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PARAMETERS FOR SEISMIC HAZARD MAPPING - A REVIEW

by

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ABSTRACT

The most common parameter used by both engineers and seismologists to characterize a strong motion accelerogram is the peak acceleration, although it is well known that this quantity does not in general correlate well with structural damage. Many other parameters derived or calculated from accelerograms have been suggested, and are herein compared from the standpoint of overall effectiveness. For engineering purposes the direct mapping of response spectrum ordinates is being increasingly used, and in the future such derived parameters may be by-passed in favor of using ensembles of accelerograms as inputs to structural models. The duration of strong shaking is an important parameter for structural design which has not as yet been either suitably defined or introduced into design codes in a widely accepted form.

INTRODUCTION

Among the earliest facts established about earthquakes are (1) that they come in different sizes, and (2) that they are not uniformly distributed over the earth, but are much more likely in some places than in others. Such knowledge immediately suggested the need for some kind of mapping, to delineate regions of potential earthquake hazard, and to give some idea of the size of the events that might be expected there. The earliest maps were, in effect, isoseismal maps, indicating regions of similar effects in the immediate vicinity of specific destructive shocks. To compare different earthquakes in different places, some generally agreed upon descriptive intensity scale was required, and numerous such scales were proposed from the 16th century on (Davison, 1927; Medvedev, 1965).

It was in 1887 that E. S. Holden, the director of the Lick Observatory in California, set himself the problem of correlating the degrees of the Rossi-Forel scale with "a common unit of a mechanical sort" (Holden, 1887). He states that "There is no question as to what unit to employ. The researches of the Japanese seismologists have abundantly shown that the destruction of buildings, etc., is proportional to the acceleration produced by the earthquake itself in a mass connected with the earth's surface . . . it would be logical to express I in fractions of the acceleration due to gravity. . . ." It is a remarkable fact that over one hundred years later peak ground acceleration is still the ground motion parameter most widely used by both engineers and seismologists, even though it is now known that this parameter does not correlate well with structural damage, and must be supplemented by much additional information. By estimating ground amplitudes and periods from Japanese seismograms for earthquakes for which the Rossi-Forel intensities were well established, Holden associated an intensity IX with a peak ground acceleration of 120 cm/sec^2. Note that this was some 50 years before ground accelerations had been directly measured. His numbers may be compared with some later correlations, made after many ground accelerations of destructive shocks had been measured. Typical correlations with a Modified Mercalli IX event (equivalent to the Rossi-Forel scale in this range) give values of 540 cm/sec^2 (Neumann, 1954), 200-400 cm/sec^2 (Medvedev, 1962), 500 cm/sec^2 (Trifunac and Brady, 1975), and 320 cm/sec^2 (Murphy and O'Brien, 1977). The somewhat lower values assigned by Holden no doubt reflect the fact that his long-period seismographs were not sampling the higher frequency range in which peak accelerations usually occur. Considering the state of knowledge at the time, Holden's estimates were remarkably successful.

EARTHQUAKE BUILDING CODES

The first seismic zoning maps, then, delineated zones in which shocks of various intensity levels might be expected. An important purpose of such maps was to form the basis for seismic design codes aimed at producing earthquake-resistant construction, and it is this aspect of the subject that will be emphasized in the present review.

The first such engineering codes referring directly to ground accelerations appeared after the great earthquake of 1908 in Messina, Italy (Freeman, 1932). It is interesting to note that the San Francisco earthquake of 1906, which resulted in major studies of geological and seismological importance, did not stimulate the development of earthquake-resistant building codes. This was perhaps because the committee which produced the monumental Carnegie report on the earthquake did not have a structural engineering member. The Royal Committee appointed to study the Messina event, after a very complete review of past studies of earthquakes from all countries, concluded that ". . . the acceleration which is one of the data that most closely concerns the builder, is as yet little less than unknown." The Committee then proceeded to make a detailed analysis of several buildings which had survived the Messina earthquake with little or no damage, and it was decided that the designs corresponded to a ground acceleration of 70-80 cm/sec^2. They then recommended that structures in earthquake regions should be so designed that they would resist, in the first story, a horizontal force equivalent to 1/12 of the weight above, and in the second and third story, 1/8 of the weight above. These values were roughly consistent with the ideas prevalent in Japan at about the same time, that the seismic coefficient should correspond to a ground acceleration of 0.1 g.

