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A NOTE ON THE SIGNIFICANCE AND USES OF ELEMENTARY ANALYSES OF STRONG EARTHQUAKE GROUND MOTION

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ABSTRACT

The advanced theoretical and empirical models of strong ground earthquake motion are built on assumptions about the nature of strong ground motion that are drawn from elementary and direct studies of recorded strong ground motion. This brief note reviews selected published elementary studies, emphasizing their significance for the subsequent advanced studies, such as detailed regression models for peak amplitudes and response and Fourier spectra of strong motion. The illustrations are mostly from published work by Strong Motion Group at University of Southern California. They contributed many such elementary studies and have later used their findings in development of advanced regression models. Specifically, this note reviews observations on: the spatial attenuation of strong motion, the interpretation of its wave content, small versus large amplitudes, the strong motion magnitude scale, and the principles of empirical scaling of strong motion for use in earthquake engineering. It also presents selected examples of how the observational evidence, as recorded on accelerograms, has contributed towards creation of new and refinement of the existing theories.

KEYWORDS: Wave Content of Strong Motion, Spatial Attenuation of Strong Motion, Strong Motion Magnitude, Large versus Small Amplitudes of Ground Motion

INTRODUCTION

The state-of-the-art methodologies for engineering description of strong ground motion, for example the comprehensive empirical models for scaling peak amplitudes and response and Fourier spectra, and the methods for synthesis of artificial accelerograms, evolved over the past seventy years mainly due to the systematic efforts to record strong ground motion (Heck et al., 1936; Cloud and Carder, 1956; Halverson, 1970), and to analyze its physical nature. The success of the advanced methodologies in predicting the characteristics of possible future shaking depends significantly on the validity of the physical assumptions these methods are built on. For example, the empirical scaling models for peak amplitudes, spectra and duration of strong ground motion are based on assumptions about the functional relationship between the scaled quantities and various input parameters (such as the earthquake magnitude, source-to-site distance, local site condition, type of wave path, etc.), and the statistical regression gives only the coefficients in these assumed functional forms. The number of input parameters and the details of the assumed functional forms are eventually a compromise between the desired detail and what can be justified as statistically significant by the quantity and quality of the strong motion data available for the regression. As the strong motion data accumulated over the years, these models became more and more detailed.

The assumptions on the nature of strong ground motion and how it is affected by the earthquake source, propagation path characteristics and the local site geology, to be used for advanced studies, are drawn based on elementary analyses of recorded data, and on studies of analytical and numerical models for the range of parameters for which data is lacking or is insufficient. These elementary analyses are exploratory in nature, and often consist of various presentations of subsets of the data and visual observation of trends. While these types of analysis do not require any advanced mathematical skills, their success depends on the ingenuity of the ways the data is presented and on the experience of the analyst and his/her ability to "see" and interpret the trends (i.e. to see "the forest from the trees" and "the trees from the forest"). Nevertheless, these elementary studies are very powerful and important, firstly because their conclusions are based most directly and solely on observations, minimizing possible

artifacts from the method of analysis, and because they represent a necessary building block of many advanced studies to follow.

