EARTHQUAKE INSTRUMENTAL INTENSITY FROM STRONG GROUND MOTION RECORDS: SAN FERNANDO EARTHQUAKE

by

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SYNOPSIS

The accelerograms recorded at 61 stations following the February 9, 1971, earthquake and their first integration are used to evaluate a new definition of instrumental intensity. This new quantity is calculated from each component of ground motion in the acceleration and velocity-time domain and takes into consideration: (a) the maximum accelerations and velocities and (b) the time duration of strong motions. These parameters are of utmost importance in the evaluation of intensity and energy. The Arias intensity is computed and compared with the new instrumental intensity and with the Modified Mercalli Intensity (MMI). A number of predictive equations expressing the maximum particle velocity as a function of MMI have been derived along with attenuation relationships in terms of MMI, Arias, the new instrumental intensity, and epicentral distance. The low instrumental intensity correlates well with hard rock, moderate intensities with unconsolidated material, and higher intensities with alluvial deposits.

INTRODUCTION

The term intensity is commonly used to describe the apparent severity of an earthquake at a specific location as determined by observers or by instruments. The empirical intensity is a measure of the effects of an earthquake determined through personal interviews in the affected area, with damage surveys, and with geologic field studies. The Modified Mercalli Intensity scale is used in the United States. This scale rates the observed effects into twelve classes and often is used as a description of the vibrational and ground effects at a given point. Intensity maps are drawn using the rating questionnaires, and these maps are useful in estimating the potential of damage due to earthquakes in a given region.

Recent studies of strong motion records of well documented earthquakes have resulted in a number of approximate relationships between ground parameters and MMI. The San Fernando Valley earthquake of 1971, recorded by a large number of accelerographs, provided an excellent opportunity to develop and evaluate an instrumental intensity. The instrumental intensities were intended to provide the earthquake engineer and the seismologist with data relevant to the problem of earthquake effects on structures. Hence in developing and refining instrumental-intensity concepts we are proposing a simple straightforward measure of the severity of earthquake ground shaking, which takes into account the duration of strong shaking and the contribution of the phase of strong ground shaking. The new instrumental intensity is evaluated directly in the time domain.

Several important contributions to the instrumental intensity concepts (1, 2, 3, 4, 5) have been made in the last two decades. Benioff proposed a

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measure of the seismic destructiveness to be of the form, SD $=\int_{\omega_0}^{\omega_1} D(\omega)d\omega$ where $D(\omega)$ is the maximum relative displacement of a single degree of freedom oscillator, undamped, and ω is the circular frequency. The range of ω_0 to ω_1 are the frequencies of 20 undamped pendulums whose fundamental periods cover the natrual period of structures. A proposed (3) spectral intensity was defined as the area enclosed by the pseudo-velocity spectrum curve between two periods of vibration. The lower and upper limits of Housner's intensity integral covers the range of natural periods of most structures in a given city. Blume (4) proposed an intensity based on the pseudo-velocity spectrum and divided into nine period ranges. Blume's intensity is then computed from the sum of the mean values in the nine period ranges for a given damping coefficient (usually 5%). This intensity (4) has a direct application to structural problems.

Arias (1) introduced the concept of instrumental intensity in a tensor form; it is defined as the sum of the energies dissipated during the time duration of strongshaking. Therefore, the intensity is given by: I (Arias) $= \int_0^{\infty} E d\omega$, where E is the energy dissipated per unit weight. The calculation of I depends on the mechanical model chosen to represent the structure; in this case it is a single degree of freedom oscillator with viscous damping. A solution for the above model yields the intensity in the x-direction, I_x, as a function of damping, λ, to be

$$I_x(\lambda) = \frac{\text{Cos}^{-1}\lambda}{\sqrt{1-\lambda^2}} \int_0^{t_f} \frac{a_x^2}{g} (t)dt, \qquad (1)$$

where $a_x(t)$ is the ground acceleration, t_f is the time duration, and g is the acceleration due to gravity. It has been shown (1) that the multiplying factor in eq. (1) varies slowly for different values of damping; therefore eq. (1) for $\lambda = 0$ is

$$I_x = \frac{\pi}{2g} \int_0^{t_f} a_x^2 (t)dt \qquad (2)$$

The total intensity is thus $I_x + I_y$, called in this paper I_{ARIAS}.

