/\bar{T})} \qquad (23)$$

derived from some results given in ref 16 for a stationary process, will be used, and a correction factor, that takes into account the fact that the process used herein is not stationary, will be estimated from the simulation results.

In this paper records in several directions will be generated for the same earthquake at the same time; the time variations of the root mean square values are generally different for each direction but they will be only computed in the directions parallel and perpendicular to the causative fault. The value of σ to be used in eq 23 will be computed in a manner explained below.

Let a_x and a_y denote the maximum ground acceleration in the records oriented as X and Y respectively. Let σ_x^2 and σ_y^2 be the maximum values of the variance in those directions; these values can be computed by using eq 21 up to the factor ν_0. Under the assumption that

$$a_x / \sigma_x = a_y / \sigma_y \qquad (24)$$

one obtains

$$a_y / \sigma_y = \bar{a} / \bar{\sigma} \qquad (25)$$

where

$$\bar{a} = (a_x + a_y)\ /2$$

and

$$\bar{\sigma} = (\sigma_x + \sigma_y)\ /2 \qquad (26)$$

There is not published an empirical correlation between maximum ground acceleration and orientation of the record for a given magnitude and focal distance. Esteva and Rosenblueth's empirical result for expected maximum ground acceleration[9] was obtained for assumed point sources by mixing the data for different orientations. For this reason the values obtained can be considered to be an average of the maximum ground accelerations taken over all directions of the records. Following these arguments it will be assumed that

$$\bar{a} = E\left[a\right] \qquad (27)$$

and

$$\bar{\sigma} = \sigma \qquad (28)$$

The value of ν_0 can then be computed by combining eqs 23, 26, 27 and 28 (see ref 12).

3. Simulation and results

In order to facilitate simulation of the analytical model developed above, it is desirable to evaluate the process at discrete, fixed interval time steps. An "equivalent" stochastic process employing random selection of the waves to be simulated at each time point can be constructed[12] which greatly simplifies the computer generation of sample functions of the model.

In order to check the proposed model for future simulation of strong-motion earthquake records, artificial samples of three known seismic motions will be generated. In this process, for the El Centro, Calif., 1940, and for the Taft, Calif., 1952, earthquakes, the observed lengths of the ruptured faults will be used, while for El Centro, 1934, the expected length must be adopted, in absence of field evidence. Fig 2 shows the interpreted relative positions between the sites of interest and the causative faults.[12]

Fig 3 shows the time variation of the theoretical variance of the stochastic processes associated with the El Centro, 1934, earthquake. These variances correspond to the motions in the directions parallel and perpendicular to the corresponding causative fault. It is observed that the root mean square value differs markedly from the constant value associated with stationary models. These results show that the root mean square value of the motion is a function of the orientation of the record relative to the fault, and that, in some cases, it is possible to get the maximum ground acceleration in the first few seconds of the record when only longitudinal waves are arriving. This statement is confirmed in fig 4 which corresponds to a simulated record of the El Centro, 1940, earthquake parallel to the fault. This record can be compared favorably with the widely published NS component acceleration of this earthquake.

Fig 5 compares observed and artificial elastic response spectra for the

Taft, 1952, earthquake. The spectra were obtained after normalizing all the records to have the same maximum ground acceleration as the real earthquake being simulated. This normalization was necessary to permit a one-to-one comparison between the samples of the simulated process and the only available sample of the real process.

In general the agreement between artificial and real spectra has been satisfactory. In some cases the artificial spectra give smaller values for large periods. This difference could be due to the fact that surface waves are not considered during the simulation process; for such reason it is convenient to add them in the model.

Fig 6 shows the graph of the ratio of the squared maximum ground acceleration, a_y^2, and the variance, σ_y^2, of the process in the perpendicular direction to the fault, to the ratio of the same parameters associated with the parallel direction. It confirms that the hypothesis made in Section 2.1.8 is reasonable, i.e., that $a_x^2/\sigma_x^2 = a_y^2/\sigma_y^2$.

To correct eq 23 which was derived for a stationary process, for the class of nonstationary stochastic process used herein, the average of the maximum ground accelerations in eight different directions was computed for each simulated earthquake. The ratio of this average simulated maximum acceleration to the expected value of the maximum ground acceleration(9) was calculated for each earthquake. The average of these ratios was 1.45. This suggests that the coefficient given by eq 23 must be divided by 1.45 in order to get, on the average, the mean maximum ground acceleration equal to its expected value. Therefore, the following equation is proposed instead of eq 23 for computing this ratio

$$E[a]/\sigma = \sqrt{\ln(2s/\tilde{T})} \qquad (29)$$

where $E[a]$ is the expected maximum ground acceleration(9), σ is the average of the maximum standard deviations of the processes associated with the directions parallel and perpendicular to the fault (X and Y directions) which are obtained from eq 21; s is the length of the record, given by eq 8 and $\tilde{T}$ is the mode of the wave periods (eq 6). The results obtained by eq 29 for the examples presented in this paper, are between 2.1 and 2.3 which are quite close to the value of 2.5 related to Levi's nonstationary process(17).

