SMIP01

SMIP01 SEMINAR ON
UTILIZATION OF STRONG-MOTION DATA

Los Angeles, California
September 12, 2001

PROCEEDINGS

Sponsored by

California Strong Motion Instrumentation Program
Division of Mines and Geology
California Department of Conservation

Supported in Part by

California Seismic Safety Commission
Federal Emergency Management Agency

The California Strong Motion Instrumentation Program (CSMIP) is a program within the Division of Mines and Geology of the California Department of Conservation and is advised by the Strong Motion Instrumentation Advisory Committee (SMIAC), a committee of the California Seismic Safety Commission. Current program funding is provided by an assessment on construction costs for building permits issued by cities and counties in California, with additional funding from the California Department of Transportation, the Office of Statewide Health Planning and Development, and the California Department of Water Resources.

In January 1997, a joint project, TriNet, between CDMG, Caltech and USGS was funded by the Federal Emergency Management Agency (FEMA) through the California Office of Emergency Services (OES). The goals of the project are to record and rapidly communicate ground shaking information in southern California, and to analyze the data for the improvement of seismic codes and standards.

In Northern California, CSMIP is partnering with UC Berkeley and U.S. Geological Survey. In October 2001, the California Office of Emergency Response will start to obtain funding for the California Integrated Seismic Network (CISN), a statewide system that includes the TriNet system. The CISN will improve seismic instrumentation and provide maps depicting the distribution of shaking intensity of ground shaking. It will also distribute and archive strong-motion records of engineering interest and seismological data for all recorded earthquakes, and provide training for users.

DISCLAIMER

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PREFACE

The California Strong Motion Instrumentation Program (CSMIP) in the Division of Mines and Geology of the California Department of Conservation promotes and facilitates the improvement of seismic codes and design practices through the Data Interpretation Project. The objective of this project is to increase the understanding of earthquake strong ground shaking and its effects on structures through interpretation and analysis studies of strong-motion data. The ultimate goal is to accelerate the process by which lessons learned from earthquake data are incorporated into seismic code provisions and seismic design practices.

Since the establishment of CSMIP in the early 1970s, over 900 stations have been installed, including 650 ground-response stations, 170 buildings, 20 dams and 60 bridges. Significant strong-motion records have been obtained from many of these stations. Significant strong-motion records have been obtained from the 1999 Hector Mine, the 1994 Northridge, the 1992 Landers, the 1992 Big Bear and the 1989 Loma Prieta earthquakes. These records have been and will be the subject of CSMIP data interpretation projects.

The SMIP01 Seminar is the 13th in a series of annual technical seminars designed to transfer recent interpretations and findings on strong-motion data to practicing seismic design professionals and earth scientists. The goal of the Seminar is to increase the utilization of strong-motion data in improving post-earthquake response, seismic design codes and practices.

In this seminar, investigators of two CSMIP-funded data interpretation projects will present the results from studies on shaking parameters for post-earthquake applications, and on development of guidelines for utilizing strong-motion data and ShakeMap in post-earthquake response. Invited speakers will present implications of data recorded in the 1999 Chi-Chi, Taiwan earthquake and 2001 Nisqually, Washington earthquake. In addition, there will be presentations on the TriNet/CISN engineering strong-motion data center and update on the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS). Professor James Brune of University of Nevada at Reno will present a luncheon address on precarious rocks and seismic hazard.

The papers in this Proceedings volume presented by the investigators of the CSMIP-funded data interpretation projects represent interim results. Following this seminar the investigators will prepare final reports with their final conclusions. These reports will be more detailed and will update the results presented here. CSMIP will make these reports available after the completion of the studies.

Moh J. Huang
Data Interpretation Project Manager

Note: The SMIP01 Seminar scheduled to be held in Los Angeles on September 12, 2001 was cancelled due to the tragic events of September 11. CSMIP is pleased to publish the proceedings for the Seminar.

