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THE ASSESSMENT OF STRONG GROUND MOTION
WHAT LIES AHEAD ?

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INTRODUCTION

Professor Emilio Rosenblueth (1926-1994) was deeply interested in the future. He agreed with Ackoff's (1974) proposal that the future is not predicted, it is designed. However, he stated that "we design our future but only to some extent; the rest is imposed upon us. To design it with some probability of success we must in some sense predict what Nature, other human beings and, against our will, our own limitations, will force upon us". He pointed out that even if multiple possibilities are contemplated, "each with its probability of realization, ... situations will arise that we will not have imagined" (Rosenblueth, 1992).

Advances in both science and technology during the current century have been phenomenal, and have had a profound influence on most aspects of human activity. It is only by assuming that they will continue to be so that we have any hope of predicting the future. Of the many lessons to be drawn from recent history the one which we would like to emphasize is: anything that is theoretically possible will be achieved in practice, no matter the technical difficulties, if it is desired strongly enough. In the 19th century Jules Verne had a similar perception when he stated "anything that one man can imagine, others can make it real". Thus, in predicting our future we must have the courage to pursue all possible technical extrapolations to their logical conclusion. Yet even this is not enough, in part because the new concepts impose some modifications on our perception of reality. To predict the future we need logic; but we also need faith and imagination, which can sometimes defy our established logic.

Perhaps, the main obstacle in our extrapolation to the future is that societies function (we wanted to write: are designed to perform) in a kind of limiting state. That is, within limitations imposed by internal and external factors whose degree of severity varies with time. These constraints determine priorities and policies when planning how to confront natural disasters. In the case of earthquakes, in general, the seismic threat is considered small as compared to other dangers. For instance, in developed countries, the number of deaths by traffic accidents is much larger than earthquake casualties. In other regions, diverse diseases account for the larger part of the death toll. Let us face it, in managing hazard the major obstacle that society has to deal with is political, not physical. The allocated resources to study the earthquake phenomena are scarce. Professor Rosenblueth used to say that "when resources are limited, the Best is often the enemy of the Better - and both may be enemies of the Good."

In this paper we address the future of Earthquake Engineering, focussing on the factors involved in the assessment of strong ground motion, namely source, path and site. The effects due to these factors on ground motion are discussed under the light of recent observations, results on seismic wave attenuation, and advancements in theoretical methods to compute seismic waves in media of complex local geological conditions and topography. The characterization of these effects is relevant to the design of building structures that will perform satisfactorily when subjected to strong ground motion. Our coverage of these subjects is far from being complete or very technical. We hope to stimulate discussion.

The assessment of the effects of local and regional site conditions on seismic ground motion and, beyond that, how to incorporate these effects into building codes were problems very dear to professor Rosenblueth. His interest in such problems was triggered by the peculiar geotechnical conditions of his beloved home city. In fact, México City was the first location in the world to incorporate explicitly seismic zonation into its building code, on Rosenblueth's (1960) initiative, following the 1957 Guerrero earthquake (Fukuta, 1991). The initial provisions were based primarily on observations of damage distribution during that event. These observations were followed in the 1960s by analytical studies of soil amplification (Herrera *et al.*, 1963) using one-dimensional flat layered models.

BACKGROUND

The progress of earthquake engineering into the future cannot deviate radically from its present course; that is the characterization of the response of a site upon the occurrence of earthquakes and the development of the corresponding design criteria. On the other hand, the devastation caused by large earthquakes during the last decade, with epicenters both away from urban areas, such as the 1985 Michoacán earthquake, and within urban areas, such as the 1994 Northridge and 1995 Kobe earthquakes, raise the questions: are we following the right approach towards the understanding of earthquake ground motion phenomena ?, are the corresponding improvements in building design the appropriate to anticipate the effects of future large earthquakes, particularly in cities with large urban and industrial developments ? The point is that most building codes use seismic design parameters which, while taking advantage of available geologic information, are in general estimated by extrapolating earthquake ground motion data recorded from past earthquakes. It is only from the past experience that we can foresee the future.

Some aspects of the effects of soils and rock on strong ground motion that need to be considered for the development of codes still cause controversy among scientists and engineers. High quality digital strong motion records have become available only in recent years. Yet, to the authors' knowledge, results from the pertaining research have triggered no fundamental changes in the codes and the changes come in very slowly. Major improvements in the past, at least in the United States, are related to the gradual replacement of old deterministic zoning criteria by probabilistic zoning, based on the new understandings of seismic hazard. The reader is referred to Donovan (1993) for a comprehensive review of this matter. Professor Rosenblueth pointed out the great importance of optimum zonation and even suggested, in view of the actual advances in computer sciences, that we should begin thinking about "continuum" risk descriptions in which the hazard at any location could be retrieved from an updated computer system.

The established criteria for modifying the codes are mainly empirical, based on studies of the performance of different types of buildings during moderate- to-large earthquakes (Heaton *et al.*, 1995). These criteria cannot, and perhaps are not supposed to, guarantee the good performance of retrofitted buildings and new designs in the case of a very large future earthquake. The "good performance" is difficult to define taking into account the huge uncertainties about maximum values. Usually this complex issue is dealt with informally and depends upon varying perceptions of hazard. For example, it has been reported that after the 1994 Northridge earthquake (M=6.7) most near-to-intermediate field steel-frame structures suffered cracks in the joints. This was surprising for such a moderate magnitude, considering that the maximum value of velocity amplitudes affecting these buildings was about 50 cm/s (Bertero *et al.*, 1994). Rupture directivity during the 1995 Kobe earthquake appears to have played a major role in the damage to some old buildings, not expected for a 6.9 magnitude earthquake (Wald, 1995).

We should point out that modern buildings (those constructed after, say, 1980) generally withstood Kobe earthquake with minor or no damage. A possible explanation may be the change of the minimum stirrups' spacing (from 30 cm to 10 cm) and other regulations that took place in the Japanese building codes of the time (M. Ordaz, personal communication). This suggests that, despite the damages, there is neat progress in the engineering practice. What is needed is to improve the assessment of future ground motion.