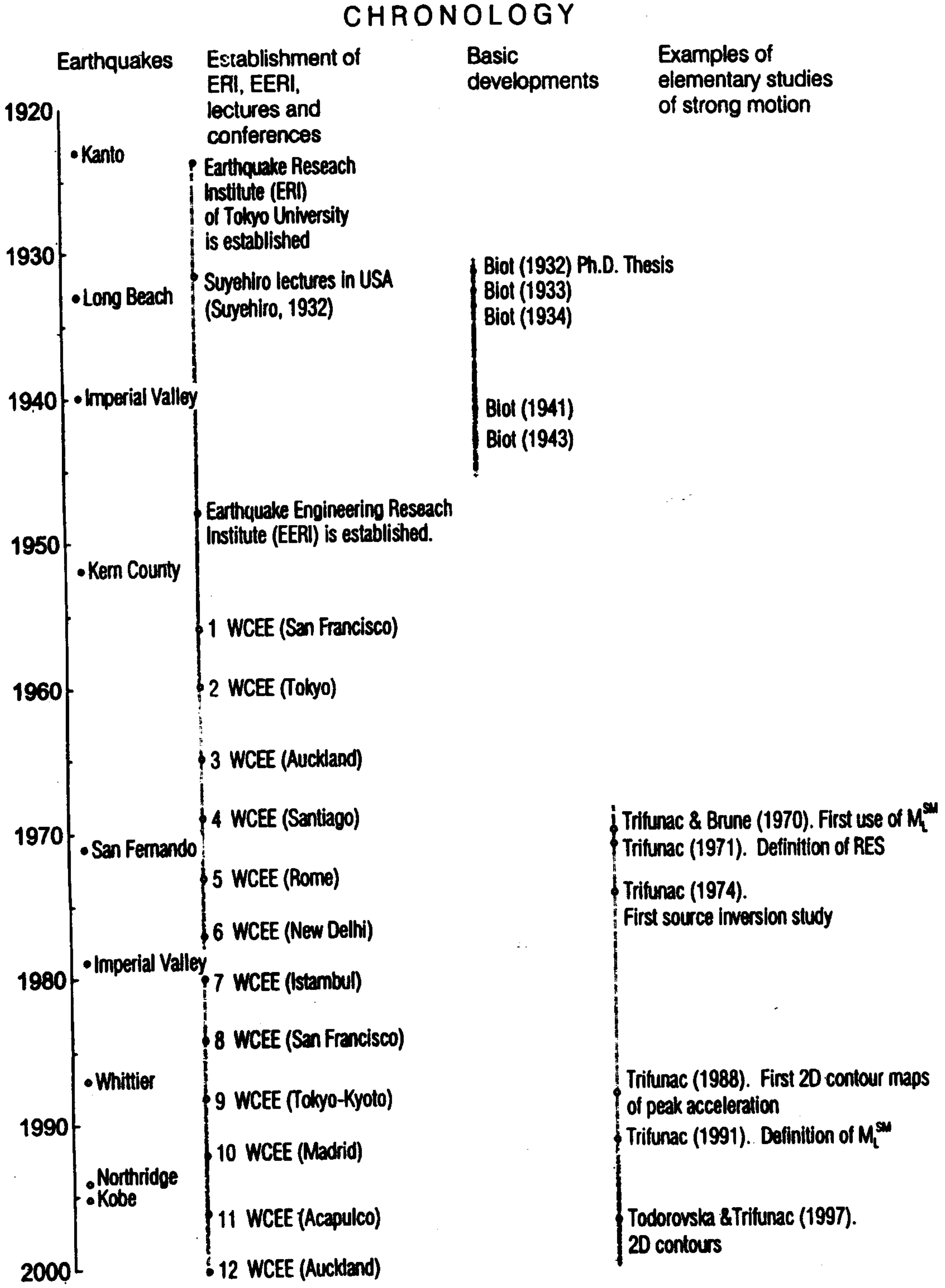

Fig. 1 Chronology of selected Trifunac's contributions to the analysis and interpretation of strong ground motion, relative to the years of occurrence of selected earthquakes, the establishment of ERI and EERI, the World Conferences on Earthquake Engineering, and the formulation of the response spectrum method in 1932 by Biot, which marked the beginning of the modern earthquake engineering

The aim of this brief note is to discuss published elementary studies of the nature of strong earthquake ground motion, with an emphasis on their importance for advanced regression analyses. The most successful empirical scaling models are those that use meticulously researched functional forms, based on physically sound interpretation of the theory and careful and comprehensive verification in terms of a large volume of recorded data. There are many excellent examples of published regression models of strong ground motion, but their review or even modest discussion are beyond the scope of this brief note. This note focuses only on selected most direct and elementary analyses of strong ground motion, citing examples mostly from the work of the Strong Motion Research Group at the University of Southern California (USC). The reason for this is that this group has contributed extensively to development of empirical scaling models of strong motion, so that the ideas and interpretations in the reviewed elementary studies in this note can be followed through their eventual application.