It is, of course, not necessary that the lateral force coefficients prescribed for various zones on a seismic zoning map be interpreted in terms of a physical quantity. In building codes the numbers associated with various seismic zones are entered into specified standard formulas which, along with many other factors such as type and material of structure, consequences of failure, natural period of structure, etc., produce the final values of the horizontal loads to be considered in the design. In fact, it may well be better to deal with arbitrary numbers or letters than to attempt to relate the zones to oversimplified physical quantities which may give an incomplete or inaccurate picture of the actual earthquake ground motions. In particular there has been much criticism of the use of peak ground acceleration to quantify seismic zones. It is well known that for some earthquakes the peak acceleration may be a very inaccurate indication of the damage that might be caused to many structures. The peak may be one single spike quite uncharacteristic of the whole accelerogram, and it can be shown that for most earthquakes the highest peaks can be truncated somewhat without much changing the response of most structures, as measured by response spectrum values (Schnabel and Seed, 1973; Blume, 1979). Nevertheless, there is sufficient similarity in the ground motions of many earthquakes so that peak ground acceleration still serves a useful purpose in the preliminary comparison of ground motions over an area for a single earthquake, and in giving approximate comparisons between different earthquakes. One of the most important problems facing earthquake engineers today is the definition of additional information needed to supplement or replace ground accelerations to provide meaningful correlations with structural damage, and this is the main theme of the present paper.

In the light of the above background it will be of interest to briefly summarize the way in which the problem is treated in current building codes, as indicated by a study of the 1988 edition of the volume "Earthquake Resistant Regulations -- a World List", issued by the International Association for Earthquake Engineering (IAEE, 1988). Examining the codes for 35 countries we find that: 13 countries map a "seismic coefficient", or "lateral force coefficient" tied to a number or letter which has no physical significance ascribed; 8 countries describe the numerical seismic factor as peak ground acceleration; 6 countries relate the seismic factor to standard intensity scales, MM or MKS; 4 countries refer to the coefficients as accelerations, and also relate them to intensities; one country relates the seismic coefficient to power spectral density; 2 countries use two seismic coefficients described as "effective" accelerations and velocities.

Most of the building codes of the past have not included a consideration of the frequency of occurrence of earthquakes or of the time frame involved. These can, of course, be important factors - it is clear that for the United States, for example, although large earthquakes may occur anywhere, they are much more frequent in the West than in the East. The expected useful lifetime of various structures can also vary over wide limits. Such thoughts have led to the development of probabilistic methods of analyzing earthquake hazard, so that the quantities being mapped can be said to have a given chance of being exceeded within a prescribed time period (Cornell, 1968; McGuire, et al, 1989; Algermissen, et al, 1982). These methods have the advantage of producing a seismic hazard map of a more uniform character over a large area, and of permitting some consideration of the economic aspects of various lifetimes appropriate for different structures. It is of interest that of the 35 building codes mentioned above, six of them include a probabilistic statement of some kind.

DESCRIPTION OF EARTHQUAKE GROUND MOTION

The most complete description of earthquake ground motion for the engineer is the acceleration-time record produced by an instrument which, with suitable data processing, can give an accurate acceleration measurement over the frequency range involved in engineering structures. With such an accelerogram as input the structural engineer can calculate the response of any given structure to a prescribed level of accuracy. In practice, this may involve computational difficulties and problems in producing adequate mathematical models of structural details, but in principle the earthquake input information is complete. The problem is that there seems to be no way to represent all likely acceleration-time curves at a particular point on a map. The solution has been to abstract from the accelerogram certain numerical quantities that can be mapped, and to hope that a small number of such parameters will be adequate to describe the likelihood of structural damage with an acceptable accuracy. It is now generally agreed that no one single quantity that can be derived from the accelerogram will be adequate to describe structural damage for all types of structure. There is a considerable difference of opinion as to the number and nature of such derived parameters that would be required. In the following, we shall summarize a number of suggestions which have been investigated, and shall try to evaluate the present state of the problem.

GROUND MOTION PARAMETERS

Attempts to define ground motion parameters that are reasonably well correlated with structural damage fall into four categories: (1) modifications of the amplitudes of the acceleration-time curve to reduce peak values in some systematic way; (2) new parameters calculated from the acceleration-time curves; (3) defined quantities associated with the response of typical systems; and (4) combinations of calculated quantities to produce composite parameters.

