RECENT DEVELOPMENTS IN THE ANALYSIS OF THE DURATION OF STRONG EARTHQUAKE GROUND MOTION

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SYNOPSIS

Duration of strong earthquake ground motion, defined in terms of the mean-square integrals of recorded motion, has been described empirically in terms of measured as well as qualitative parameters characterizing the earthquake source, the wave transmission path, the recording site conditions and the overall level of shaking at a point. The parameters considered include: (a) earthquake magnitude, (b) epicentral distance, (c) geology surrounding the recording station, (d) the reported Modified Mercalli Intensity at the recording station and (e) the frequency content of recorded motions.

INTRODUCTION

This paper outlines some of the principal characteristics of the duration of strong earthquake ground motion which may be useful for ongoing earthquake engineering research and applications. It represents a brief and partial summary of our recent studies [1,2] which dealt with three related quantities: (i) total energy content of recorded strong shaking at a point, (ii) duration of the time interval of strong shaking contributing most to this energy and (iii) the average time rate of increase of the integrals of squared acceleration, velocity and displacement during the time interval associated with strong shaking. The results reviewed here focus on the duration of strong shaking only. The definition of the duration of strong shaking employed in our recent work [1,2] has been based on that portion of recorded accelerations which contribute 90% to total available energy to excite all single degree of freedom oscillators whose response is portrayed by the response spectra. Though this definition now seems to be convenient from the structural response viewpoint and can be shown [1,2] to be useful for many other applications, other different definitions may be more appropriate in some instances.

Duration of strong shaking clearly plays a major role in determining the degree of possible or experienced structural damage. During nonlinear yielding response, to accommodate excessive energy input, structures may have to undergo progressive damage and possibly reach failure. In addition to the amplitudes of strong shaking, this response will also depend on the number of cycles of repeated stress reversals. Because, so far, more attention has been devoted to the amplitudes of strong shaking only, the purpose of this paper is to reemphasize the fact that the duration of strong-motion should also be considered simultaneously with the amplitude characteristics as an essential parameter in characterizing strong ground motion for earthquake engineering research and design applications.

The data base used in this summary has been recorded on 186 accelerograph records which were obtained during 57 earthquakes in the Western

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United States of America. These digitized and corrected accelerograms can be taken to accurately represent ground acceleration in the frequency band between about 0.12 cps and 25 cps. For the purposes of this analysis this data was band-pass filtered into six frequency bands centered at 0.2, 0.5, 1.1, 2.7, 7.0 and 18.0 cps. It has been assumed [1,2] that these frequency bands are narrow enough so that the computed duration of strong accelerations, velocities and displacements are the same within each frequency band. Though all computed data on duration have been used in deriving the correlation coefficients [1,2] summarized in this paper, we will concentrate in this presentation on accelerations only.

It should be noted that the data consisting of 186 accelerograms is far from adequate to characterize strong shaking for the complete range of the parameters we used to describe it. For example, about 70% of data results from earthquakes in the magnitude range between 6.0 and 6.9, while only 4% of data is available for magnitudes between 7.0 and 7.9. More than 60% of all data has been recorded on alluvium (labeled by $s = 0$), about 30% on "intermediate" sites (labeled by $s = 1$) and less than 10% on sound igneous or basement rock sites (labeled by $s = 2$) [1,2]. There are virtually no recordings for epicentral distance less than ~10 km and most data points fall between about 20 km and 250 km. For correlations with the Modified Mercalli Intensity (I_{MM}) reported at the recording sites, the data may be adequate for preliminary analyses for I_{MM} levels V, VI and VII only. Consequently, even though all available data points have been used in the development of the correlation functions presented here the inferences summarized in this paper can be considered to be reliable only for the range of the respective parameters where the data points are available. Therefore, our recent studies [1,2] and this summary can only be taken as preliminary and the functional form of the regression equations and the coefficients in these equations will have to be improved or at least updated when more representative records become available.