Specifically, this note reviews observations on: the spatial attenuation of strong motion, the interpretation of its wave content, small versus large amplitudes, the strong motion magnitude scale, and the principles of empirical scaling of strong motion for use in earthquake engineering. It also presents selected examples of how the observational evidence, as recorded on accelerograms, has contributed towards creation of new and refinement of the existing theories. The obvious need for continued and comprehensive observation of strong earthquake motions, in structures and in soils, will be emphasized to illustrate the quantity and quality of data that is needed to guide future theoretical and empirical developments in description and prediction of strong ground motion for engineering design.

ENGINEERING AND DESCRIPTIVE ANALYSES OF RECORDED MOTIONS

The modern era of earthquake engineering began with the second chapter of Biot's Ph.D. dissertation at California Institute of Technology in 1932, entitled "Vibration of Buildings during Earthquakes" (Biot, 1932). Biot's ideas were further refined in Biot (1933, 1934), and fully developed into the general theory of response spectrum superposition method in Biot (1941, 1942) (see Figure 1 for the chronology of his contributions relative to the times of significant (from engineering point of view) earthquakes, and the times of the World Conferences on Earthquake Engineering). It is remarkable that Biot was able to formulate so simple and ingenious methodology (still representing the basis for earthquake resistant design today, seventy years later), before any strong motion data were recorded in Southern California. By the time Biot presented his last two papers on earthquake engineering in 1941 and 1942, there were only five strong motion records (Long Beach, 1933, Ferndale, 1937, 1938, and El Centro, 1940, all in California; and Helena, 1935, in Montana).

Many studies of the basic properties of strong motion and of its scaling for engineering applications have been motivated by or can be traced back to either speculative comments or to intuitive discussions in Biot (1941, 1942) papers. Those roots and early formative concepts will be illustrated in some of the following examples.

In the late 1930s, the first recorded accelerograms were analyzed to describe the maximum response of a family of single-degree-of freedom representations of structures. Response spectra were computed with mechanical spectrum analyzers (torsional pendulum; Biot, 1941), for the purpose of developing "standard" response spectrum shapes to be used in design practice. The difficulty at that time was that the number of recorded strong motion accelerograms was small (Long Beach, 1933; Helena, 1935; Ferndale 1937, 1938; El Centro, 1940), and the fluctuations of the computed spectra were so large that only preliminary "spectral shapes" could be considered (Biot, 1942) for design.

Little changed until 1971. The seismic activity in Southern California was relatively low, and the number of recording instruments was small, resulting in slow accumulation of recorded accelerograms (Figure 2, Trifunac and Todorovska, 2001a). Examples of the first well-recorded earthquakes, with multiple triggered stations close to the causative faults, are the 1966 Parkfield (Housner and Trifunac, 1967; Hudson et al., 1969) and the 1971 San Fernando (Trifunac and Hudson, 1971) earthquakes in California. The Parkfield earthquake was recorded by five strong motion accelerographs (Trifunac and Udwadia, 1974), while the San Fernando earthquake produced 94 free-field and building basement records (Figure 2, Trifunac, 1974). An analysis of the Parkfield data suggested that "important structures to be located close to a fault ... should be designed to withstand a 10 inch displacement pulse without serious consequences. ... Also of special engineering significance was the fact that the earthquake ground motion of 40 to 50 percent of g ... can be recorded near a surface fault" (Housner and Trifunac, 1967).

These estimates were soon exceeded during the San Fernando earthquake in 1971, with long period peak displacement approaching 50 cm (20 in) and peak ground acceleration exceeding 1.25g, at the Pacoima dam site (Trifunac and Hudson, 1971). This "large" peak acceleration revived the debates on how large peak accelerations are in the vicinity of causative faults (Ambraseys, 1973), but eventually and following other later recordings of even larger peak accelerations, its significance was reduced to a "normal" data point (Trifunac, 1976a).