Lopez-Arroyo and Espinosa (5) have proposed another definition of instrumental intensity which can be correlated to the Arias tensorial intensity; which divides up the frequency range in sub-intervals. They (5), however, arrive at an intensity tensor for each frequency range. The procedure followed in their (5) intensity evaluation is as follows: first, the accelerogram is Fourier analyzed, filtered, then convolved, and the quadrature spectra obtained. Next the inverse Fourier transform is evaluated, the instantaneous amplitudes computed, and finally the intensity evaluated, $I_j^1 = \int_0^{t_f} [A_j^1(t)]^2\, dt$. This intensity evaluation is obtained by displaying the instantaneous amplitudes of acceleration as a function of time and period. Some of the foregoing measures of intensities and their shortcomings have been reviewed elsewhere (1, 6).

The purpose of this paper is to present correlations between the empirical MMI, with the Arias, and with the proposed new instrumental intensity. Also, other objectives are to present general trends and comparisons of the new intensity with source-to-station distance, with site conditions, and with maximum horizontal particle velocity.

DEFINITION OF INSTRUMENTAL INTENSITY

The measure of earthquake instrumental intensity is based on the recordings of strong ground motions at near and intermediate epicentral distances. The ultimate purpose of an intensity scale is to present an indication of potential damage that could take place, due to an earthquake, in a given area. This intensity should, therefore, be a measure of seismic destructiveness and be simple to calculate. In order to calibrate the instrumental intensity to a given level or amount of damage experienced by structures, a relation is developed with the MMI.

The instrumental intensity, I_h, is defined as the sum of the areas included by the envelopes of the acceleration or the velocity-time curves of the horizontal strong ground motion components (Fig. 1). This procedure of evaluating the intensity thus takes into consideration two important parameters in earthquake engineering; (a) time duration and (b) the maximum amplitudes of strong shaking. A similar procedure was developed (7) for a different study.

The intensity obtained by the above method is similar to the Arias intensity but much easier to evaluate. Each component of motion represents a scalar intensity quantity which is the intensity in that preferred direction. In the text that follows the I_h is computed from 61 strong-motion records (122 horizontal components) of the 1971 San Fernando Valley earthquake. The Arias intensity is computed with the aid of eq. (2). Our instrumental intensity, when compared to other instrumental intensities, does not represent the energy stored by a population of structures during an earthquake, but rather the energy flux at a point. In this respect it eliminates the problem of chosing a specific damping for the structure and still provides the earthquake engineer with an adequate measure of seismic destructiveness.

CORRELATIONS BETWEEN INSTRUMENTAL INTENSITY WITH MODIFIED MERCALLI INTENSITY AND EPICENTRAL DISTANCE

The MMI scale is based on the observed effects of earthquakes on human beings, on objects, on geological features, on ground deformations, on animal behavior, and on damage sustained by manmade structures. Henceforth, empirical scales are descriptive and qualitative. The quantitative rating of the MMI is a first order approximation of the earthquake intensity at a given locale. The MMI, in its abridged version, contains nonvibrational effects which create confusion and dispersion of the data (8, and oral comm. R. Nason, 1976). Therefore, it is necessary to correlate the instrumental intensity with the MMI, since most of the available classification of earthquake intensity has been done using the guidelines prescribed by the MMI or the Medvedev, Sponheur, and Karnik (MSK) scales.