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Representatives from each Subcommittee

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Los Angeles Airport Marriott Hotel, California
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IMPROVED SHAKING AND DAMAGE PARAMETERS FOR POST-EARTHQUAKE APPLICATIONS

Yousef Bozorgnia[1] and Vitelmo V. Bertero[2]

ABSTRACT

In this study, various ground shaking, response and damage parameters are examined for post-earthquake applications. Peak ground motion values, elastic response spectra, spectrum intensity, drift spectrum, inelastic spectra, and hysteretic energy spectrum are examined. Two improved damage spectra are also examined. The improved damage spectra will be zero if the response remains elastic, and will be unity when the displacement capacity under monotonic deformation is reached. Furthermore, the proposed damage spectra can be reduced to the special cases of normalized hysteretic energy and displacement ductility spectra. The proposed damage spectra are promising for various seismic vulnerability studies and post-earthquake applications.

INTRODUCTION

The objectives of this study are to examine various existing ground shaking, response and damage parameters and also to develop an improved damage parameter for post-earthquake applications. There are numerous ground shaking and damage parameters available. These include: peak ground acceleration, peak ground velocity, elastic response spectra, spectrum intensity, inelastic response spectra, interstory drift ratio, drift spectrum, hysteretic energy spectra, among others.

In this study the above parameters are examined. Additionally, improved *damage spectra* are introduced and examined in details. The damage spectra are based on normalized response quantities of a series of inelastic single-degree-of-freedom (SDOF) systems. They provide simple means for considering the demand and capacity related to strength, deformation and energy dissipation of the structural system. The proposed damage spectra will be zero if the structure remains elastic, and will be unity under the extreme condition of reaching the maximum deformation capacity under monotonically increasing lateral deformation. Following an earthquake, generation of near-real time contour maps of damage spectral ordinates can provide information on the spatial distribution of damage potential of the recorded ground motions for specified types of structures. Such maps can be useful for various post-earthquake applications, damage assessments, and emergency response; as well as for evaluation of the damage potential of earthquakes. Utilization of an up-to-date inventory of existing structures enhances the reliability of such maps in identifying the damaged areas.

Various ground shaking parameters as well as the proposed damage spectra are computed for hundreds of the ground motions recorded during the Northridge and Landers earthquakes.

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Additionally, these parameters are compared for specific cases of a seven-story reinforced concrete (RC) frame, and 17 low-rise ductile RC frames affected by the Northridge earthquake.

SHAKING AND DAMAGE PARAMETERS CONSIDERED

Following an earthquake, maps of the spatial distribution of the recorded and computed data are rapidly generated and posted on the Internet by TriNet (Wald, et al., 1999). These maps are used for a wide variety of post-earthquake applications. Currently six maps are generated: contour maps of peak ground acceleration (PGA), peak ground velocity (PGV), elastic spectral accelerations at periods 0.3, 1.0, and 3.0 seconds, and instrumentally derived seismic intensity. In this study the following other ground shaking, response and damage parameters are also examined.

Damage Spectrum: Structural performance or damage limit states can be quantified by *damage indices* (DIs). A damage index is a normalized quantity that will be zero if the structure remains elastic (i.e., no significant damage is expected), and will be one if there is a potential of structural collapse. Other structural performance states (such as minor, moderate and major damages) fall in between zero and one.

Damage spectrum represents variation of a damage index versus structural period for a series of SDOF systems subjected to a recorded ground motion. Bozorgnia and Bertero (2001) introduced *two improved DIs and their corresponding damage spectra to quantify damage potential of the recorded earthquake ground motions*. The improved damage spectra explicitly satisfy the structural performance definitions at the limit states of being zero and one. Details of the definitions and characteristics of these damage spectra are presented in the following section. Damage spectra for hundreds of horizontal accelerations recorded during the Northridge and Landers earthquakes are computed, and to demonstrate an application of such spectra, contour maps of damage spectral ordinates are plotted.

Displacement Ductility: Structural damage is usually associated with inelastic response rather than elastic structural behavior. *Displacement ductility*, μ, defined as the maximum displacement of an inelastic SDOF system divided by the yield displacement, is a measure of inelastic response. Ductility spectrum, which is the variation of μ with period, can provide some useful information about general inelastic response behavior. Characteristics of inelastic spectra and the contrasts between inelastic and elastic spectra have been extensively studied for various input ground motions (e.g., Newmark and Hall, 1982; Bertero, et al., 1978; Mahin and Bertero, 1981, among other studies). Ductility spectra for hundreds of horizontal ground accelerations recorded during the Northridge and Landers, California, earthquakes are computed for 20 structural periods ranging from 0.1 to 4.0 seconds, and contours of constant ductility are presented and examined.