From the results given above and in ref 12, it is concluded that the physically based stochastic model for strong-motion-earthquake records simulation, is quite satisfactory. This model makes possible statistical studies of responses of structures on firm ground at instrumental focal distances between 20 and 500 km and with any orientation and relative position between the site of interest and the causative fault.

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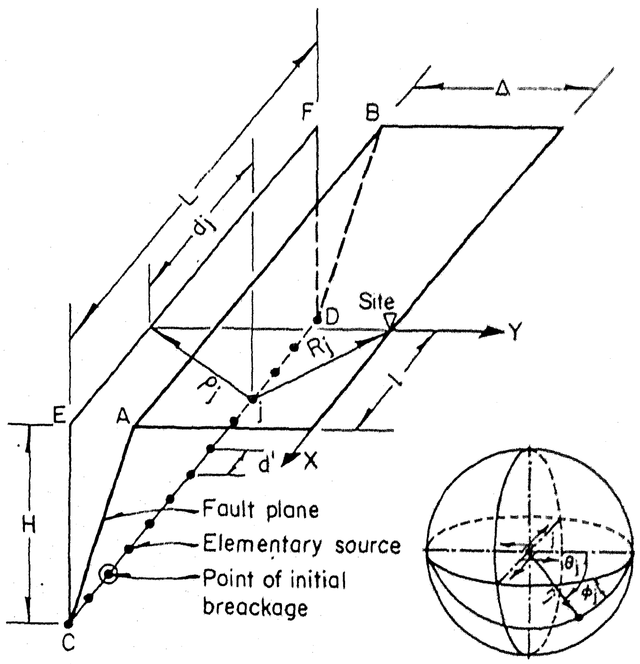

Fig 1 Geometric relation between the causative fault and the site of interest.

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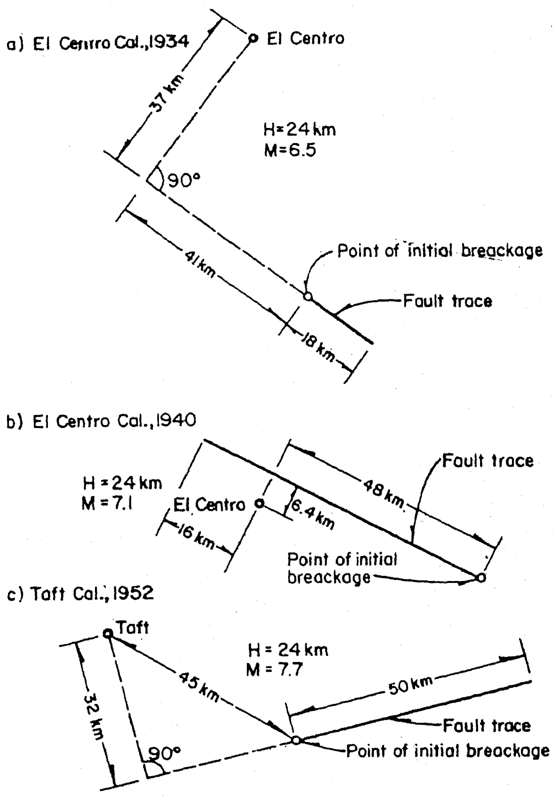

Fig 2 Relation between the fault and the site of interest.

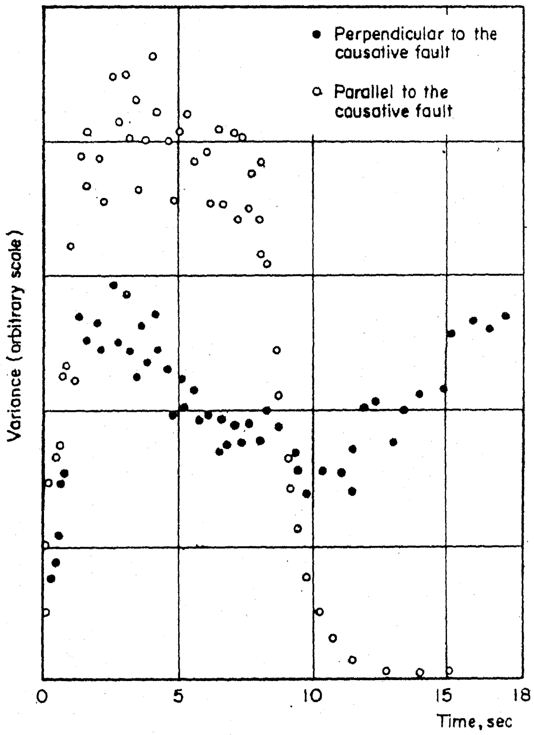

Fig 3 Variance of the stochastic process associated to El Centro Cal., 1934, earthquake.