The I_h as measured from accelerograms and their first integration are shown in Fig. 2. In this Fig. the instrumental intensity is correlated with the MMI (9). An adequate number of points is available for the first time from the San Fernando earthquake. Using this data base, a regression analysis was performed where the MMI is the independent variable, thus

$$\log_{10} I^{acc} = 0.26 + 0.19\, I_{mm} \qquad (3)$$

and

$$\log_{10} I^{vel} = -0.09 + 0.25\, I_{mm} \qquad (4)$$

where I_{mm} is the MMI rating and I^{acc} and I^{vel} are the horizontal instrumental intensities in the acceleration and velocity-time domain. MMI V and VII show the least amount of scatter of the data, and the largest amount of scatter is approximately one order of magnitude for MMI VI.

Figs. 3(a) and 3(b) show the attenuation relations for I_h. The data scatter in Fig. 3(b) correlates with the geological site condition beneath the recording stations. The lower intensities are associated with stations located on hard rock, while higher instrumental intensities correlate with stations deployed on shallow alluvial deposits.

The I_h obtained from the accelerograms, shown in Fig. 3(a) as a function of distance, can be expressed as

$$\log_{10} I^{acc} = (3.11 \pm 0.14) - (0.97 \pm 0.09) \log_{10} \Delta \qquad (5)$$

and as obtained from their first integration is expressed as

$$\log I^{vel} = (3.28 \pm 0.21) - (1.07 \pm 0.12) \log_{10} \Delta \qquad (6)$$

where Δ is the epicentral distance in km.

The above eqs. (3) through (6) are essential for the process of calibration and attenuation of the new proposed instrumental intensity. The correlation among the above parameters should be useful in the development of predictive models which could be used in seismic risk studies. In particular eqs. (4) and (6) can be used to predict the level of ground shaking for different geological environments. The influence of soil conditions on the earthquake-resistant behavior of structures varies from one locale to a nearby one, and hence it would be desirable to study the local variations of the instrumental intensity in order to ascertain the possible ground amplification effects in that region. The result from the above correlations with other ground motion parameters, such as particle velocity and ground displacements, will aid in the formulation of design codes. The above remarks are based on the excellent data collected from the San Fernando earthquake. However, this data-base is limited and follow up studies with future strong motion records may indicate some variation or changes in the above formulation.

CORRELATION BETWEEN ARIAS INTENSITY, MODIFIED MERCALLI INTENSITY AND EPICENTRAL DISTANCE

The Arias intensity is correlated with MMI and with distance, and the results are shown in Fig. 4. The data scatter in this figure for MMI VI is more than two orders of magnitude. In comparing Fig. 4 with Fig. 2 it is evident that the data scatter is less in Fig. 2. The approximate trend of the mean Arias intensity versus MMI is described by the following equation.

$$\log_{10} I_{Arias} = (-2.54 \pm 0.4) + (0.61 \pm 0.07) I_{mm} \qquad (7)$$

and the attenuation relationship as shown in Fig. 5 is described by

$$\log_{10} I_{Arias} = (4.30 \pm 0.35) - (1.77 \pm 0.21) \log_{10} \Delta.$$

Figs. 4 and 5 when compared with Figs. 2 and 3 show that the Arias intensity has a faster attenuation rate than our proposed instrumental intensity. Also, it shows that the scatter of the data is greater in the Arias intensity, making it somewhat unstable.

CORRELATION BETWEEN PARTICLE VELOCITY, EPICENTRAL DISTANCE AND INTENSITY

The maximum horizontal particle velocity measured from the first integrated accelerograms of the San Fernando earthquake (10), the MMI ratings, and the epicentral distance are used to formulate the following equation:

$$\log_{10} \dot{x} = 1.27 - 0.79 \log_{10} \Delta + 0.16 \, (I_{mm}) \qquad (9)$$

where $\dot{x}$ is the maximum horizontal particle velocity in (cm/sec).

The above equation can be used to predict the level of ground shaking, $\dot{x}$, at a given station deployed on hard, consolidated, or alluvial material. A correction due to the geological site conditions must be applied therefore, and this correction is in the form of an intensity decrement, δI. This decrement has been derived with respect to crystalline rock: $\delta I_1 = 0$ for granite, $\delta I_2 = 1$ for other cyrstalline rock, $\delta I_3 = 1.58$ for consolidated material, and $\delta I_4 = 2.59$ for alluvium. Similar values were obtained (11) for the San Francisco bay region.