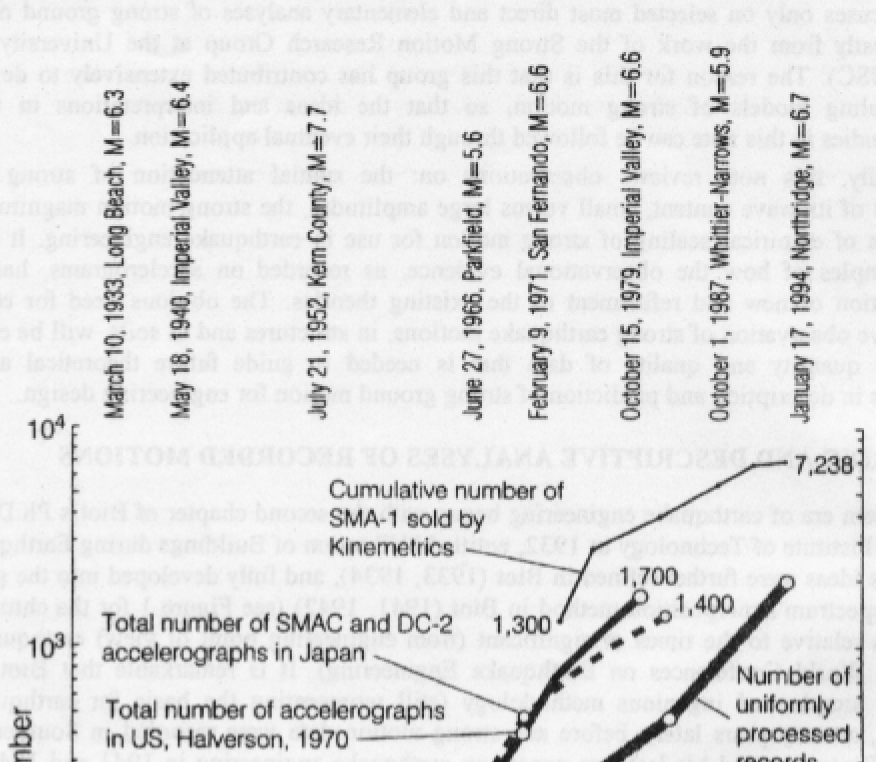

Fig. 2 Cumulative number of strong motion accelerographs in California and in Japan up to 1980, of uniformly processed three-component strong motion records used in three generations of comprehensive empirical scaling studies (Lee and Trifunac, 1995a, 1995b), and of the total number of recorded "free-field" records of main earthquake events

With the accumulation of recorded and uniformly processed (Trifunac et al., 1971, 1972a, 1972b) strong motion accelerograms (Figure 2), the emphasis in publications describing the nature of recorded peak amplitudes gradually shifted to the analysis of their spatial variations and attenuation (Todorovska and Trifunac, 1977a, 1977b; Scientists from USGS and SCEC, 1994), as discussed in the following.

SPATIAL ATTENUATION EFFECTS

Since the 1940s, many empirical studies were carried out to develop empirical scaling laws to predict peak amplitudes of strong motion for use in engineering design. Many of these early scaling laws are reviewed in Trifunac and Brady (1975a), and subsequent papers on this subject are cited in Lee et al. (1995a,1995b). A common characteristic of all these empirical equations is the large uncertainty of the estimates, typically by about a factor of 2. In these papers, peak acceleration, velocity or displacement are plotted versus some representative source-to-site distance, and the differences due to the source radiation pattern and different propagation paths are viewed as "random" fluctuations of the data.