Interstory Drift Ratio, or more properly ***Story Drift Ratio***: It is the ratio of the maximum story displacement over the story height. It has both practical and experimental significance as a measure of structural and non-structural damage. For example, for the purpose of *performance–based seismic design*, "SEAOC Blue Book" (SEAOC, 1999) has provided tentative values for drift ratios associated with different structural performance states. The interstory drift ratios demanded by the recorded ground motions are estimated using the calculated displacement ductility ratio.

Hysteretic Energy: E_H, is a measure of the inelastic energy dissipation demanded by the earthquake ground motion (Mahin and Bertero, 1981; Uang and Bertero, 1990; Bertero and Uang, 1992). Hysteretic energy includes cumulative effects of repeated cycles of inelastic response and, therefore, the effects of strong-motion duration are included in this quantity. If the response of the structure remains elastic, E_H will be zero. "Equivalent hysteretic energy velocity," $V_H = (2\ E_H/M)^{1/2}$ has also been used (Uang and Bertero, 1988), where M is the mass of the SDOF system. V_H spectra demanded by horizontal ground motions recorded in the Northridge and Landers earthquakes are also computed for a series of inelastic SDOF systems. Contours of constant V_H spectral ordinates are also plotted.

Housner Spectrum Intensity: Housner (1952) defined spectrum intensity (SI) as the area under the pseudo-velocity response spectrum over a period range of 0.1 to 2.5 seconds. It is a measure of the intensity of ground shaking for elastic structures (Housner, 1975). SI is computed for 5% damping for hundreds of horizontal ground acceleration records. Contour map of SI for the Northridge earthquake is also presented.

Drift Spectrum: This quantity represents maximum story drift ratio in multi-story buildings demanded by the ground motion (Iwan, 1997). The formulation is based on linear elastic response of a uniform continuous shear-beam model. It requires ground velocity and displacement histories as input motions. Drift spectra of the ground motions recorded during the Northridge earthquake are computed and contours of constant drift spectral ordinates are plotted.

There are other shaking parameters whose characteristics and effects directly or indirectly are included in the above parameters. For example, a parameter of interest is the duration of strong ground motion (Bolt, 1973; Trifunac and Brady, 1975). The effects of the strong-motion duration through repeated cycles of inelastic response are included in the hysteretic energy and damage spectra.

Another parameter of interest is Arias Intensity (Arias, 1970), which, in its commonly used version, is the area under the total energy spectrum in an undamped elastic SDOF system. Energy in SDOF systems is included in both V_H and damage spectra, and these parameters are evaluated over a wide range of natural periods.

In the following sections, descriptions of damage spectra and their characteristics are presented, followed by the results for the other shaking and response parameters.

DAMAGE SPECTRUM

In the following sections a brief overview of various damage indices are provided. Improved damage indices are then introduced and damage spectra are presented.

Review of Most Commonly Used Damage Indices

A damage index (DI) is based on a set of structural response parameters such as force, deformation and energy dissipation. One method of computing the DI is to compare the response parameters demanded by the earthquake with the structural "capacities" (Powell and Allahabadi, 1988). Traditionally, the "capacities" or ultimate values of the response parameters are defined in terms of their maximum values under monotonically increasing deformations. For example, a fraction of the ultimate deformation capacity of the system under monotonically increasing lateral deformation (u_{mon}) has been used as the deformation capacity during the earthquake motion.

There are different damage indices available. For example, damage index may be based on plastic deformation (e.g., Powell and Allahabadi, 1988; Cosenza, et al., 1993):

$$DI_{\mu} = (u_{max}-u_y)/(u_{mon}-u_y) = (\mu -1) / (\mu_{mon} - 1) \quad (1)$$

where u_{max} and u_y are the maximum and yield deformations, respectively, and u_{mon} is maximum deformation capacity of the system under a monotonically increasing lateral deformation. In equation (1) $\mu = u_{max}/u_y$ is displacement ductility demanded by the earthquake and $\mu_{mon} = u_{mon}/u_y$ is “monotonic ductility capacity”.