In this paper the data on strong shaking, the magnitude scale and the Modified Mercalli Intensity scale as well as other implicit properties of recorded motions are all representative of the Western United States only. While many results on strong-motion duration as presented in this paper may be useful and applicable in other parts of the world, caution must be exercised in using the equivalent magnitudes and/or intensities I_{MM}, taking into account any systematic biases that may exist between such scales in the Western United States and other parts of the world. Modified Mercalli Intensity, I_{MM}, for example, only represents a crude and brief description of the degree of structural damage and the phenomena associated with soil and rock deformations. Even though the descriptive characteristics of this and analogous scales in other countries may appear similar or even identical, the methodology of data collection and analysis may introduce systematic differences from one seismic zone to another [3].

DEPENDENCE OF DURATION ON MAGNITUDE, DISTANCE AND SITE CONDITIONS

The duration of strong shaking can be represented as a sum of durations corresponding to: (i) multiple scattering and reflections along the propagation path and through the discontinuities near the recording station, $a(\omega_c)s$, (ii) duration of faulting, $b(\omega_c)M$, and (iii) dispersion of waves with increasing epicentral distance, $c(\omega_c)\Delta$, as follows:

$$\text{duration of strong shaking} = a(\omega_c)s + b(\omega_c)M + c(\omega_c)\Delta + d(\omega_c) \; . \qquad (1)$$

Here $a(\omega_c)$, $b(\omega_c)$, $c(\omega_c)$ and $d(\omega_c)$ are frequency dependent "coefficients" which can be determined, for example, by least squares procedure for six frequency bands with center frequencies at $\omega_c = 2\pi f_c$, and for $f_c = 0.2$, 0.5, 1.1, 2.7, 8.0 and 18.0 cps. s represents recording site classification with $s = 0$ being assigned to alluvium sites, $s = 2$ to basement rock sites and $s = 1$ to intermediate sites [1,2]. M and Δ stand for magnitude and epicentral distance, respectively.

The effect of site conditions, s, on the computed duration of strong shaking is shown in Fig. 1. It is seen that the "coefficient" $a(\omega_c)$ is always negative and that its values range from about -4 to -6 (for low-frequencies) to about -1 (for high-frequencies). This means that for long period waves and on alluvium sites the expected duration of strong shaking may be 8 to 12 seconds longer than for the corresponding motions recorded on basement rock. For short periods the duration increases with magnitude for all but the lowest frequency band ($f_c = 0.2$ cps). This can be explained by low signal-to-noise ratio for waves with periods longer than about 2 seconds [1,2]. The "coefficient" $c(\omega_c)$ is nearly constant and equal to about 0.08 except for the highest frequency band. These amplitudes are consistent [1,2] with an estimate of $c(\omega_c) \approx 1/V_{min} - 1/V_{max}$, where V_{min} and V_{max} are minimum and maximum wave speeds for the waves in a given frequency band and for $V_{min} \sim 3$ km/sec and $V_{max} \sim 4$ to 5 km/sec.

In studies which examine the damaging characteristics of strong shaking and analyze nonlinear response of yielding structures it is useful to consider the number of stress reversals which would be experienced by an equivalent linear oscillator during the duration of strong shaking. This can be computed by multiplying the duration of strong shaking by the natural frequency of the oscillator. For the range of earthquake magnitudes from 4.5 to 7.5 and for epicentral distances between 0 km and 150 km, for example, the number of stress reversals varies from less than 10 for $f_c = 0.2$ cps to about 500 for $f_c = 18$ cps. The number of stress reversals for fixed intermediate or high frequencies, f_c, increases with magnitude, M, and from hard rock sites ($s = 2$) to alluvium sites ($s = 0$), but these changes are considerably smaller than the dependence on frequency and epicentral distance, Δ.