The deployment of the Los Angeles and Vicinity Strong Motion Network in 1979/1980 (Trifunac and Todorovska, 2001a), and the first significant recordings of the 1987 Whittier-Narrows earthquake, which triggered most stations of this network, started to change this simplified picture. For the first time, it became possible to plot contour maps showing attenuations of various strong motion parameters (Trifunac, 1988). In 1994, following the Northridge, California, earthquake, such maps could be presented for peak accelerations (Trifunac et al., 1994), peak velocities and surface strains (Trifunac et al., 1996; Trifunac and Lee, 1996), amplitudes and polarity of the peaks of strong motion (Todorovska and Trifunac, 1997a), the distribution of pseudo spectral velocity (Todorovska and Trifunac, 1997b), of duration of strong motion, of energy of strong motion, and of its average and maximum power (Trifunac et al., 2001).

The seemingly large fluctuations of strong motion amplitudes (Trifunac, 1976a) have influenced the development of stochastic representations of ground motion, and the use of the concept of coherence, which describes the degree of variability of strong motion with respect to separation distance. For example, for surface soils with shear wave velocity of 250 m/s and 65 m separation distance, the published values of coherency may be 0.5 at 1 Hz and 0.07 at 2 Hz. The contour maps of various peak amplitudes of strong motion and of their associated spectral amplitudes for the Northridge earthquake, however, show an entirely different picture of "slowly and continuously" changing peak amplitudes, over distances large relative to the wavelengths involved. Based on these observations, Todorovska and Trifunac (1997a) conclude that "Using stochastic representation and analysis of response seems convenient, because it takes advantage of the significant body of knowledge on stochastic processes in other fields. However, by assuming random nature of strong ground motion this approach reduces or eliminates the opportunities for further understanding and discovery of the true physical nature of the processes involved." There is no doubt that recording strong motion with dense arrays is invaluable for quantification of all characterizations of spatial randomness of strong motion.

An example of how detailed two-dimensional maps of peak amplitudes of strong motion (Todorovska and Trifunac, 1976a), and of the spectral amplitudes, can influence the development of the next generation empirical scaling equations is provided in the reports by Lee et al. (1995a, 1995b). These reports show how the attenuation laws for strong motion amplitudes can be refined to include path dependency, and how this reduces the scatter of the regression model.

The stochastic method of analysis and interpretation of strong ground motion and of the response of structures can be traced back to the studies of Kanai and his coworkers in Japan (Kanai, 1957; Tajimi, 1960), Rosenblueth (1956) in Mexico, Bolotin (1960) in Soviet Union, Bycroft (1960) in Canada, and Goodman et al. (1958) and Caughey and Stumpf (1961) in U.S., for example. It is based on evolves from the classical papers by Rice (1944, 1945) and Cartwright and Longuet-Higins (1956), and has been fully developed for stationary response of linear structures (Gupta and Trifunac, 1996), when the basic description of strong motion is viewed through its power spectrum density. However, for non-linear response, this body of theory breaks down, and new approaches must be developed with focus on what governs non-linear and damaging response. The short and impulsive nature of the largest peaks of velocity of ground motion, may offer the simplest and the most direct way to describe design power and design energy the structure can take before collapse (Trifunac et al., 2001). This however call for new scaling of strong motion in terms of the power associated with one or several of the largest peaks of ground velocity. Thus, the discovery that the peaks of strong motion and their polarity change slowly and continuously over large areas (Todorovska and Trifunac, 1997a) may change significantly the way we characterize amplitudes and frequency content of strong motion. In particular, it will change the way we specify excitation of structures which are long and which have multiple support points (bridges, dams, tunnels,...).