Displacement ductility alone does not reveal information on the repeated cycles of inelastic deformations and energy dissipation demand (e.g., Mahin and Bertero, 1981; Mahin and Lin, 1983). Hence, other structural response parameters such as hysteretic energy dissipation has also been used. Seismic input energy to a structural system (E_I) is balanced by (Uang and Bertero, 1988; and 1990):

$$E_I = E_H + E_K + E_S + E_{\xi} \quad (2)$$

where E_H , E_K , E_S and E_{ξ} are irrecoverable hysteretic energy, kinetic energy, recoverable elastic strain energy, and viscous damping energy, respectively. Hysteretic energy (E_H) includes cumulative effects of repeated cycles of inelastic response and is usually associated with the structural damage. If the response of the structure remains elastic, E_H will be zero, by its definition. For SDOF systems, Mahin and Bertero (1976; and 1981) defined normalized hysteretic energy $E_H/(F_y\, u_y)$ and its corresponding normalized hysteretic energy ductility:

$$\mu_H = E_H/(F_y\, u_y) + 1 \quad (3)$$

where F_y and u_y are yield strength and deformation of the system, respectively. Numerically μ_H is equal to the displacement ductility of a monotonically deformed equivalent elastic-perfectly-plastic (EPP) system that dissipates the same hysteretic energy, and has the same yield strength and initial stiffness as the actual system.

A damage index can be based on hysteretic energy. For example, for EPP systems, Cosenza, et al. (1993) and Fajfar (1992) used:

$$DI_H = [E_H/(F_y\, u_y)] / (\mu_{mon} - 1) = (\mu_H - 1) / (\mu_{mon} - 1) \quad (4a)$$

For a general force-deformation relationship, the above DI can be rewritten (Cosenza, et. al,1993):

$$DI_H = E_H / E_{Hmon} \quad (4b)$$

where E_{Hmon} is hysteretic energy capacity of the system under monotonically increasing deformation.

A combination of maximum deformation response and hysteretic energy dissipation was proposed by Park and Ang (1985):

$$DI_{PA} = (u_{max} / u_{mon}) + \beta\, E_H/(F_y\, u_{mon}) \qquad (5)$$

where $\beta \geq 0$ is a constant, which depends on structural characteristics. DI_{PA} has been calibrated against numerous experimental results and field observations in earthquakes (e.g., Park et al., 1987; Ang and de Leon, 1994). $DI_{PA} < 0.4$ to 0.5 has been reported as the limit of repairable damage (Ang and de Leon, 1994). Cosenza, et al. (1993) reported that experimental-based values of β have a median of 0.15 and for this value, DI_{PA} correlates well with the results of other damage models proposed by Banon and Veneziano (1982) and Krawinkler and Zohrei (1983). DI_{PA} has drawbacks; two of them will be mentioned here. First, for elastic response, when E_H=0 and the damage index is supposed to be zero, the value of DI_{PA} will be greater than zero. The second disadvantage of DI_{PA} is that it does not give the correct result when the system is under monotonic deformation. Under such a deformation, if the maximum deformation capacity (u_{mon}) is reached, the value of the damage index is supposed to be 1.0, i.e., an indication of potential of failure. However, as it is evident from (5), DI_{PA} results in a value greater than 1.0. Chai et al. (1995) modified DI_{PA} to correct the second deficiency of DI_{PA}, as mentioned above; however, the first deficiency of DI_{PA} was not corrected. Despite its drawbacks, DI_{PA} has been extensively used for different applications. This is, in part, due to its simplicity and its extensive calibration against experimentally observed seismic structural damage.