DEPENDENCE OF DURATION ON MODIFIED MERCALLI INTENSITY AND SITE CONDITIONS

In correlations of computed duration of strong shaking with the Modified Mercalli Intensity at a site, I_{MM}, we employed linear regression of the form

$$\text{duration of strong shaking} = A(\omega_c) + B(\omega_c) I_{MM} \qquad (2)$$

where $A(\omega_c)$ and $B(\omega_c)$ are frequency dependent "coefficients" computed from six frequency bands and whose amplitudes are shown in Fig. 2. In contrast to equation (1), in (2) we purposely eliminated all dependence on epicentral intensity and on the epicentral distance. Additional terms which would model these effects would probably reduce the overall scatter of data about the linear regression in (2) but would explicitly or implicitly introduce the dependence of the results on the attenuation of wave amplitudes which are characteristic for the Western United States. Eliminating these terms, of course, does not qualify equation (2) for direct use in other parts of the world, but at least formally permits one to estimate the duration of strong shaking at a point provided some equivalent of the Modified Mercalli Intensity scale is available.

Fig. 2 presents the frequency dependent "coefficients" A and B. Negative values of B show that the durations, as defined in this and our recent papers [1,2], decrease for each level of I_{MM} by about 5 seconds for low frequency band ($f_c = 0.2$ cps) and by about 2 to 3 seconds for high frequency bands. Fig. 3 shows the mean amplitudes and standard deviations for the duration of acceleration. This data, together with computed durations of velocity and displacement was used to compute $A(\omega_c)$ and $B(\omega_c)$ shown in Fig. 2. In Fig. 3 six amplitudes correspond to six frequency bands centered at $f_c = 0.2$, 0.5, 1.1, 2.7, 7.0 and 18.0 cps, from left to right. The average durations are longer for low frequencies ($f_c = 0.2$ and 0.5 cps) than for high frequencies ($f_c = 7.0$ and 18.0 cps) by roughly 10 sec (for higher intensities) to 20 sec (for lower intensities).

Dependence of computed durations of strong-motion acceleration on site conditions is shown in Fig. 4, where the averages and standard deviations have been plotted versus Modified Mercalli Intensity levels IV through VIII. It is seen that the durations are shorter for basement rock sites ($s = 2$) than for alluvium sites ($s = 0$). For the data shown, at basement rock sites the duration does not vary with frequency by more than ~10 seconds, while for the alluvium sites ($s = 0$) the variation with frequency is about 20 seconds. For $s = 0$, 1 and 2 the duration tends to be longer for low frequency waves than the duration for high frequency waves. The standard deviation of computed durations tends to be longer for alluvium sites ($s = 0$) than for basement rock sites ($s = 2$) which perhaps results from a greater number of repeated reflections at $s = 0$ sites. Again, Fig. 4 presents groups of six data points corresponding to the same six frequency bands shown in Fig. 3 and for frequency increasing from left to right. Additional and more detailed discussion of these and other related characteristics of the duration of strong earthquake ground motion at a point may be found in the references [1,2].

REFERENCES

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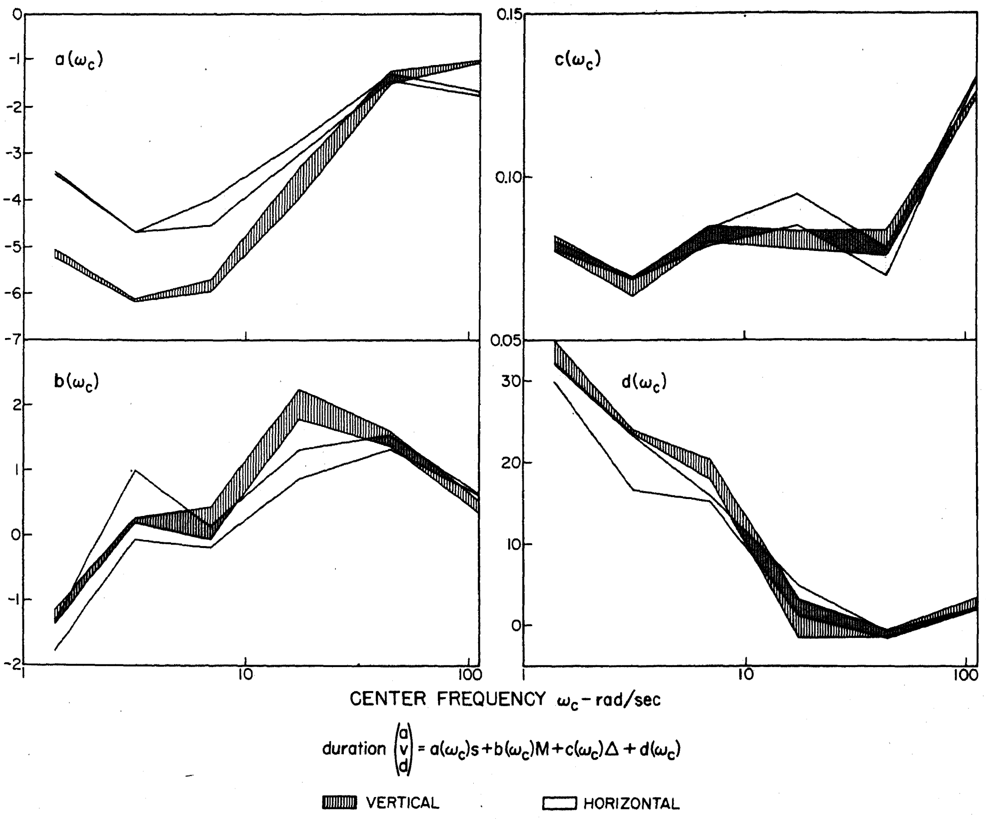