In the first category may be mentioned various filtering techniques, e.g., instead of using peak accelerations of the accelerogram, pick the peak acceleration from a filtered signal from which frequencies higher than those of structural interest have been eliminated (Page, et al, 1972). Another approach uses instead of the maximum acceleration of the highest peak, a lower peak which may be more representative of the repeated amplitudes of the strong-motion portion of the record. Examples are the "sustained maximum acceleration", defined as the value of the third or fifth largest peak values (Nuttli, 1979), and the "repeatable high ground acceleration", which is the average of several high acceleration peaks below the one or two major peaks (Ploessel and Slosson, 1974). Another approach examines a histogram of the number of peaks as a function of acceleration, and defines the "significant peak acceleration" as some percentile level, say 90%, of this distribution (Bolt and Abrahamson, 1982). Still another suggestion is to truncate the level of the accelerogram so that the integral of the reduced accelerogram squared over the length of the record (the input energy) is some standard fraction, say 95%, of that produced by the original record (Sarma and Yang, 1987).

All of the above ideas aim at producing an acceleration value which may be more appropriately used for design purposes than the peak acceleration itself. None of these proposals have been sufficiently widely accepted to replace peak accelerations as the parameter most used in current engineering practice.

We shall next consider the second category of ground motion parameters, those derived by calculation from the acceleration-time record. Perhaps the most useful is the integral of the acceleration squared over the length of the record - the total energy in the record. This can be shown to be the same, except for the constant multiplier ($\pi/2g$), as the Arias Intensity, which is the sum of the energy dissipated per unit weight by all structures in a population covering the whole period range (Arias, 1970). A plot of the acceleration squared integral versus time can give a very useful picture of the way energy is fed into a structural system, as shown in the typical example of Figure 1. The integral approaches a well-defined asymptotic value which can be shown to correlate well with damage for many typical structures (Housner and Jennings, 1977). Note that the slope of this energy-time curve gives the mean square acceleration, and the square root of the slope is the RMS acceleration at each point in time.

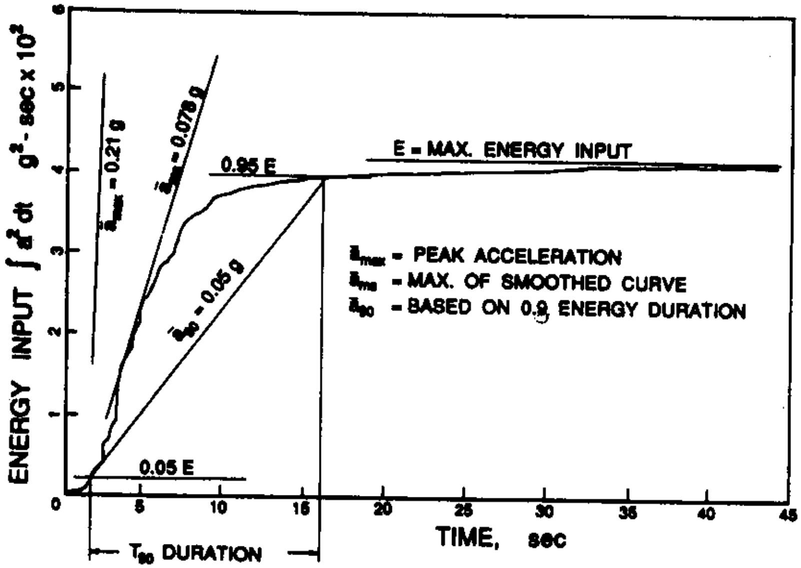

Fig. 1. Cumulative Energy Release. San Fernando 1971 Earthquake. Hollywood Storage Lot N90E.

The RMS acceleration has often been suggested as an appropriate measure of ground motion (McCann and Shah, 1979). Among the advantages of this quantity are: (1) it would be expected to be a more stable parameter than peak acceleration because it involves many peaks instead of just one; (2) it is directly related to such faulting parameters as stress drop, seismic moment, etc.; and (3) it is easily related to certain probabilistic specifications of design accelerations. It will be seen from Figure 1, however, that the RMS value (the square root of the slope of the curve) is not well defined but varies widely with time. The definition of the RMS value is much dependent on the definition of the duration of strong motion. For a very short time duration, the maximum RMS value approaches the peak acceleration, whereas for the whole record it has a very much lower value. It also appears that the expected stability of the RMS accelerations is not realized in practice. An examination of the correlations between RMS and peak accelerations for many earthquake accelerograms has shown that the RMS values show about the same scatter as peak values (McGuire and Hanks, 1980; McCann and Boore, 1983; Peng, Elghadamsi and Mohraz, 1989). In any event, RMS acceleration has so far not been generally accepted in engineering practice as a basic ground motion parameter.