The Northridge and Kobe earthquakes, which under the current codes are considered moderate-to-large, have shown an unexpected potential for causing great damage. The reason for this may be related to near-field phenomena; their effect on buildings structures is already under study. For instance, theoretical calculations show that near-source ground motions corresponding to a M 7 near-field thrust earthquake may cause 5% drift in the lower floors of both steel and concrete frame buildings, far into the inelastic range of deformation (USGS-SCEC, 1994).

Considering that the estimations of seismological factors for building codes are not strictly based on the understanding of the complex seismic wave mechanisms (source, path, site) that produce strong ground motion (Heaton, 1995), and our lack of experience with very large near-field earthquakes to upgrade the established criteria, it becomes apparent that future research should be focused on improving our ability to predict strong ground motions. Specifically, progress needs to occur in three directions: (1) Experimental - Empirical approaches, (2) Theoretical - Numerical Modeling, and (3) Seismic Attenuation, Intensity and Hazard. Let us give a look to each of them.

EXPERIMENTAL - EMPIRICAL APPROACHES

The acquisition of data, whether from permanent seismic stations (networks) or from field experiments with portable instruments has been crucially important in the study of strong ground motion. Prospects for research in the subject have been enhanced by the recent incorporation of broad-band seismometers and large data storage capabilities. Strong motion instrumentation programs in some earthquake-prone countries have grown tremendously, providing large amounts of high quality records of source - path - site scenarios that only a few years ago were just a dream for seismologists. The analysis of these data is enlarging our view of strong ground motion, particularly on issues relevant to maximum values and their uncertainties. It certainly must have an impact on future earthquake engineering research.

The impressive growth of the strong motion network in México since the 1985 Michoacán earthquake - up to a ten-fold increase among free-field, downhole and structural type instruments in the Valley of México - resulted in dense coverage of the M 7.4 Copala, Guerrero (September 14) 1995 subduction thrust earthquake. It was recorded at over 400 sites, distributed along the Pacific coast adjacent to the Guerrero and San Marcos gap, and in the various zones with different soil characteristics in México City (Anderson *et al.*, 1995). The analysis of these data and their correlation with similar data from the Michoacán 1985 earthquake has high priority in future research regarding mechanism, path and site effects, as well as in the calibration of the current attenuation curves.

The near-field site scenario best covered to date is in Southern California, by a massive deployment of the Southern California Seismic Network (SCSN) operated by US Geological Survey - Pasadena, the California Institute of Technology Seismological Laboratories, and the Southern California Earthquake Center (Wald *et al.*, 1995). This network recorded the 1994 Northridge earthquake, among others of importance. But perhaps one of the highlights of this network concerning the future is its easy accessibility via Internet. This certainly brings a new, powerful tool into the research scene that was not even imagined 10 years ago. Although the access to SCSN data has been in place only recently, many scientists have been trying it already and, perhaps, benefited from it (e.g. Figure 6 of Wald *et al.*, 1995). We can only imagine the benefits of future research when scientists around the world can retrieve, contribute, and analyze data in real time on a regular basis.

A class of experiments that begins to widen the scope in the study of near surface propagation of seismic waves, including their amplification, attenuation and scattering, relies on data gathered from deep borehole seismometer arrays. There have been previous studies pertaining to seismic attenuation and non-linearity using downhole measurements in boreholes of about a 1 km depth (Archuleta *et al.*, 1992). But the recordings in the 3.5 km deep Cajon Pass borehole, penetrating 500 m of Miocene sandstone, then crystalline, granitic basement rock, provide a striking view of the differences of waveforms of an earthquake recorded both at the wellhead and at 2.5 km depth, in bedrock. This is shown in Figures 1a and 1b, top and bottom, respectively, of a M_L 1.7 earthquake at 10 km epicentral distance (Abercrombie, 1995a). Figure 1c shows the comparison of the corresponding *S*-wave spectra. For an instant, and allowing ourselves a non-rigorous analogy with the observation of celestial bodies in deep space without the light distorting Earth's atmosphere, the idea that a deep borehole is a sort of "Hubble-telescope" capable of observing a clean, small earthquake without much distortion from the upper surface heterogeneities, is appealing. In fact, by comparing corresponding *S*-wave spectra up and downhole of several local (within 15 km range) earthquakes of M_L between 1.3 - 2.8, Abercrombie (1995b) shows that 50 % of the amplitude attenuation for those earthquakes occurs around the upper 300 m, while more than 90% of attenuation occurs in the upper 3 km. It is shown, as well, that the amplification by the near surface rocks appears to be more site dependent than the associated attenuation, with amplifications of *S*-waves varying from the free-surface factor (of 2) at a nearby granitic site, up to around 10 at the wellhead. In general, it is observed that at the surface seismic waves are amplified below 10 Hz and severely attenuated above 30 Hz (Figure 1c).

From the point of view of source characterization, the high signal/noise ratios in deep borehole allows the recording of very small earthquakes with high frequency content that would be hardly observable at the surface. This in turn allows the extension of the magnitude range of catalogs from surface observations. For any of these very small earthquakes, the *S*-wave corner frequencies at the wellhead and at 2.5 km downhole, as determined from curve fitting to the ω^{-2} model, are significantly different. Observing at depth can result in improved estimations of the source dimensions and other source parameters.

This raises the important issue of the factors controlling f_{max}, i.e. the frequency at which the acceleration spectrum of an earthquake appears to decay (Hanks, 1982). Some authors claim that its value is controlled by the source (Archuleta *et al.*, 1982, Campillo, 1983, Aki, 1988, Papageorgiou, 1988), while others that it is controlled by path and site effects (Boore, 1983, Anderson and Hough, 1984). This issue has not been fully resolved by the deep borehole measurements. On one hand, Abercrombie and Leary (1993), and Abercrombie (1995a) analyzed nearly a hundred small earthquakes (less than M_L 4.0) recorded at 2.5 km depth in Cajon Pass, and they found that there is no breakdown in self-similarity of source structure leading to f_{max}. Rather, they found evidence that the non-scaling may be due to strong attenuation above 10 Hz, that is, an artifact intrinsic to events recorded on the surface. On the other hand, Kinoshita (1992) obtained source-controlled characteristics for earthquakes recorded in bedrock at 2.3 km downhole in the Tokyo (Japan) metropolitan area. He used an estimate of the average $Q(\omega)$ for *S*-waves in a given region, and found that the ratio of reflected downgoing to upgoing waves is small, less than 10% for frequencies higher than 5 Hz, which establishes the similarity of the upgoing waves to those recorded downhole. He estimated values of f_{max} corresponding to different epicentral regions of the recorded earthquakes. Although the work of both Abercrombie and Leary (1993), and Kinoshita (1992) shows that the effects of free-surface on the downhole records are negligible beyond 5 Hz (due to attenuation), the difficulty appears to be in the interpretation of the spectra, in relation to frequency bands, size of the earthquakes and hypocentral distances. New data, in particular from deep boreholes, must be required to resolve this controversy in the near future.