Improved Damage Indices

Bozorgnia and Bertero (2001) introduced two improved damage indices for a generic inelastic SDOF system. These damage indices are as follows:

$$DI_1 = [(1 - \alpha_1)\,(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_1\,(E_H/E_{Hmon}) \qquad (6)$$

$$DI_2 = [(1 - \alpha_2)\,(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_2\,(E_H/E_{Hmon})^{1/2} \qquad (7)$$

where,

$$\mu = u_{max} / u_y = \text{Displacement ductility} \qquad (8a)$$

$$\mu_e = u_{elastic} / u_y = \text{Maximum elastic portion of deformation} / u_y \qquad (8b)$$

= 1 for inelastic behavior; and

= μ if the response remains elastic

μ_{mon} is monotonic displacement ductility capacity, E_H is hysteretic energy demanded by the earthquake ground motion, E_{Hmon} is hysteretic energy capacity under monotonically increasing lateral deformation, and $0 \leq \alpha_1 \leq 1$ and $0 \leq \alpha_2 \leq 1$ are constants. Using the definition of hysteretic ductility μ_H (Mahin and Bertero,1976; and 1981) given in equation (3) for both earthquake and monotonic deformations, the new damage indices can be rewritten as:

$$DI_1 = [(1 - \alpha_1)\,(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_1\,(\mu_H - 1) / (\mu_{Hmon} - 1) \qquad (9)$$

$$DI_2 = [(1 - \alpha_2)\,(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_2\,[(\mu_H - 1) / (\mu_{Hmon} - 1)]^{1/2} \qquad (10)$$

For the special case of elastic-perfectly-plastic (EPP) systems:

$E_{Hmon} = F_y\,(u_{mon} - u_y)$ and $\mu_{Hmon} = \mu_{mon}$ (11)

$DI_1 = [(1 - \alpha_1)(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_1 (E_H/F_y u_y) / (\mu_{mon} - 1)$ (12)

$DI_2 = [(1 - \alpha_2)(\mu - \mu_e) / (\mu_{mon} - 1)] + \alpha_2 [(E_H/F_y u_y) / (\mu_{mon} - 1)]^{1/2}$ (13)

Few characteristics of the improved damage indices are listed below:

1) If the response remains elastic, i.e., when there is no significant damage, then $\mu_e = \mu$ and $E_H = 0$, and consequently both DI_1 and DI_2 will become zero. This is a characteristic expected for any damage index.

2) Under monotonic lateral deformation if $u_{max} = u_{mon}$, the damage indices will be unity. This is true for a general force-deformation relationship.

3) If $\alpha_1 = 0$ and $\alpha_2 = 0$, damage indices DI_1 and DI_2 (equations 6 and 7) will be reduced to a special form given in equation (1). In this special case, the damage index is assumed to be only related to the maximum *plastic* deformation.

4) If $\alpha_1 = 1$ and $\alpha_2 = 1$, damage indices DI_1 and DI_2 will be only related to the hysteretic energy dissipation E_H. Specifically, in this case, damage index DI_1 will be reduced to a special form given in equation (4b). If additionally the force-deformation relationship is EPP, damage index DI_1 given in (12) will be reduced to a special form given in equation (4a).

5) Equivalent hysteretic velocity V_H (Uang and Bertero, 1988) was defined as:

$V_H = (2\,E_H/M)^{1/2}$ (14)

where M is the mass of the system. It is evident from the definition of DI_2 given in (7) that DI_2 is related to the normalized equivalent hysteretic velocity. If V_H spectrum is already available, DI_2 can be easily generated.

<u>Development of Damage Spectra</u>

As mentioned before, damage spectrum of a recorded ground motion represents variation of a damage index versus structural period for a series of SDOF systems. Once a damage index, such as DI_1 and DI_2, is defined, damage spectrum can be constructed. The steps involved in developing the damage spectrum are summarized in Figure 1.

Examples of damage spectra are presented in Figure 2. This figure shows damage spectra for the 1940 Imperial Valley earthquake recorded at El Centro, and for the Northridge earthquake recorded at Sylmar County Hospital. For this figure, the following characteristics were used: viscous damping ?=5%; EPP force-displacement relationship; yield strength was based on elastic spectrum of UBC-97 (without near-source factors) reduced by R_d=3.4; also μ_{mon}=10, α_1= 0.269, α_2=0.302 were used. These values for α_1 and α_2 are based on an analysis of the Northridge earthquake records, as explained below. Computer program Nonspec (Mahin and Lin, 1983) was employed to compute the basic response parameters such as displacement ductility and hysteretic energy demands. DI_1 and DI_2 were then computed according to equations (12) and (13). The damage spectra for periods longer than 0.5 sec are plotted in Figure 2. For the structures with shorter periods, generally larger over-strength factor and μ_{mon} should be used. The contrast between the two damage spectra presented in Figure 2 is an evidence of very different damage potentials of these two ground motion records for the SDOF systems considered.