A parameter which has recently been suggested as being related to structural damage is the "cumulative absolute velocity", the integral of the absolute acceleration over the time duration of the earthquake. This is equivalent to summing the velocity change from positive to negative peak for all of the cycles of the acceleration (Reed, et al, 1988). An investigation of the correlation of several damage parameters with Modified Mercalli intensity indicated a somewhat better correlation with the cumulative absolute velocity than with Arias Intensity, peak acceleration, or averaged response spectral acceleration based on filtered accelerograms.

The frequency content of earthquake ground motion is usually described by seismologists by the Fourier Amplitude Spectrum, For the engineer, the reponse spectrum is the preferred representation of frequency content, since it is more directly related to structural behavior. In particular, the smoothed Fourier Spectrum lacks the clear physical meaning of the damped response spectrum (Udwadia and Trifunac, 1973).

Another quantity which can be calculated from the accelerogram is the Power Spectral Density, and this has been proposed as a useful representation for earthquake engineering investigations. Power Spectral Density versus frequency curves have been used to reveal significant differences between earthquake motions in rock and in various soils (Lai, 1982). More important is its use in estimating various statistical properties of earthquake ground motions (Mohraz and Elghadamsi, 1989; Peng, Elghadamsi and Mohraz, 1989). It is of interest to note that in the Portuguese standard building code, in addition to a map showing seismic hazard zones related to lateral force coefficients, tables are included giving Power Spectral Density in various zones at selected periods, as well as standard acceleration response spectrum curves (IAEE, 1988).

RESPONSE SPECTRA REPRESENTATIONS

Considering next proposed design parameters associated with system response, we look first at the direct use of response spectrum ordinates. Since acceleration response spectral values directly relate to the lateral force coefficients to be used for earthquake resistant design, structural engineers have become accustomed to basing their designs on such response spectra. Because the peak ground acceleration corresponds to spectral acceleration at the high frequency end of the scale, one important use of peak acceleration by design engineers is to define one point on the response spectrum curves. A logical suggestion is to by-pass the peak acceleration entirely, and to produce the basic seismic hazard map directly in terms of response spectrum values (McGuire, 1974; McGuire, 1977; Anderson and Trifunac, 1978; Katayama, 1979). Although this requires several maps, one for each spectrum period, this is no practical disadvantage, since it is now universally accepted that no single quantity, be it peak acceleration or any of its proposed substitutes, will be adequate to describe structural damage. By using the probabilistic methods mentioned above, spectral ordinates can be determined for a particular site at several key points which will have an equal probability of being exceeded in a prescribed time period, thus producing a "uniform hazard spectrum" which can then be used as a basis for seismic design. By repeating such calculations for many sites, a seismic hazard map can be produced. Such maps are now being prepared for the United States for 5% damping and two periods of 0.3 and 1.0 sec., it having been shown that these two points define the response spectrum sufficiently well for many practical design purposes (Algermissen, et al, 1991).

A number of methods based on replacing actual response spectrum curves by simplified representations, usually by one or several straight line segments, have been widely used in practice. An averaged spectral acceleration over a prescribed period range is perhaps the simplest suggestion (Reed, 1988). A procedure using several straight line segments has been used for many years in a basic specification for seismic design of nuclear power plants by the Nuclear Regulatory Agency. For the high frequency portion of the spectrum, a constant acceleration spectrum is obtained by multiplying the peak ground acceleration by a constant determined from a study of the spectra of recorded earthquakes; for the intermediate frequency range, a constant velocity is obtained by multiplying the peak ground velocity by another constant, and for the low frequency range, a constant displacement spectrum is obtained by multiplying the peak ground displacement by a third constant (Newmark and Hall, 1982).