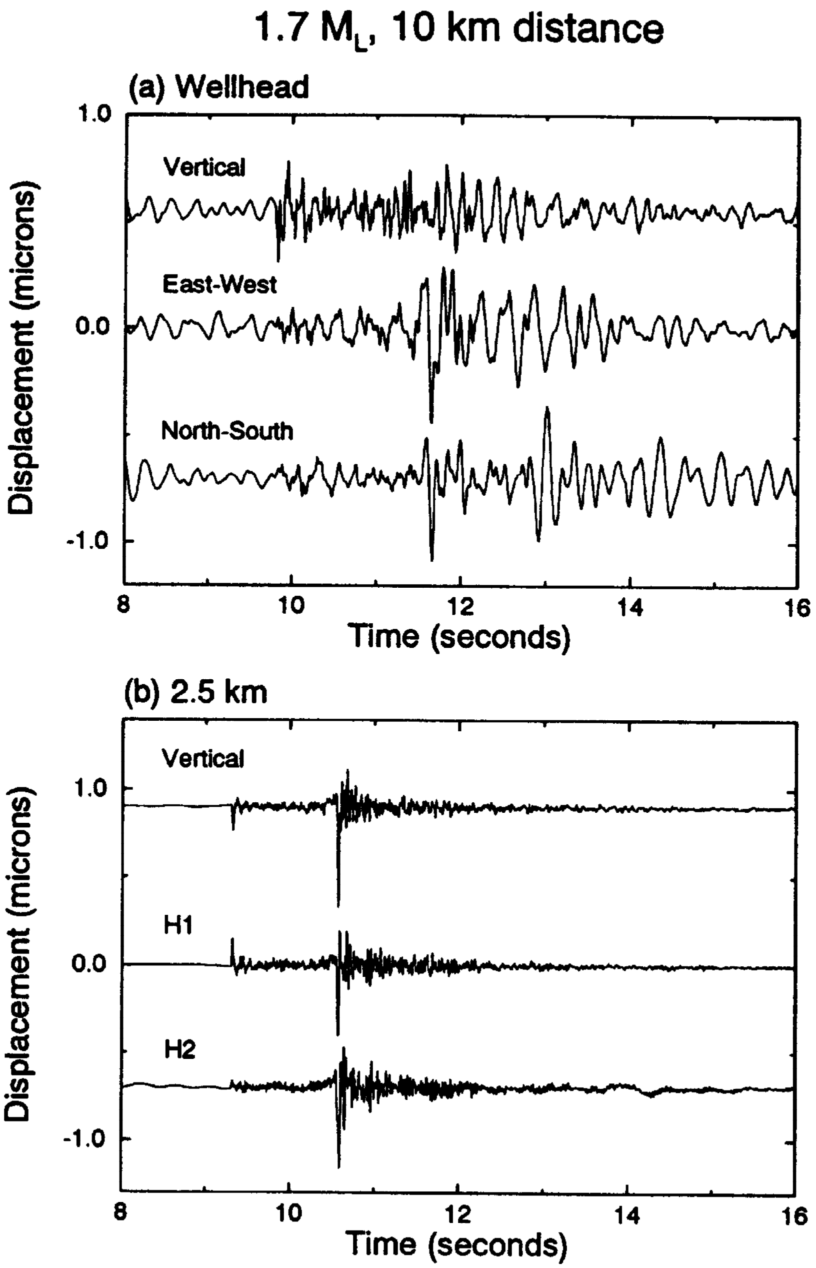

Fig. 1. Displacement waveforms for a M_L 1.7 event at the San Andreas Fault (SAF) recorded 10 km away at Cajon Pass borehole observation site. (a) The uppermost traces give the three displacement components recorded at the wellhead. (b) The lower frame displays the records obtained at a depth of 2.5 km. The deep H1 and H2 components were determined to be 18 and 288 degrees from N (towards W). The H2 component is almost parallel to the SAF and compares well with the atop E-W. The opposite is true for H1 (after Abercrombie, 1995a).