ANALYSIS OF THE NATURE OF RECORDED STRONG MOTION WAVES

With proper spatial and temporal scaling, the classical seismological theory of linear elastic wave propagation in layered and inhomogeneous medium is directly applicable to strong earthquake ground motion (Trifunac, 1971a, 1971b, 1973, 1974). In other words, recorded strong motion consists of body, surface and scattered (coda) waves. During most shallow and surface earthquakes, with focal depths less than 20 km (typical of Southern California), in the near-field and in the areas close to the fault, the bulk of wave energy arrives at the building site "horizontally". This has been first demonstrated for strong motion accelerograms by Trifunac (1971a), and has led directly to the development of a sequence of comprehensive methods for synthetic construction of artificial translational accelerograms (Trifunac, 1971b), torsional and rocking accelerograms (Lee and Trifunac 1985, 1987), curvograms (Trifunac, 1990), and time histories of strain associated with strong motion (Lee, 1990). Thus, a sequence of papers by Trifunac in 1971, is an example of how simple and direct analyses of the nature of strong motion via multiple filters can lead to the development of a realistic and physically sound method for synthesis of artificial accelerograms.

First studies of the effects of local soil and geologic site conditions (Kanai, 1983) have considered site models, which are excited by vertically incident shear waves. Such one-dimensional models are still used in many engineering analyses today, but those are not capable of providing a basis for the analysis of wave passage effects, and are associated with the torsional and rocking excitations, accompanying non-vertical incidence of body waves and surface waves. With interpretation of the wave content of strong motion and subsequent development of artificial accelerograms, it is now possible to excite soil-structure systems with most realistic and general ground motions (Todorovska et al., 1995).

Comprehensive studies of the frequency-dependent duration of strong motion are capable of identifying the nature of the waves scattered by and reflected from an interface between sediments and basement rock and from the edges of alluvial valleys (Novikova and Trifunac, 1993a, 1993b, 1994a, 1994b, 1994c), and of the duration of fault motion in California (Trifunac and Novikova, 1995). These studies suggest deterministic and identifiable dependence of the duration of strong motion on the chosen scaling variables up to frequencies of 6 to 7 Hz. Beyond about 7 Hz, the integral measures of duration (Trifunac and Brady, 1975b; Trifunac and Novikova, 1994) suggest that the strong motion consists of randomly scattered waves.

Combined with the results of Todorovska and Trifunac (1997a) on spatially coherent peak accelerations, velocities and displacements, these results suggest that for frequencies up to about 7 Hz, the largest peaks of strong motion can propagate in a deterministic fashion over great distances and through irregular geology. It appears that irregular geology acts as a complex, yet predictable and certainly not as a strong randomizing, agent for the waves longer than about 100 m. Since the large pulses of strong motion velocity can be related to the destructive power of waves incident upon structures and their foundations (Trifunac et al., 2001), it is clear that new scaling and attenuation equations will have to be developed to quantify this power for use in engineering design.

LARGE VERSUS SMALL AMPLITUDES OF GROUND MOTION

Strong earthquake ground motion is a rare event, which cannot be predicted in time or space, making it difficult to organize experiments and tests of theoretical calculations and of model-based simulations. To study amplification of strong motion waves by soft sediments and surface soils, for example, it has been suggested that microtremors and microseisms (which shake the ground continuously) could be used (Kanai, 1983). The amplitudes of microseisms and microtremors depend on the location, and are usually larger in metropolitan areas and close to the seashore. Their amplitudes are 10^5 to 10^8 times smaller than the amplitudes of a destructive strong motion (e.g. Trifunac and Todorovska, 2000a).

The usefulness of microtremors for site amplification studies has been a controversial subject, even in the approximately linear range of response of shallow surface soil layers (Kanai, 1983; Trifunac and Udwadia, 1974, 1977; Udwadia and Trifunac, 1972, 1973), but microtremors continue to be used in engineering site amplification studies. Part of the difficulty in interpreting and predicting the site amplification function is that the observed amplification does not always reoccur during the next strong motion shaking (Trifunac et al., 1999). A more serious problem is that the destructive strong earthquake shaking leads to non-linear soil response (Trifunac and Todorovska, 1996a), which can shift or completely change the shape of the site amplification function versus frequency, as determined from linear response (Trifunac and Todorovska, 2000b). Microtremor waves have been used by some researchers to estimate the amplification of strong motion waves, but it is generally acknowledged that their nature and propagation paths are different from those of strong motion waves.