A variation of this approximate spectrum method is that proposed in a comprehensive study by the Applied Technology Council of the Structural Engineers Society of California (Applied Technology Council, 1978). Since this ATC 3-06 document is perhaps the most elaborate study so far produced by practicing engineers, and has been considered as a starting point for the development of several new earthquake resistant design codes, these proposals will be briefly reviewed here. The two basic hazard maps in this ATC 3-06 document involve two quantities called the "effective peak acceleration" and the "effective peak velocity-related acceleration". The effective peak acceleration is defined by dividing a constant average spectral acceleration curve in the period range of 0.1 to 0.5 sec. by a constant factor of 2.5. The effective peak velocity-related acceleration is obtained by dividing a constant average response velocity curve around the period of 1 sec., by the same constant 2.5, and then consulting a table for the value of the mapped parameter. Although these two mapped parameters are thus closely related to response spectrum curves, it does not appear that the maps were produced by first calculating response spectra at many sites, and then reducing them to the mapped parameters using the above definitions (Donovan, Bolt and Whitman, 1978). The effective peak acceleration maps were apparently prepared by starting with a probabilistic peak acceleration map (Algermissen, et al, 1982) which was then modified in certain regions for which the lateral force coefficients in local building codes had been extensively calculated by field studies after destructive earthquakes. Similarly, the velocity-related map was based primarily on a peak ground velocity map (Algermissen, et al, 1982), somewhat smoothed and modified. In the customary use of the ATC 3-06 procedures, the mapped coefficients are entered into standard formulas to produce the design lateral seismic forces at any period, which in effect prescribes the design spectra without the need to refer to the physical meaning of the mapped values in terms of their precise definitions. The ATC 3-06 proposals are a notable attempt to introduce two mapped parameters while retaining the code format familiar to practicing engineers.

It is interesting to note how these ATC 3-06 mapping methods have been introduced in several modified forms in successive editions of the "NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings" (FEMA, 1985, 1988, 1991). The 1985 edition simply reproduced the maps of ATC 3-06 retaining the "effective peak acceleration" and the "effective peak velocity-related acceleration" parameters used in that document. The 1988 edition also included alternative maps of peak acceleration and peak velocity, being essentially the maps of Algermissen, et al, 1982. This 1988 edition also includes alternate procedures aimed at producing the same lateral force coefficients for either set of maps. In the 1991 edition, equal probability response spectrum ordinates were directly mapped for the United States in a set of maps giving response spectrum accelerations at 0.3 second period and at 1.0 seconds, for 90% probability of nonexceedance in 50 years and in 250 years.

Referring to response spectral representations, it should be mentioned that many proposals have been made for modifying the simplified linear elastic response spectra to allow for nonlinear plastic action which is expected for most destructive earthquake response (Newmark and Hall, 1982; Kennedy, et al, 1984). This requires of course the introduction of additional parameters such as yield ratios.

Another spectrum derived quantity which has been proposed and widely investigated as a parameter related to structural damage is the Housner Spectrum Intensity, defined as the area under the 20% damped velocity response spectrum curve between periods of 0.1 to 2.5 sec. (Housner, 1952). Other values of damping and period limits have also been studied. In practice, the correlation between spectrum intensity and structural damage for a whole range of structures has not been conspicuously better than peak acceleration or other measures discussed here.

We come now to the final category of potential mapping parameters - those involving combinations of measured quantities to produce a composite parameter which can hopefully be shown to correlate with structural damage. A first example is a so-called "destructiveness potential", which is equal to the Arias Intensity divided by the square of the number of zero crossings per second of the accelerogram (Araya and Saragoni, 1984). It has been shown that this factor correlates well with Modified Mercalli Intensities for a selected series of earthquakes, and that it orders earthquake damage to typical building structures reasonably well. A second example is a factor defined on the basis of experience with concrete structures, which is equal to the product of the RMS acceleration to the 1.5 power and time duration of shaking to the 0.5 power (Ang, Wen and Park, 1984). The basic difficulty with all such composite parameters is that they apply to only a limited range of structures and earthquakes. In any event, no destructiveness factors of this type have so far been widely accepted, and none have been mapped for design purposes (Bertero, 1991).

A NOTE ON DURATION

It is well known that a long-continued ground shaking involving many repeated load cycles is more damaging to structures than a short duration excitation. Damage is usually associated with non-linear behavior in structural components, and repeated loadings cause deteriorating effects which must be accounted for. As long as the system remains linear, response spectrum techniques include the effects of duration. Once the system goes into plastic range, which is to be expected for the most damaging earthquake ground motions, the duration of strong motion becomes an important additional parameter. The number of cycles of shaking, and hence duration, also has a major influence on such phenomena as soil liquifaction, which often results in structural damage.