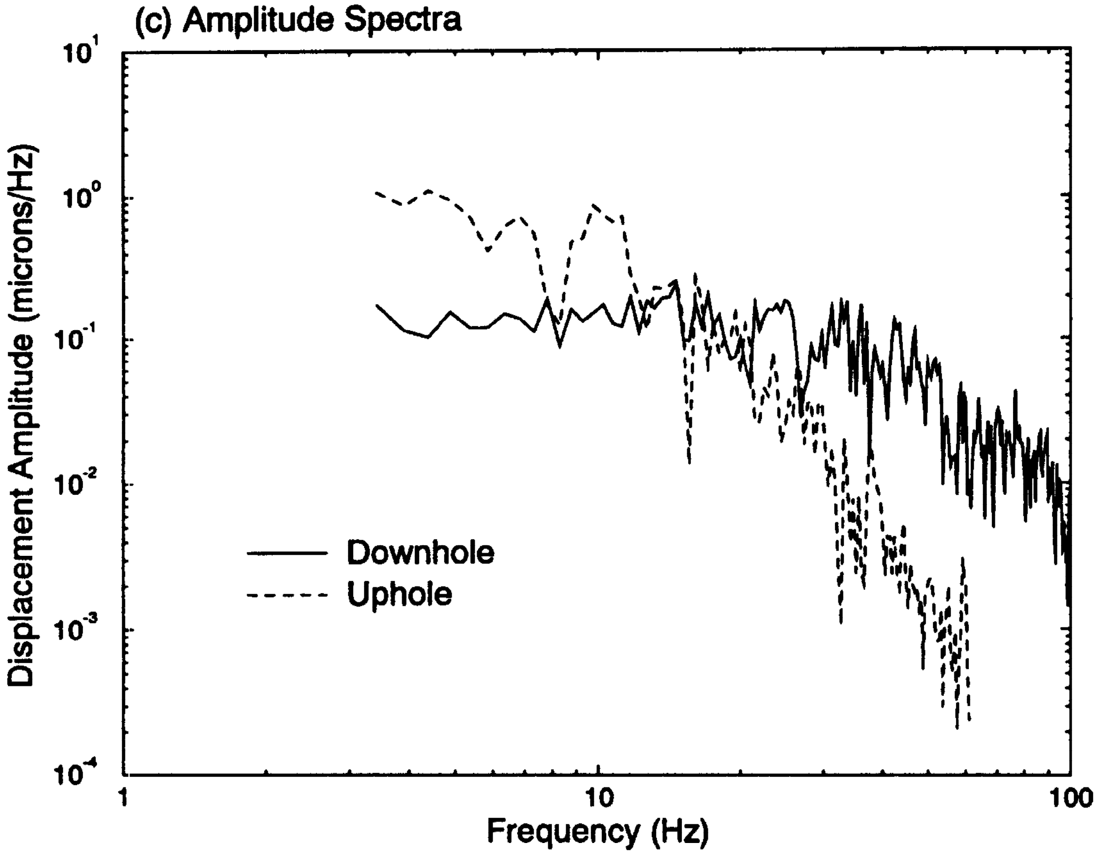

Fig. 1c. Average *S* wave amplitude spectra for displacement waveforms for various local events (M_L between 1.3 - 2.8) recorded at the Cajon Pass, California, test site. The continuous and dashed lines correspond to the downhole and surface records, respectively (after Abercrombie, 1995b).

The study of site effects will also require the continuation of seismic experiments to measure weak ground motion at specific sites, either because their stratigraphies are well known, or because they have suffered the impact of historical events. We have learned a great deal about site effect from past experiments. For example, Davis and West (1973) studied the effects of topography due to three mountain ranges of different sizes. They found systematic amplifications at the crest in all cases, of factors up to 30, at characteristic periods that broaden with the size of the mountain. It can be associated with the relationship between the dimensions of the width of the mountain at its base and the wavelength of the incoming seismic wave. It has also been found that amplification by topography can be larger than that caused by superficial layers of sediments. Tucker *et al.* (1984) studied three sediment-filled valleys and found that there was no strong azimuthal dependence of the average valley response. Rather, there was a significant dependence on impedance contrast between basement and sediments, although there was no high Q resonance of the sediments. Since these pioneering studies, many other authors have contributed by performing similar experiments, and others by introducing statistical approaches (e.g., Trifunac, 1989, Trifunac and Lee, 1989), a combination of simple physical principles and regression analyses (Trifunac, 1990), and random vibration theory to describe both ground motion and response spectra (Boore, 1983).

In using these experimental techniques questions have been raised concerning the validity of spectral ratios (Aki and Richards, 1980) and the computation of transfer functions, in relation to signal-to-noise ratio, extensive averaging, and coherence of the wavefield used to estimate the ratios. In the case of topography, comparisons with corresponding theoretical predictions show a clear mismatch (Geli *et al.*, 1988), with the observed amplifications much larger than those predicted by theoretical models, as depicted in Fig. 2.