Figure 1

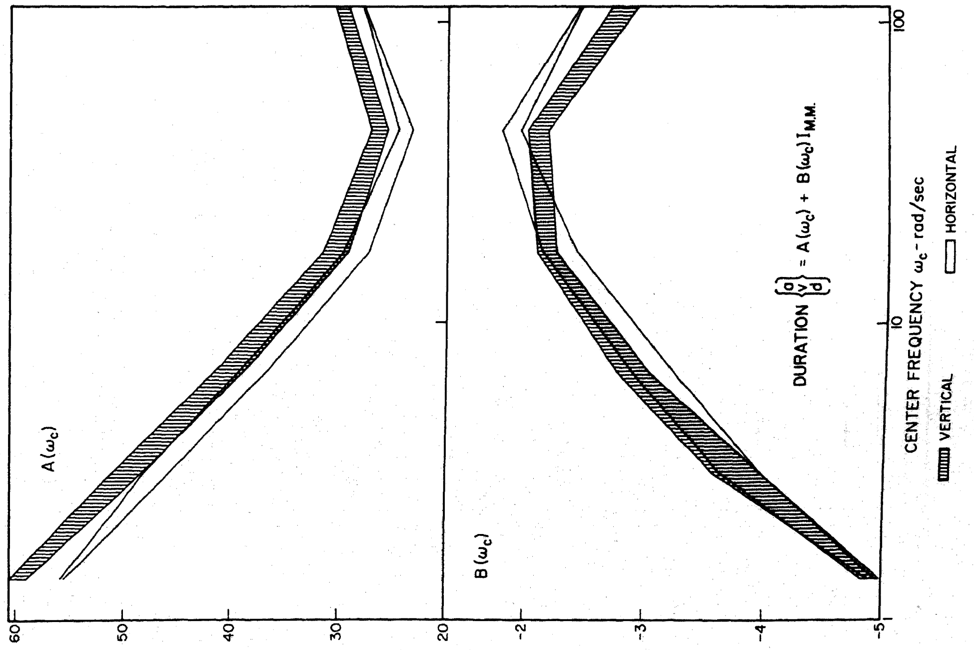

Figure 2

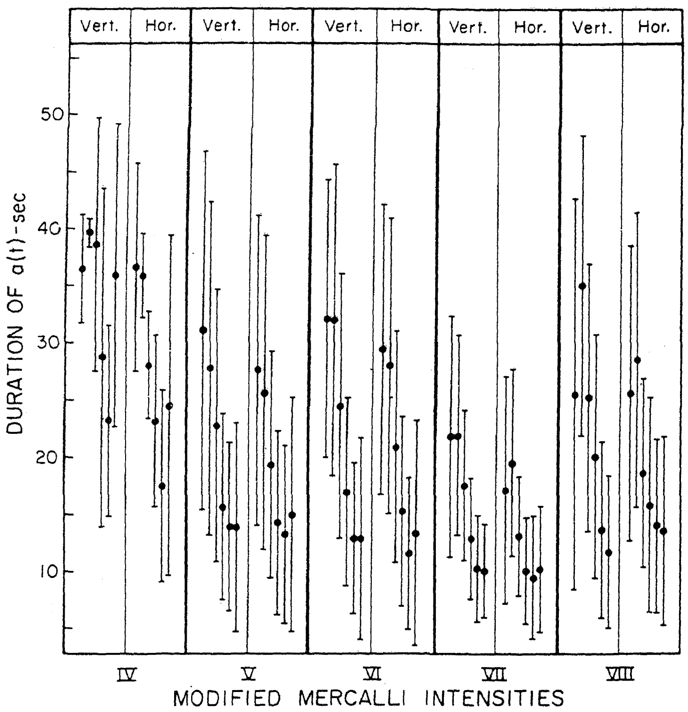

Figure 3

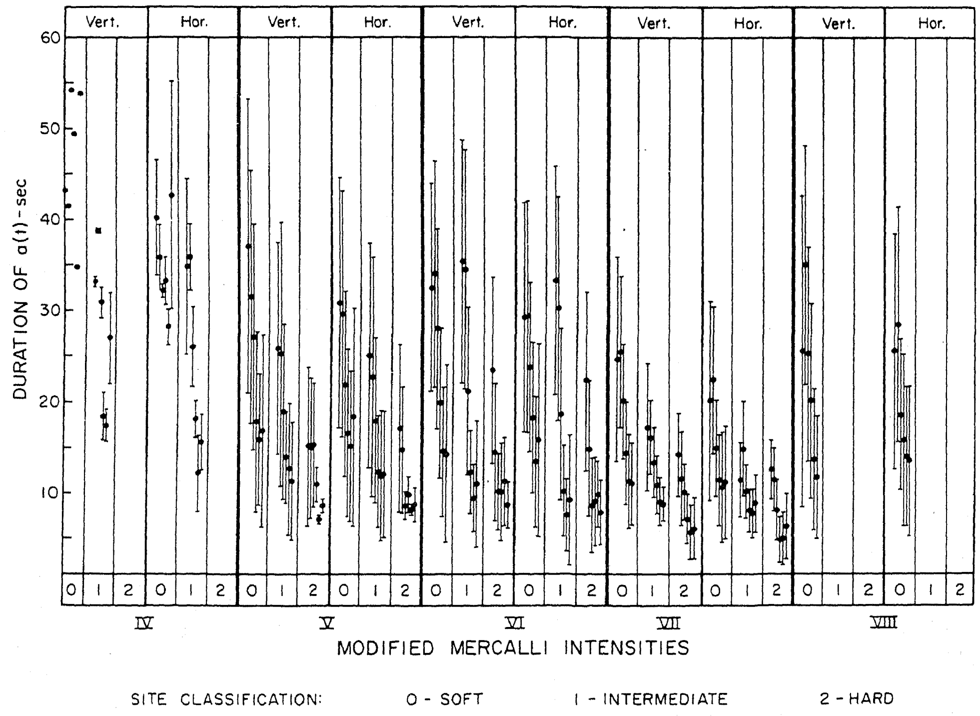

Figure 4

DISCUSSION

Ismael Herrera (Mexico)

Duration of earthquake must be strongly influenced by depth of deposits of soils. Thus, it must be included when establishing correlations between this and others parameters of earthquake.

Author's Closure

I agree with the comment of Mr. Herrera and believe that the depth of soil and alluvium deposits should be included in the correlations between duration of strong shaking and other earthquake parameters. We are at present conducting research which addresses this very point.

There are instances, however, when the depth of geologic strata of the station is not available and when it is necessary to estimate duration of strong shaking solely on the basis of superficial geology. The methodology which we have presented in this paper addresses that problem.