As mentioned previously, DI_{PA} has been already calibrated against numerous experimental and field cases. However, because of its deficiencies, it is not reliable at its low and high values. Thus, in the intermediate range of the damage index, a comparison between values of DI_1 with those of DI_{PA} can result in an estimate for α_1. Hence, the following procedure was used to estimate α_1: ductility and hysteretic energy spectra and DI_{PA} were computed at 20 structural periods ranging from 0.1 to 4.0 seconds using 220 horizontal ground acceleration records of the Northridge earthquake. Then coefficient α_1 was determined through regression analyses, i.e., by comparing values of DI_1 with those of DI_{PA} (for $0.2<DI_{PA}<0.8$). A similar process was repeated to estimate coefficient α_2 in DI_2. The same procedure was also carried out using 176 horizontal acceleration records of the 1992 Landers, California, earthquake. The computed α_1 and α_2 coefficients using the ground motion records of the Northridge and Landers earthquakes are listed in Table 1. Subsets of the results of the regression analyses for the Northridge earthquake are also graphically presented in Figure 3.

Effects of Strong-Motion Duration

Experimental studies have demonstrated that failures of structural members and systems are influenced by the number of inelastic cycles of response (e.g., Bertero, et al., 1977). In other words, structural systems generally become more vulnerable if they go through repeated cycles of inelastic motions. This generally occurs when the structure is subjected to a strong ground motion with a long duration. Hence, in quantifying damage potential of the recorded ground motion it is desirable to include the effects of strong ground motion duration.

Hysteretic energy E_H through its definition (e.g., Uang and Bertero, 1981) is a cumulative quantity. More cycles of inelastic deformations correspond to a larger value for the hysteretic energy dissipation. Thus, the effects of repeated cycles of inelastic response and strong-motion duration are reflected in E_H. Hence, in the damage indices that include hysteretic energy terms, the effects of repeated cycles of inelastic deformations and strong-motion duration are also included. An example of the duration effect on E_H and damage spectrum is shown in Figure 4.

In 1999 two major earthquakes occurred in Turkey: (1) on August 17, 1999 an earthquake of magnitude Ms 7.8; and (2) on November 12, 1999 another major earthquake of magnitude 7.5 (EERI, 2000). For both events, the ground accelerations were recorded at Duzce station. Figure 4 shows the ground accelerations recorded in these two events, with 10 seconds of zero ground acceleration added in between. Time variation of the hysteretic energy demand is also plotted in Figure 4. Damage spectra of the first and second events individually, as well as the damage spectrum of the combined acceleration records were computed and presented in Figure 4. The results shown in this figure are based on the same basic parameters as used in Figure 2 (except with $\mu_{mon}=8$, $a_1=0.286$ and include near-source factors). Displacement ductility spectra are also plotted in Figure 4. As it is expected, the time variation of the hysteretic energy clearly shows that E_H incorporates the cumulative effects due to the strong-motion duration. Because the damage spectrum includes E_H spectrum (see Figure 1), the damage spectrum is also influenced by the cumulative effects. Such an effect, however, is not included in the displacement ductility spectra. It should be noted that the effects of the sequence, and therefore the history, of different hysteretic loops are not considered in proposed damage spectra.

Attenuation of Damage Spectra

Once damage spectral ordinates for numerous ground motion records are computed, it is possible to evaluate the attenuation of damage spectra. Such an attenuation model can be used to estimate the variation of the damage spectral ordinates with site-to-source distance. To demonstrate the concept, attenuation of the damage spectral ordinates for the Northridge earthquake was computed. First, damage spectra for the horizontal accelerations recorded at alluvial sites during the Northridge earthquake were calculated for the same set of parameters as used for Figure 2. Then, regression analyses were performed on the following attenuation model:

$$\ln (DI_1) = a + d \ln [R^2 + c^2]^{1/2} + e \qquad (15)$$

where R is the closet distance from the site to the surface projection of the fault plane, e is a random error, and a, c, and d are the regression parameters to be computed. Site soil conditions at the recording stations and site-to-source distances were taken from a comprehensive ground motion database compiled by Campbell and Bozorgnia (2000) and Bozorgnia et al. (1999). The distance scaling of the damage spectral ordinates is shown in Figure 5. The median damage spectra for distances 3, 10, 20, and 40 km form the fault are also plotted in the same figure. It should be noted that the damage spectra shown in Figure 5 are based on the assumption that structural over-strength factor and μ_{mon} are constant over the period range. These factors, however, are possibly higher at short periods (e.g., for low-rise buildings) than those at long periods.

SPATIAL DISTRIBUTION OF VARIOUS PARAMETERS

For any specified structural characteristics and using the recorded ground motions at various recording stations, it is possible to rapidly generate damage spectra and plot their spatial distribution at selected periods. As an example, contours of damage spectral ordinates based on 220 horizontal accelerations recorded during the Northridge earthquake are plotted in Figure 6 for periods 1.0 and 3.0 seconds. For computation of damage spectra, the same basic parameters as Figure 2 were used, except μ_{mon} =12. Also, uniform basic structural characteristics over the area were assumed. Soil conditions at the recording stations were taken from the strong-motion database compiled by Campbell and Bozorgnia (2000) and Bozorgnia et al. (1999). The soil conditions were used to adjust F_y/W of the SDOF system at the recording site (see Figure 1). At each recording station the maximum of the damage spectral ordinates for the two horizontal components was taken. Figure 6 also shows the epicenter of the earthquake and the surface projection of the fault plane. Contour plots for DI_2 (not shown here) are very comparable to those plotted in Figure 6. As mentioned above, this figure is for uniformly distributed structural characteristics in the area, except for the adjustment of F_y/W for the local soil conditions. However, the distribution of the damage spectral ordinates can be modified to incorporate the data from an inventory of the existing structures in the area. For example, for buildings, data on the structural material, structural system, number of stories, age of the structure, etc. can be approximately translated into the basic structural data needed to generate damage spectra. If a better estimate of the spatial distribution of the basic structural characteristics is used, more realistic contour plots of the damage spectral ordinates can be generated.

Plotted in Figure 6 are also the distributions of the displacement ductility demanded by the recorded ground motion at periods 1.0 and 3.0 seconds. The same basic parameters were used as those for the damage spectral ordinates.

Given the displacement ductility, and consequently the maximum displacement of the SDOF system, interstrory drift ratio can be estimated. The following procedure was implemented: First, given the specified structural period, building height was estimated using the period-height relationship suggested by Goel and Chopra (1997) for reinforced concrete moment-resisting frames. For the purpose of estimating the drift, the smaller height estimated by the period formulas, was used. Then, the tentative guidelines provided by SEAOC (1999), Appendix I, were used to approximately estimate the interstory drift ratio. Figure 7 shows the contour plots of interstory drift demanded by the recorded ground motion.

Equivalent hysteretic velocity V_H (equation 14) is directly related to the hysteretic energy dissipation demanded by the recorded ground motion. As mentioned before, the effects of cycles of inelastic response and strong-motion duration are included in V_H, as well as in the damage spectra. As an example, distribution of V_H spectral ordinates at a period of 1.0 second is also shown in Figure 7.

Housner spectrum intensity (Housner, 1952; and 1975) for 5% damping was also computed for the horizontal accelerations recorded in the Northridge earthquake. At each recording station, maximum of the spectrum intensities of the two horizontal components was taken. Spatial distribution of the spectrum intensity is also shown in Figure 7.

Drift spectrum (Iwan, 1997) is a measure of maximum interstory drift ratio using a linear shear-beam model. Contours of drift spectral ordinates at the base level of the structure at periods 1.0 and 3.0 seconds for 5% damping ratio are shown in Figure 8. Computation of the drift spectra requires ground velocity and displacement histories (Iwan, 1997). To avoid any distortion of long-period information, the available velocity and displacement histories of the near-source records without band-pass filtering were used (Iwan, 1995). This may be one possible source of the difference between the drift plots in Figures 7 and 8.