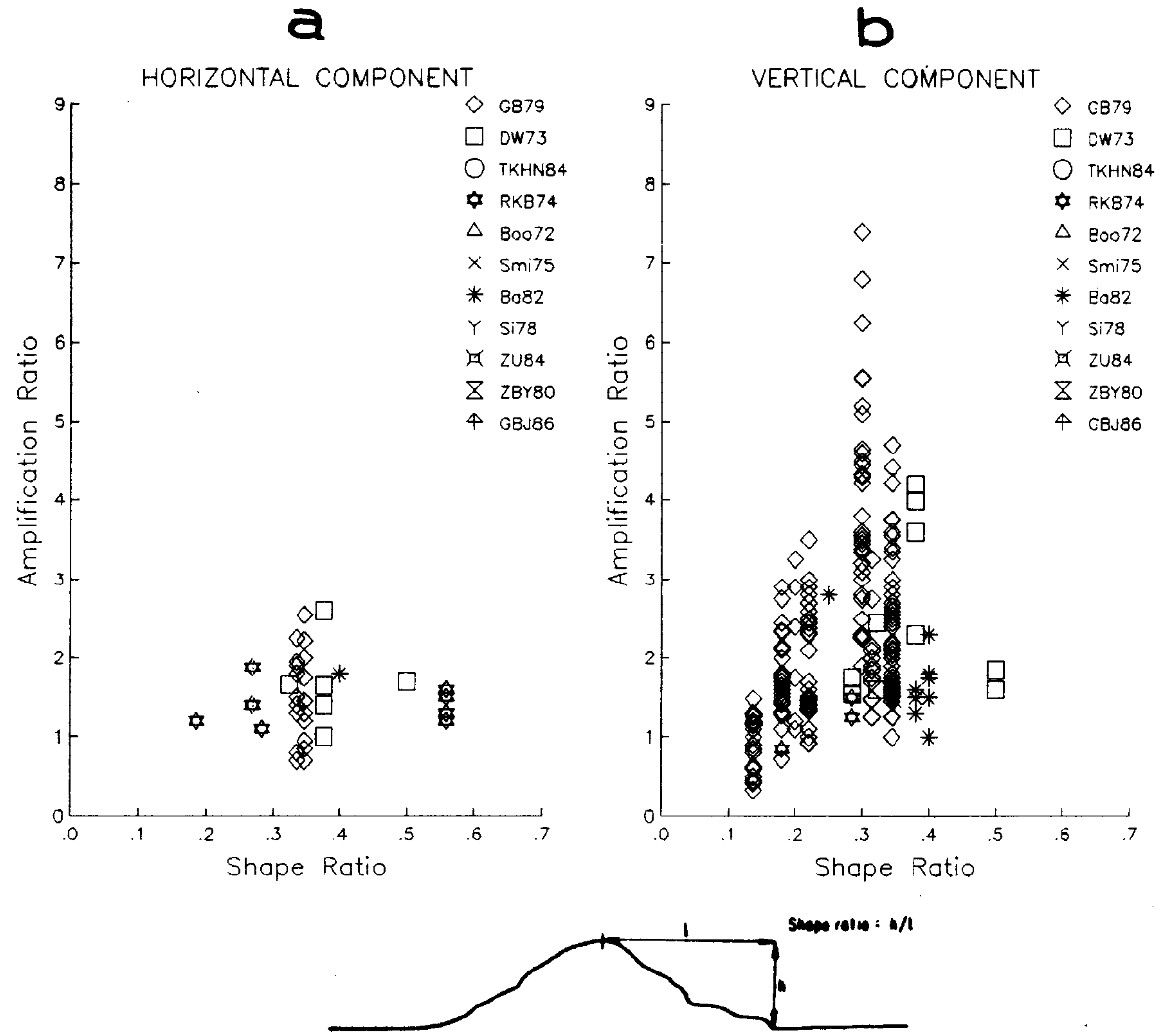

Fig. 2. Peak to peak time domain crest/base amplification as reported in the literature and plotted as a function of the apparent shape ratio (i.e., ratio between crest and base recording site altitudes to their horizontal distance). Open symbols (squares, circles,etc.) indicate experimental field studies, while others (cross, stars, etc) indicate results of theoretical studies. (a) Horizontal motion. (b) Vertical motion. Each symbol corresponds to different authors' results as follows: GB79 = Griffiths and Bollinger, 1979; RKB74 = Rogers *et al.*, 1974; DW73 = Davis ang West, 1973; Ba82 = Bard, 1982; Smi75 = Smith,1975; Si78 = Sillis, 1978; TKHN84 = Tucker *et al.*, 1984; ZBY80 = Zhenpeng *et al.*, 1980; Boo72 = Boore, 1972; and ZU84 = Zahradnik and Urban, 1984. (Modified after Geli *et al.*, 1988).

New approaches combine 3-D array deployments (although to date the downhole recordings have been less than few tens of meters) with simple 1-D modeling techniques. Cramer (1995) used such a method to measure transfer functions for site specific and profile studies in the Turkey Flat site effects area, near Parkfield, California. He found that transfer functions may be sensitive to 5% changes in *S*-wave velocity, which is a very important result determining the uncertainties of ground motion prediction.

Hartzell *et al.* (1994) used an array deployment to study the causes of the large structural damage and ground cracking on the top of Robinwood ridge after the 1989 Loma Prieta earthquake. They incorporated coherency to identify wave propagation directions and apparent velocities, by determining the vector slowness of arrivals that produced the maximum correlation between successive portions of seismograms recorded in the array. In this way they found that the source directivity and radiation pattern were the main causes of the large ground motions in the region. In addition, there were complex interactions between Love and Rayleigh waves. Obviously, future research of specific sites using weak ground motion measurements, incorporating array analysis and degree of coherency will be much enriched by using broad-band instruments in the deployment, hopefully having deeper boreholes in order to have a good control of slowness.

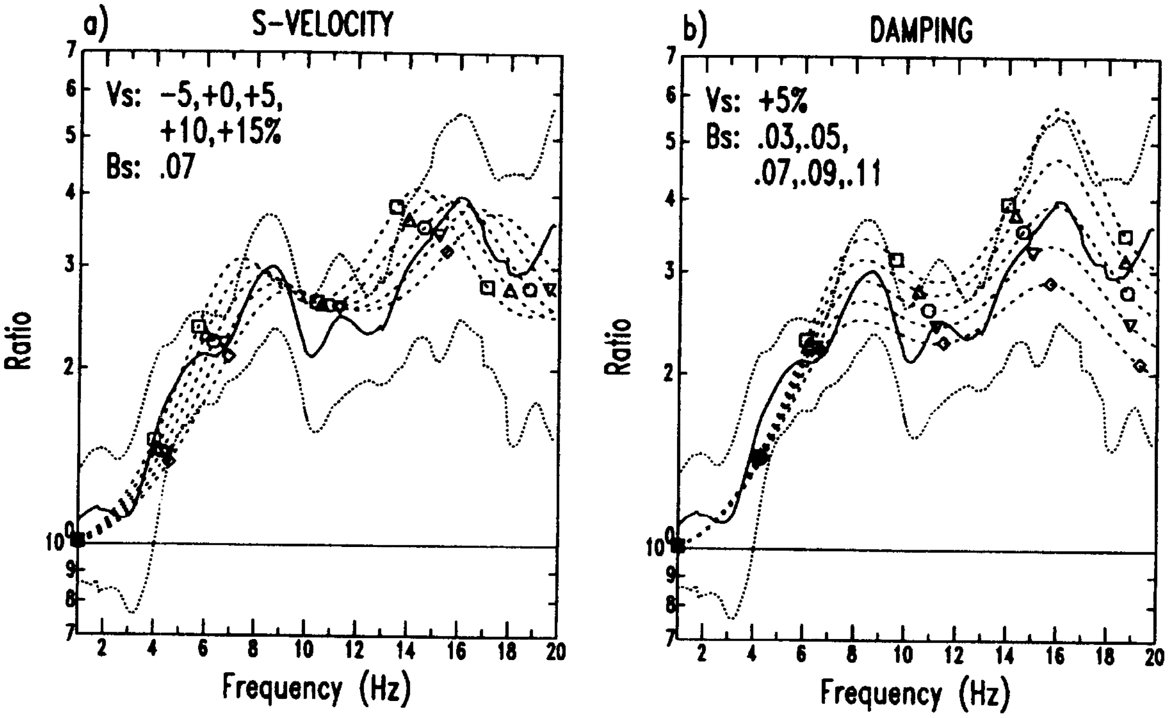

Fig. 3. *In situ* results for the center of the valley at Turkey Flat, U.S. Sensitivity to changes in (a) *S*-velocity and (b) damping are shown by means of spectral ratios (ordinates) against frequency with respect to a reference site, due to a series of weak seismic events. Squares, triangles, octagons, inverted triangles, and diamonds on dashed lines indicate the results for the first, second, third, fourth, and fifth parameter values listed in each plot, respectively. Vs lists model *S*-velocity percent change from the initial, *in situ*, model *S* velocity, and Bs lists model soil damping values. The observed mean spectral ratios for the weak motion and their standard deviations are shown as solid and dotted lines, respectively (after Cramer, 1995).