SUMMARY

The usefulness of the new instrumental intensity measurements proposed in this study: (1) correlates in the velocity-time domain with the lithology under the station; (2) takes into account the time duration of strong motion; (3) takes into account the maxima of the amplitudes in the time domain; (4) has less data scatter than the Arias instrumental intensity; (5) is a simple straightforward procedure which allows an objective determination of the effects of ground shaking; (6) has a lower rate of attenuation than the Arias intensity; (7) correlates better with the MMI than do other instrumental intensities; (8) and shows an amplification effect which correlates with site conditions. This new intensity could be a useful tool in predicting the earthquake hazard associated with different levels of ground shaking at a given site. The available data from a single event at near- and intermediate-distances, such as this, had permitted an evaluation of strong ground shaking which may be used in seismic zonation on a regional scale. The new instrumental intensity should be a reasonably good measure of the damage potential to manmade structures. However, further analysis of strong motion recordings, on different surficial geologic conditions, is needed before the above predictive models can be used with confidence as a substitute for already established design codes. The correlation found between site conditions and the resulting average intensity increments, and the relations between intensity and distance could be used for delineating general ground shaking problems in a given geological regime.

REFERENCES

1. Arias, Arturo, (1970), A measure of earthquake intensity in seismic design for nuclear power plants: R. J. Hansen, ed., MIT Press, p. 438-483.

2. Benioff, H., (1934), The physical evaluation of destructiveness: Bull. Seismol. Soc. Am., v. 24, no. 4, pp. 398-403.

3. Housner, G. W., (1970), Strong ground motion in earthquake engineering: R. L. Wiegel, ed., Prentice Hall.

4. Blume, J. A., (1970), An engineering intensity scale for earthquake and other ground motion: Bull. Seismol. Soc. Am., v. 60, no. 1, pp. 217-229.

5. Lopez-Arroyo, A., and Espinosa, A. F., (1973), Earthquake intensity from strong motions: Am. Geoph. Union, EOS, (Abs.), v. 54, p. 372.

6. Housner, G. W., (1975), Measures of severity of earthquake ground shaking, in Proc. of U.S. National Conf. on Earthquake Engineering, Michigan, pp. 25-31.

7. Brune, J. N., Espinosa, A. F., and Oliver, J., (1964), Relative excitation of surface waves by earthquakes and underground nuclear explosions: J. of Geoph. Res., v. 68, no. 11, pp. 3501-3513.

8. Espinosa, A. F., Husid, R., and Quesada, A., (1976), Intensity distribution and source parameters from field observations, in the Guatemalan earthquake of February 4, 1976: A. F. Espinosa, ed., Geological Survey Prof. Paper No. 1002.

9. Scott, Nina H., (1971), Preliminary report on felt area and intensity, in the San Fernando earthquake of February 9, 1971: Geological Survey Prof. Paper 733.

10. Espinosa, A. F., (1976), Particle velocity attenuation relations (unpub. data).

11. Borcherdt, R. D., Joyner, W. B., Warrick, R. E., and Gibbs, J. F., (1975), Studies for seismic zonation of the San Francisco Bay Region: R. D. Borcherdt, ed., Geological Survey, Prof. Paper 941-A.

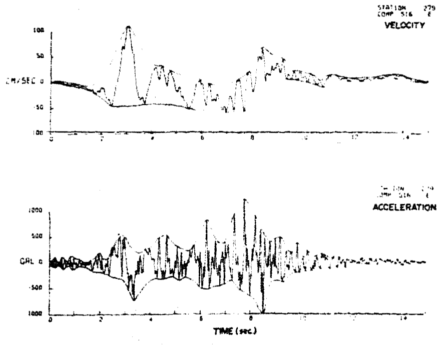

Fig. 1. Procedure followed to evaluate the instrumental intensity from strong ground motion records in the time domain; acceleration and velocity records shown.