Detailed spatial correlation studies of observed damage, reported site intensities, and recorded strong motion amplitudes, following Northridge, California earthquake of 1994, have shown that if microtremor studies are to be used to predict local site amplification, this may be possible only in the zones of essentially linear response of surface soil, that is, where strong motion amplitudes are small (Trifunac and Todorovska, 2000a, 2000b). In the zone of strong motion, where buildings and underground pipes get damaged, so far, neither microtremors nor aftershocks and small earthquake records could be used to predict spatial variations and amplifications in the presence of non-linear soil response.

STRONG MOTION MAGNITUDE, M_L^{SM}

Since 1935, the local magnitude scale M_L (Richter, 1935) has been one of the most useful and physically meaningful indicators of the earthquake size for scaling of strong ground motion. This is because it is measured at small epicentral distances (less than 600 km) and because it samples the amplitudes of ground motion at periods near 1 s, which is near the "center" of the largest amplitudes of the spectrum of strong ground motion (typically in the range between 0.1 and 25 Hz).

The local magnitude scale saturates near $M_L = 6.5$, because the corner frequency of the Fourier amplitude spectra of source displacement shifts to frequencies smaller than 1 Hz. In their quest for an ideal, single parameter scaling of the size of an earthquake source, seismologists first proposed to use the surface wave magnitude, M_s (Gutenberg, 1945), and more recently, the moment magnitude, M_w (Hanks and Kanamori, 1979). The surface wave magnitude samples the amplitudes of 20 s period Rayleigh waves, at teleseismic distances, while M_w is computed via empirical scaling equation from the seismic moment $M_0 = \mu \bar{u} A$, where μ is the rigidity of the rocks in the source region, $\bar{u}$ is the average dislocation, and A is the area of the fault. Magnitude M_w is then equal to ($\log_{10} M_0 - 16$)/1.5. Magnitudes M_s and M_w have become popular in geotechnical earthquake engineering, in spite of their dubious ability to scale the spectral amplitudes of strong motion for periods between 0.04 and 10 s. M_s samples 20 s period teleseismic Rayleigh waves and M_w samples periods $T \to \infty$, and so both of these magnitudes sample spectral amplitudes which are far outside the frequency range of a typical strong ground motion. If the strong motion spectrum had a constant or well-defined and stable shape (Trifunac, 1993a, 1994a), all magnitude scales could be equally useful and reliable. Since this spectrum has variable shape (Trifunac, 1994b), and because in the near-field, its shape is significantly different from that in the far-field, it is seen that for engineering scaling of strong motion, M_L is physically the most meaningful scale (Trifunac, 1991a).

The response of a Wood-Anderson torsional seismometer (Richter, 1935) can be calculated by numerical integration of its differential equation of motion, when subjected to excitation by a recorded strong motion accelerogram. Thus, recorded strong motion accelerograms can be used to compute the local magnitude scale, M_L^{SM}. This approach was first proposed in the study of aftershocks of the Imperial Valley, California, earthquake of 1940 (Trifunac and Brune, 1970), but the general definition and calibration of M_L^{SM} were presented by Trifunac (1991a, 1991b). A related correlation of seismoscope response with earthquake magnitude and Modified Mercalli Intensity was presented by Trifunac and Brady (1975c). Calibration of M_L^{SM} for attenuation of strong motion in South-Eastern Europe was presented by Lee et al. (1990), and its relationship to other magnitudes, as determined by regional seismological stations in South-Eastern and Central Europe, was presented by Trifunac and Herak (1992). Examples of computing M_L^{SM} for the Dharamshala, 1986, earthquake in India, and the Loma Prieta, 1989, earthquake can be found in Trifunac (1993b, 1994c).