The use of small events as empirical Green's function to synthesize a corresponding large earthquakes is one of the best hopes for testing design parameters, as we wait for the earthquake to occur. This follows the pioneering work by Hartzell (1978) and Irikura (1983). The Green's function accounts for the mechanism and for the path and site effects, and correlates to the earthquake source by a suitable scaling law. Several scalings will correspond to several source realizations, and the corresponding output wavefield will be used statistically. For example, Ordaz *et al.* (1993) predicted the ground motion at a site in México City for a M 8.2 earthquake originating in the Guerrero gap. They relied on three approximate methods that use empirical and theoretical transfer functions for the site, relative to firm ground, using as empirical Green's functions the records from a M 6.9 earthquake. The prediction is reached through a Bayesian scheme similar to one that combines expert opinions (Rosenblueth and Ordaz, 1990).

The empirical Green's function method has been simplified for engineering purposes, to directly estimate peak ground accelerations from large earthquakes (Midorikawa, 1993). The fault of the assumed large earthquake is discretized into small elements and the acceleration waveforms envelopes from the elements are determined using empirical relations. These are synthesized to produce the waveforms envelope of the large earthquake. Midorikawa (1993) computed peak accelerations for the 1985 Central Chile (M_s=7.8) earthquake, for which a large number of strong motion records were obtained near the source. Some results are shown in Fig. 4.

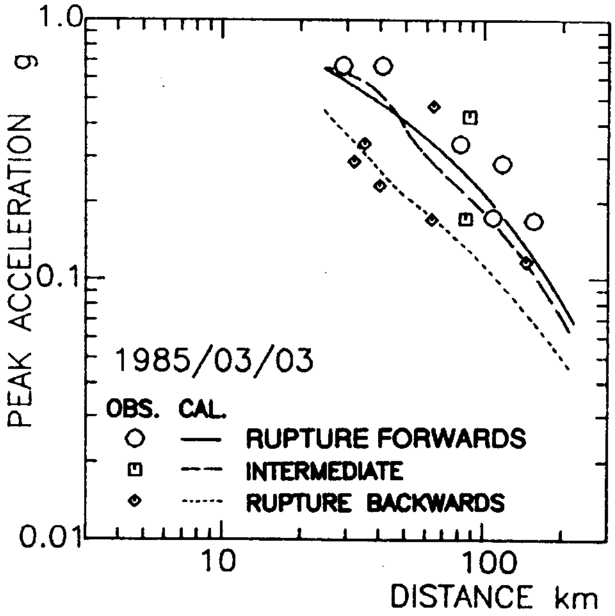

Fig. 4. Computed and observed peak ground accelerations against distance for the 1985 Central Chile earthquake (after Midorikawa, 1993).

Important conclusions from calculations are that the peak accelerations become independent of magnitude in the near-field, and that the source directivity significantly affects the values of the peak acceleration. The method needs to be further investigated in terms of its uncertainties with respect to the scaling relation. Recent advances include the probability distribution of origin times in order to precisely match the seismological ω^{-2} model for the source (Ordaz *et al.*, 1995). The task for the future is to build up a data bank of earthquakes that can be used as Green's functions at particular sites. At present this is quite rare, and researchers must resort to site effects computed by theoretical methods.

To summarize this section, the following points must be emphasized as important tasks for the future:

-acquisition of supporting data in terms of soil properties and stratigraphy (reflection-refraction experiments, VSP analysis).

-design experiments to measure large strain ground motion. Study technical issues concerning site-specific effects of soils and rocks on ground motion (e.g. plasticity, non-linearity).

-study site-dependent response spectra using data from recent near-field and far-field earthquakes. Assess the uncertainty in earthquake response design parameters.

-seek an appropriate standard scale for peak ground motion and response spectra in the near-field. Do these values saturate with earthquake magnitudes ?

-incorporate deep borehole data analysis in the characterization of attenuation near the surface, source dimensions and corner frequency. Cajon Pass (Abercrombie and Leary, 1993), Tokyo Basin (Kinoshita, 1992) represent two good case studies.

-pursue standardization of data processing, analysis and visualization through the Internet.

THEORETICAL - NUMERICAL MODELING

Predicting strong ground motion theoretically implies solving the elastodynamic equations in complex media, which can be either linear or non-linear, to produce the complete seismic wavefield. To this end, the progress on analytical and numerical methods has been tremendous, with great success for 2-D media, and to a lesser extent for 3-D. In the latter, the major constraint has been computational rather than mathematical.

We consider the following contributions as breakthroughs, in the sense that they triggered the development of powerful methods to compute ground motion:

- The Sommerfeld's (1896) problem of a scalar wave diffracted by a semi-infinite screen (Sommerfeld, 1954).
- Lamb's (1904) problem for the time history of displacements in a half-space under the sudden application of a point load.
- First representation of sound waves, and their diffraction (Rayleigh, 1945).
- Thomson-Haskell matrix propagator methods (Thomson 1950; Haskell, 1953).
- Gutemberg's account of effects of the ground type on earthquake motion (Gutenberg, 1957).
- Gilbert and Knopoff's (1960) theory for scattering from topographies.
- Introduction of potential methods in elasticity (Kupradze, 1963).
- The Aki-Larner discrete wave number method (Aki and Larner, 1970).
- Trifunac's (1971, 1973) closed form solution for semicircular alluvial basins and topographies.
- The Finite Difference Method applied to seismic wave propagation (Boore, 1972).
- The Finite Element Method applied to seismic wave propagation (Lysmer and Drake, 1972).
- Wave potential expressed as surface distribution of wave sources in the exterior region (Ursell, 1973).
- Wong and Jennings' (1975) approach to topographical effects using boundary integrals.
- 1-D and 2-D non-linear soil response (Joyner and Chen, 1975; Joyner, 1975).
- Hartzell's (1978) theory on earthquake aftershock as Green's function.
- Brebbia's (1978) book on the Boundary Element method.
- Aki and Richard's (1980) book on Quantitative Seismology.

Most of the present state-of-the-art methods are based on the theories established in these original works. In essence, their combined power can address almost any problem related to seismic wave propagation in complex media relevant to ground motion, whether generic or realistic. If new information on the nature of the soils becomes available, these methods can be modified accordingly. For example, if the material behavior is inelastic then one must consider appropriate modifications of the governing equations to incorporate elastoplastic constitutive relations.