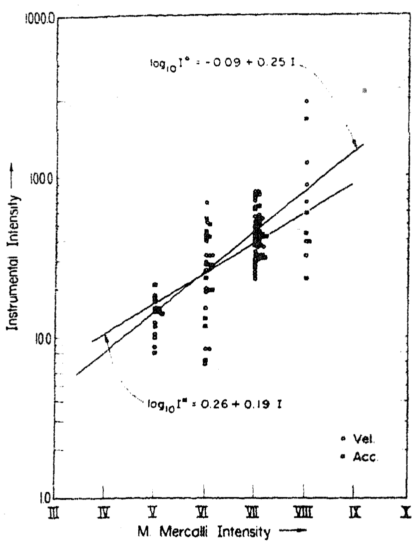

Fig. 2. Instrumental intensity from accelerograms and velocity records in (cm/sec) and (cm) as a function of Modified Mercalli intensity.

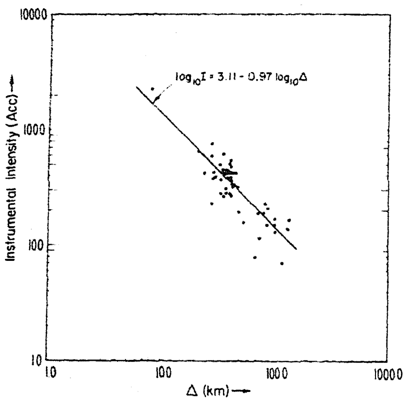

Fig. 3(a). Attenuation for instrumental intensity (cm/sec) from accelerograms.

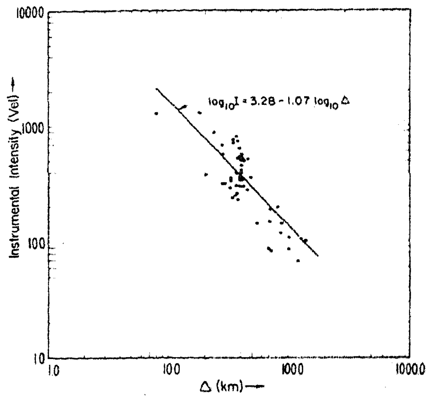

Fig. 3(b). Instrumental intensity (cm) from velocity records from the San Fernando earthquake.

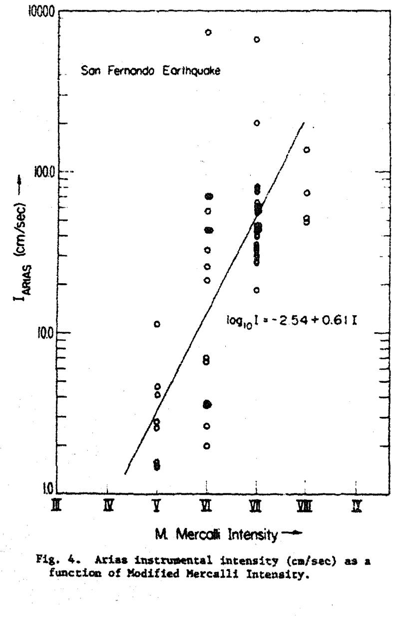

Fig. 4. Arias instrumental intensity (cm/sec) as a function of Modified Mercalli Intensity.

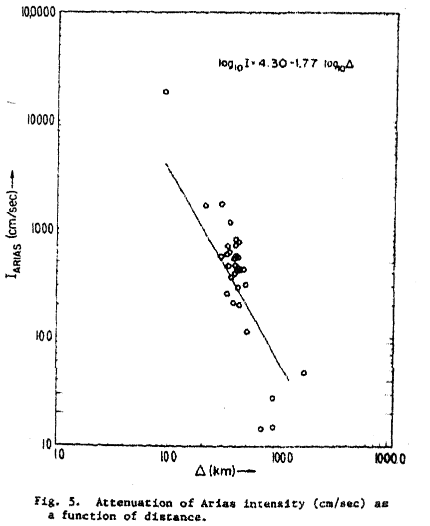

Fig. 5. Attenuation of Arias intensity (cm/sec) as a function of distance.