Systematic studies of the trends of the differences between M_L^{SM} and M_L (Trifunac, 1991b) can be used to understand the changes in spectral amplitudes of near-field and far-field strong motions. This helps in understanding and improving the ideas on how to develop empirical scaling equations for prediction of strong motion amplitudes. Studies of the differences in M_L^{SM} between different tectonic provinces, and of strong motion accelerograms recorded on geologic strata of different ages (Lee et al., 1990), help in the process of learning how to use empirical equations for scaling strong motion amplitudes, developed in one region (e.g., Southern California), for empirical predictions in another region. Finally, comparison and quantitative correlation of M_L^{SM} with regionally computed magnitude scales (Trifunac and Herak, 1992) helps in relative calibration of the regional magnitude scales, and thus is a step toward homogenizing earthquake catalogues for future seismic hazard studies.

SCALING OF STRONG MOTION FOR ENGINEERING DESIGN

The oldest and still commonly used scaling parameter of strong ground motion, used to quantify engineering design spectra for earthquake-resistant design calculations, is the peak ground acceleration. The idea that a standard shape of response spectrum should be established and that its amplitudes can be scaled by the representative value of ground acceleration can be traced back to the work of Biot. In his 1941 paper, he states: "...for design purposes standard spectrum should be established, giving the equivalent acceleration as a function of the frequency. These standard curves would be the envelopes of a collection of earthquake spectrums and could be made to depend on the nature and magnitude of the damping and on the location."

With the accumulation of strong motion data by the 1970s, and with an improved understanding of the spectral character of the earthquake source (Trifunac, 1972a, 1972b, 1976b, 1993a, 1994b), it is now possible to select physically meaningful parameters for scaling of strong motion for structural (Trifunac, 1991c, 1992, 1994b) and for geotechnical earthquake engineering design (Trifunac, 1995).

Up until late 1960's and early 1970's, peak acceleration was used for essentially all scalings of strong motion in engineering design. It is the directly measurable quantity (from any analog record) and its measurement does not require data processing or use of computers. Since the absolute acceleration spectrum converges to the peak acceleration of ground motion, when the oscillator period approaches zero, peak acceleration is also convenient to use for scaling the standard design spectrum amplitudes. Today, however, it is recognized that better and physically more meaningful scaling parameters or functions should be selected, on the basis of the nature of the phenomenon, which is being analyzed (Trifunac, 1992). For example, peak ground velocity should be used for estimation and mapping of peak strains in the soil (e.g., Todorovska et al., 1995; Todorovska and Trifunac, 1996). Peak ground velocity is further ideal for elementary scaling of damage potential of strong motion (Trifunac and Todorovska, 1997a, 1997b; Trifunac et al., 2001). For rational development of spectral shapes, representative for a given area and optimized for geometrical and temporal characteristics of locally contributing earthquake sources, Uniform Hazard Spectrum (UHS) scaling is most suitable, when the design methodology can be carried out using equivalent linear response representation (Todorovska et al., 1995). For non-linear design of earthquake-resistant structures in the near field, at present, the most promising elementary tool appears to be the peak power of strong motion, combined with the total incident wave energy (Trifunac et al., 2001).

SUMMARY AND CONCLUSIONS

This brief note presented examples of selected published elementary studies of engineering interpretation of strong earthquake ground motion, based directly on recorded accelerograms. It cited examples of studies that: (1) systematically describe the basic properties of the recorded motion, (2) describe the two-dimensional variations of the attenuation (enabling interpretation of its dependence on the geology along the propagation path), (3) interpret the time series of recorded accelerograms to identify the wave content, (4) interpret amplification of strong motion via recordings of small amplitude motions (such as microtremors and microseisms), (5) measure the "size" of earthquakes via strong motion magnitude, and (6) present the prelude to empirical scaling models of strong motion amplitudes.

It is concluded that such studies and their findings must continue to play a central role in guiding theoretical and empirical modeling of strong ground motion in adopting realistic and significant assumptions about the nature of strong motion and its representation for engineering practice. It is hoped that more rigorous and denser future observations of strong motion will generate data for further new and more comprehensive descriptions of its properties.

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