Although the applicability of these methods to realistic cases, in particular those of interest in earthquake engineering, can be argued upon the present limitations of computers, it is plausible that these will not be a major obstacle in the near future. The main problem appears to be, rather, our limitations to know with precision the material and geometrical properties of the soils underneath the site, and the character of the input motions. If the values of these parameters are not well known, then the corresponding results by any of the advanced methods are uncertain for correct applications. What is the use of a powerful method then ? The answer will come along with the interpretation of new data using these methods.

A major goal is to analyze site effects for frequencies up to 2 Hz on a large valley underline by very soft clay and other soft sediments. Certainly, at present this is beyond the capabilities of our computers. Yet, it seems that within the next few years this feat can be accomplished, judging from promising recent results. An example in this direction is the simulation of ground motion in Los Angeles basin as a result of a magnitude 7.75 earthquake rupturing a section of the San Andreas fault (Olsen *et al.*, 1995). The simulation was performed with finite differences, and for frequencies of up to 0.4 Hz that required some 23 millions of blocks using a state-of-the-art nCUBE-2 parallel computer with 2 GByte RAM.

Non-linear analysis of ground motion in seismology applications is performed in time domain, mainly using a FD method developed by Joyner and Chen (1975) for 1-D, and Joyner (1975) for 2-D, which incorporates soil rheology through a hysteretical stress-strain relationship. The method is based on a spring-friction element introduced by Iwan (1967). The method was seldom used for more than ten years, but it suddenly became popular after the 1989 Loma Prieta earthquake, which apparently produced some evidence of non-linear site effects (Chin and Aki, 1991). Marsh *et al.*, (1995) compared the linear and non-linear responses of a heterogeneous valley to high-strain in-plane and out-of-plane input motions, using a modified non-linear soil model of practical use in earthquake engineering. These authors show that some features of the non-linear response can be reproduced by the linear model by choosing an appropriate value of Q, while others, such as maximum values, are underestimated. An important continuation of this work is to incorporate the near-field radiation pattern of a finite fault, with prescribed directivity and rupture velocity.

Traditional FD methods have the great advantage over other discretization procedures in that these are based on structured meshes that require minimum memory for their complete description. The location of any particular node and any of its neighbors can be identified readily by simple integer denumeration. Structured meshes, however, have the disadvantage that their size, which is normally taken to be uniform over the entire domain, is determined by the softest soil. This makes for unnecessarily fine meshes if the impedance contrast between the hardest and the softest materials is large, for any prescribed maximum frequency. In addition, if one uses explicit time integration schemes as is customary in wave propagation problems, the maximum allowable time step is controlled by the ratio of the mesh size and the velocities of wave propagation in the stiffest material. This means that one might be forced to use, due to stability requirements, a time step that is significantly smaller than that required for accuracy.

To circumvent these difficulties, analysts make use of unstructured meshes (with non-uniform mesh size), which allow one to tailor the mesh to the geometry of the valley and to the mechanical properties of the materials. The most common methods of this type are the unstructured finite differences based on an octree design and the finite element methods. For any given problem, an unstructured mesh will always have a much smaller number of nodes, especially if the problem involves both stiff and soft soils and rock, and hence, smaller systems of equations. On the other hand, the memory and communication links required to store an unstructured mesh are significantly greater than for a structured one. Thus, each technique has its advantages and disadvantages.

An unstructured finite difference methodology for studying seismic ground motion in large basins has recently been developed by Day and his co-workers (McLaughlin and Day, 1994; Magistrale *et al.*, 1996). They have already made a first attempt at simulating the ground motion in the San Fernando Valley, California, due to the 1994 Northridge earthquake (Day *et al.*, 1994).

Finite elements have been used only infrequently in seismology (e.g. Lysmer and Drake, 1972; Smith, 1975; Marfurt, 1984; Li *et al.*, 1992). Recently, Bielak and his colleagues have started the development of a finite element methodology on parallel architectures for modeling earthquake ground motion in large basins. A set of software tools, named Archimedes, has been developed for the purpose of shielding the application specialist form the details of high-performance computing. Archimedes is a special purpose compiler that supports the mapping of unstructured meshes computations arising from the solution of PDEs on parallel systems. It includes a mesh generator, a mesh partitioner, placement and routing heuristics, and code generator. It also includes provisions for support of absorbing boundaries used for minimizing wave reflections from the artificial domain boundaries and the effective forces by which the seismic excitation is introduced into the problem. This methodology is currently being used to simulate the seismic motion in the San Fernando Valley due to an aftershock of the 1994 Northridge earthquake for a model whose lowest shear wave velocity is 500 m/s, and a maximum frequency of 2 Hz. The model of the valley used for this study is one constructed by Magistrale and Day (1996).

Linear dependency of the wavefield on the harmonic term $\exp(-i\omega t)$, where $\omega = 2\pi f$, f is frequency, and $i^2 = -1$, allows one to seek the solution of the elastodynamics equations in terms of spatial coordinates and frequency. Many ingenious analytical solutions and numerical methods for computing ground motion developed arose from the necessity of either performing rapid calculations when no powerful computer capabilities were available, or to express fundamental mechanisms of wave propagation explicitly. For the details of these methods the reader is referred to the comprehensive review by Sánchez-Sesma (1996).

In the realm of incredibly fast - huge RAM supercomputers, the effort to find rapid solutions cannot be relegated to the past. The fact is that for some time supercomputing will be beyond the reality of many practical issues of earthquake engineering. Therefore, simplified, practical methods, which are already needed in engineering, will have to be developed to a large extent. Such practical devices will be calibrated and tested against data and the more rigorous techniques (e.g. Sánchez-Sesma *et al.*, 1988)

It is probably not a great exaggeration to affirm that Trifunac's closed form solutions for a 2-D semicircular valley (Trifunac, 1971) and canyon (Trifunac, 1973) are among the most frequently cited solutions on the subject of site effects computation. This is not only because of their direct applications, but because they have been used as benchmarks for testing the validity of new techniques designed to deal with more complex problems. Other analytical solutions as important, independently of computer availability, are the Thomson-Haskell (Thompson, 1950; Haskell, 1953; 1960; 1962), and the generalized coefficient method (Kennett, 1983), which allows complex sources embedded in layered media.