So far there seems to be no generally accepted definition of the duration of strong shaking. Perhaps the most widely used measure refers to the energy-time curve of Figure 1, and defines the duration as the time between the 5% and 95% energy levels (Trifunac and Brady, 1975). Other fractions of the total energy level have also been suggested (Kennedy, et al, 1984). Other approaches include the "bracketed" duration, the time from the first exceedance of a specific ground acceleration to the time at which the signal subsides below that level (Bolt, 1974), or the "fractional" duration which bases the threshold acceleration levels on fractions of the peak acceleration (McGuire and Barnhard, 1979). A variation of this approach takes as a threshold acceleration the value at which a particular structure would begin to yield (Xie and Zhang, 1988). A third approach examines the cumulative RMS acceleration values, taking the end of the strong motion as the time at which the cumulative RMS value starts a steady decrease, and the beginning as the similar time for a time-reversed record (McCann and Shah, 1979). Still another procedure is to use the time of faulting for the time duration of strong ground motion (McGuire and Hanks, 1980). This of course requires a knowledge of source mechanism of the earthquake which is not always available. Unfortunately the various definitions of duration result in wide differences of numerical values, and this has been one of the difficulties in arriving at well-defined values for RMS acceleration.

In spite of the importance of duration for structural damage, there has been to date no agreed-upon procedures for incorporating duration into design building codes. Two recent proposals are aimed in this direction. The first develops a method for estimating response spectra using RMS accelerations and a factor which accounts for duration of strong shaking (Peng, Elghadamsi and Molraz, 1989). A second approach takes as a starting point the three-straight line response spectrum approximation discussed above, and modifies the amplification factor in the mid-period range to account for the strong motion duration (Fajfar and Fischinger, 1990).

It has been suggested that a probabilistic seismic hazard map should be produced for strong motion duration along the lines of those prepared for peak accelerations, peak velocities, and response spectrum ordinates. An investigation of the feasibility of such a map showed first that durations cannot be predicted with sufficient accuracy given the information likely to be available, and second, that such a map would not add significantly to the information available from peak motion parameters, as measured by Modified Mercalli Intensity or by several factors associated with yielding response spectrum values (McGuire and Barnhard, 1979).

SPECIFICATION OF DESIGN GROUND MOTIONS

As was mentioned above, the most complete information available on earthquake ground motions is the accelerograph record itself. The best way to incorporate such factors as duration into seismic design would be to calculate the response of particular structural models to actual earthquake accelerograms. It is likely that future earthquake resistant design will increasingly by-pass special parameters derived from accelerograms in favor of the records themselves as inputs to models. An engineering workshop convened in 1984 to decide on the recommended form for ground motion specification concluded that the most desirable information for design would be an ensemble of ground motion time histories of design size earthquakes measured in the vicinity of a particular structure (Jennings, 1985). The same conclusion was arrived at from a seismological viewpoint by a study which concluded that in the future seismologists would move away from the preparation of zoning maps in terms of a particular parameter and would instead calculate complete seismograms from which engineers could calculate any desired parameters (Aki and Irikura, 1991). A similar conclusion was reached in a recent investigation of seismic zoning in the Eastern United States (Whitman and Algermissen, 1991).

To carry out such a plan will require the preparation of extensive catalogs of strong-motion accelerograms, along with complete information as to the conditions under which they were obtained. Such records and information will need to be in a widely available computer format so that accelerograms can be classified in various ways and searched and displayed with ease. An important step in this direction is a catalog displaying accelerograms to the same amplitude and time scale, along with response spectra and related data, which serves as an index to digital files on disks which can be accessed by telephone link (Lee and Trifunac, 1987).

CONCLUSIONS

1. No single parameter can be expected to describe enough of the information in an earthquake accelerogram to serve as a complete basis for earthquake resistant design.

2. In spite of the obvious shortcomings of single-parameter representations, they are still commonly used. Peak ground acceleration is still the most widely used parameter for this purpose and no other parameters, such as RMS acceleration, peak velocity, or spectral averages, have been convincingly shown to be more stable parameters, or to in general correlate better with structural damage.

3. The direct use of response spectrum ordinates as mapping parameters offers advantages to the engineer, at the expense of requiring more parameters and hence more zoning maps.

4. Rather than define special parameters, design engineers will increasingly move in the direction of assembling groups of typical accelerograms to serve as inputs to computer models.

5. The problem of defining strong-motion duration, and introducing it into feasible design procedures, has not yet been solved.

6. So-called "effective" parameters, which have been modified in various ways in an attempt to improve correlations with structural damage, should be used with great caution. There have been so many different definitions of the words "effective", "significant", etc., that misunderstandings are likely to occur.

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