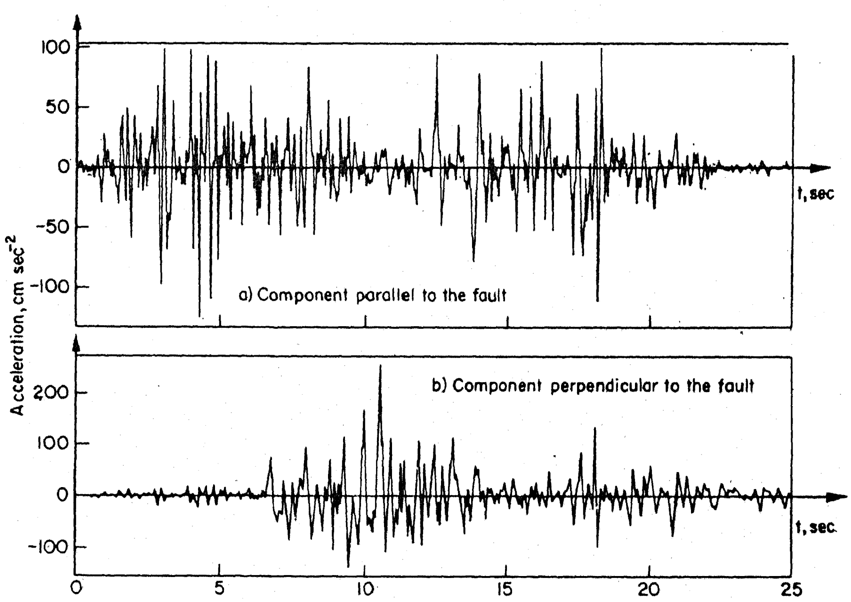

Fig 4 Simulated records of El Centro Cal., 1940, earthquake.

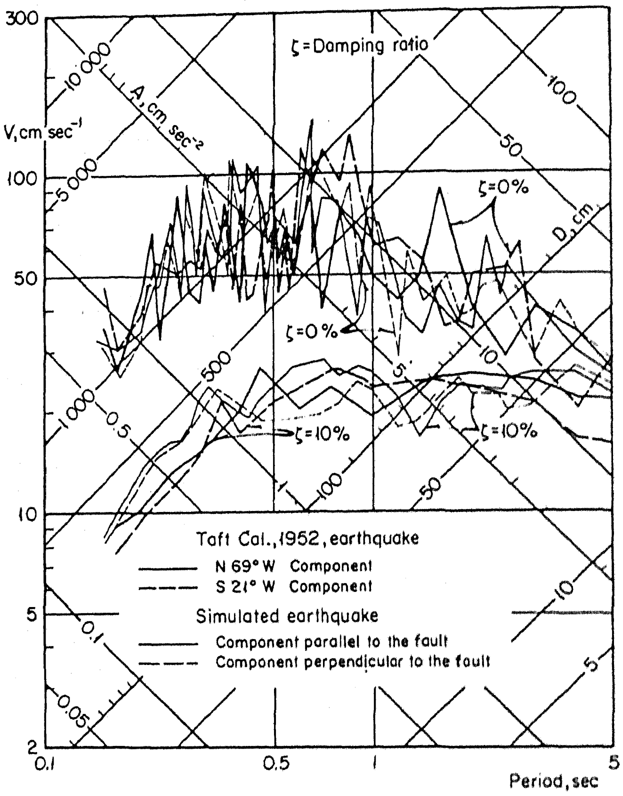

Fig 5 Comparison between real and simulated spectra.

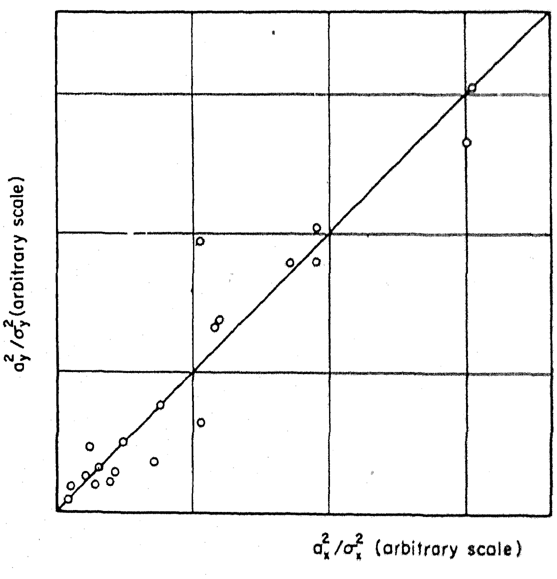

Fig 6 Relation between a_x^2/σ_x^2 and a_y^2/σ_y^2