It is fair to say that these solutions have no disadvantages, as they are analytical solutions for a particular media, and can be combined with other methods to solve other circumstances of media complexity. Numerical methods in frequency domain have sprung profusely, since Aki and Larner (1970) introduced their discrete wave number computational scheme. In fact, the methods since then could well be organized into groups of wavenumber methods, boundary methods, asymptotic methods, and hybrid methods that combine them all. Significantly, along this line of reasoning we have the contributions of Bard and Bouchon (1980a, b) and Kawase and Aki (1989). Regarding other approaches based on the boundary element method, the reader is referred to Sánchez-Sesma and Luzón (1995).

We complete this section by suggesting the following tasks:

-continue the study of 3-D variations in soil properties, free-surface topography and underlying geological structure for frequencies of interest in earthquake engineering, using deterministic and random input sources. Dealing with realistic cases is desirable but not a restriction. Research using generic cases is crucial to characterize ground motion in terms of shape ratios (e.g. to which extent 2-D models are representative of 3-D motions ?), and input source (e.g. can representative ground motions be obtained from statistical analysis corresponding to random input motions ?). Important results for earthquake-resistant design must be identified.

-model near-source wavefields due to complex fault ruptures and use them as input to study the response of various types of building structures.

-establish the extent to which non-linear soil behavior limits the applicability of linear methods (e.g. have elastic small-strain ground motions any value in earthquake-resistant design ?)

SEISMIC ATTENUATION, INTENSITY, HAZARD

New data will introduce dramatic changes in our views of earthquake hazard. The human records of past earthquakes barely cover the last two centuries; only for some locations (e.g. China, Italy) such information span much further back into time. In some cases historical information is limited to define quantitative ground motion estimates. Promising results are coming from paleoseismological studies of well identified faults in which, through the use of precise dating methods, ancient ground motions can be inferred (*e.g.* Weldon II and Sieh, 1985; Fumal *et al.*, 1993). In any event, the blurred images of the past may help us to foresee what could happen in the future.

If new, more resistant and ductile materials are developed, the earthquake threat will be reduced. On the other hand, if the present trends towards earthquake disaster mitigation persist, it is quite likely that seismic ground motions will still frighten the last human being. But as Rick, the character played by H. Bogart in the famous film "Casablanca", it is quite certain that we, humans, "never plan that far ahead."

A major task for the immediate future is to continue with the analysis of existing data. Its importance is emphasized, for example, by the discovery of anomalous regional amplification of ground motion in the México plateau for subduction earthquakes (Ordaz and Singh, 1992). For some reasons, not yet understood, seismic waves are amplified in a wide frequency band along their path from the Pacific coast to México City. They also studied the first broad-band records obtained in the valley of México (Singh and Ordaz, 1993), and suggested that the long duration of motion at lake-bed sites in the valley is due to a very long continuous arrival of incoming waves to the valley, probably produced by multipathing or by the interaction of waves with crustal features. Such waves could not trigger the recorders at firm ground sites but, once amplified by the sediments, the ground motion could be recorded at lake-bed sites. This allows to see the problem of the long duration from another point of view and shifts the puzzle from the detailed response of the valley to the nature of incident waves. Further discussion of this issue is presented elsewhere (Singh *et al.*, 1995 and Sánchez-Sesma and Luzón, 1996).

Considering the changes of hazard scenarios, particularly those posed by blind-thrust faults, the work for future should include:

-using near-field data, to upgrade the attenuation laws prescribed by damage patterns and identify to which extent these are representative of seismic wave attenuation.

-to construct reliable (perhaps instrumental) measures of severity of ground shaking in terms of its potential to produce damage and investigate the relationship between such a measure with peak ground acceleration and duration of ground motion.

-can an explicit theoretical or empirical formula be obtained to describe such relationships ?

-to identify the factors that scatter the amplification factors estimated from spectral ratios. How can the uncertainties concerning the average values be reduced ? Are spectral ratios of any use ?

-to use GPS to monitor possible blind-thrust faults.

-to use Internet, not only to retrieve and gather data, but to standardize software for analysis and data processing.

CONCLUDING REMARKS

Presently, we continue to witness an impressive growth and development of urban environments. New cities are founded and existing ones grow to the point that the process implies many problems even to the extent of challenging their survival as organized communities. Besides environmental problems, the rapid growth of cities is sometimes accompanied by increased exposure to natural hazards. The potential for damage of moderate near-field earthquakes is at least as large as that from very large far-field seismic events. The 1995 Kobe and the 1985 Michoacán earthquakes, respectively, are, perhaps the most dramatic examples of these two kinds of events, having shown how important site effects can be.

Most of the earthquake-prone zones are well identified. But the real hazard is unknown in many cases. Potential site effects for many poorly-known geothechnical and geological situations are inferred with huge uncertainty margins. This neglect is probably fueled by an erroneous perception of the cost/benefit ratio, which is frequently invoked to justify low investment on research. Almost all the achievements of science and technology of this century are by-products of research; investing less may compromise the future. To put it in Rosenblueth's words: "the costs to perform a good research project are recompensed by the benefits to society."

In addition to an enormous death-toll of more than six thousand people killed by the January 17, 1995 Kobe earthquake the material losses amounted to more than 200 billion dollars. Typically, a medium-size research group on seismology and earthquake engineering may require, say, a million dollars per year (without overhead and other costs). That is to say, less than a 0.0005 percent of the actual material losses in Kobe. This attempts to give perspective on the huge amount of the material losses in a recent earthquake and the cost of studying the phenomenon. Allocating resources for disaster prevention may be a good investment. If no substantial effort is undertaken to actively promote research on the seismic threat, the future awaits us with endless disasters. We believe that strict adherence to building codes is our best option at present to mitigate the devastation by earthquakes. However, we must keep in mind that " ... there is no such a thing as the perfect code ...", as professor Rosenblueth used to point out. The search for developing better ways of translating scientific understanding into improved engineering practice must go on at an accelerated pace.

In connection with the Space Shuttle tragic accident of 1986, but with obvious resonances here, it is instructive to remember what R. Feynman, a distinguished physicist, wrote: "For a successful technology, reality must take precedence over public relations, for Nature cannot be fooled". Professor Rosenblueth knew of Feynman and once said of him: "a fine man..!"

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