Selected results for the Landers earthquake are also shown in Figure 9. This figure shows the damage spectral ordinates DI_1, with the same SDOF characteristics as used in Figure 2, except for μ_{mon}=12, and a_1=0.316. Again, a uniform distribution of structural characteristics in the area was used. The fault trace and the epicenter of the earthquake are also mapped in the figure. Displacement ductility and interstory drift ratio at period 1.0 second are also presented in this figure. For the computation of the interstory drift ratio, the same procedure was used as that for Figure 7.

Various contour plots in Figures 6-9 reveal information about different measures of the severity of the recorded ground motion at different locations. Some of them also reveal more information about performance of a set of simple structural models subjected to the recorded ground motion. One obvious advantage of the spectral damage contour plots is that they conveniently represent normalized values. For example, compare the contour plots of the damage spectral ordinates with displacement ductility demands. In order to compare them, ranges of ductility values need to be correlated to various structural performance descriptions (such as “operational”, “life safe”, “near collapse”, etc.). Using, for example, such a tentative correlation given in SEAOC (1999), Appendix I, contour plots of the damage spectra and displacement ductility are generally consistent. However, the damage spectral plots, representing a normalized quantity, are more convenient for post-earthquake applications. Additionally, as mentioned before, they include more features of the inelastic response than most of the other parameters considered.

COMPARISON OF PARAMETERS FOR SPECIFIC CASES

Ground shaking and damage parameters considered were compared for specific cases. This section presents a summary of the comparison.

Van Nuys seven-story hotel is an instrumented building which experienced major structural damage during the Northridge earthquake (California Seismic Safety Commission, 1996; Moehle, et al., 1997). The structure is a seven-story reinforced concrete frame building constructed in 1966 and no seismic retrofit work was performed prior to the Northridge earthquake. The details of the building are reported by California Seismic Safety Commission (1996), and Moehle, et al. (1997). Structural damage was primarily restricted to the longitudinal perimeter frames, and the damage included column shear failures, and immediately after the earthquake the building was “red tagged”. Various ground motion and damage parameters were computed using the recorded accelerations at ground level in EW direction. For the damage spectrum, basic structural characteristics were taken from the previous detailed analyses (California Seismic Safety Commission, 1996; Moehle, et al., 1997). In a reverse process, having assigned a damage index of 0.8 (for a “near collapse” damage state), value of μ_{mon} was estimated for different values of a_1 and a_2. Summary of the results are given in Table 2. A range of 4.2 to 5.6 was computed for μ_{mon}. Compared with the results of the previous detailed nonlinear analyses, this seems a reasonable range. Computed drift ratio of 1.3%, estimated by both inelastic SDOF and drift spectrum analyses, is also within the range of 1.2 to1.9% based on the recorded motions of the building. This example shows that it is possible to estimate the damage spectrum with a good accuracy, if the needed basic structural characteristics are accurately estimated.

Another case study is a set of 17 low-rise (1 to 3-story) ductile moment-resisting reinforced concrete frame buildings constructed between 1979 and 1990. These buildings were affected by the Northridge earthquake. Singhal and Kiremidjian (1996) assigned damage indices (DIs) to these buildings. These assigned DIs were based on the reported repair costs, not rehabilitation costs, and not based on direct field observations. The assigned DIs are very low -- an indication that the damage to these buildings was not severe. The highest reported DI is 0.26 for building #17 located at about 1.8 km from the Rinaldi Receiving Station (RRS). For each building, the closest free-field recording station located at the same general soil category was identified in the present study. Using the recorded motions various shaking and damage parameters were computed. Regression analyses were performed to compare the computed and assigned values of the damage indices, and to estimate μ_{mon}. The results, although very scattered, all indicate that in order to obtain the very low assigned DIs, the values of μ_{mon} and/or over-strength factor should be very high. This is conceptually consistent with the general understanding that the available global ductility and over-strength factor for low-rise ductile buildings are high. Another observation is that the recorded motion at RRS, which is close to building #17, is a very strong motion by almost all measures. For example, the peak horizontal ground acceleration (PGA) is 0.84g, peak ground velocity (PGV) is 159 cm/sec (Iwan, 1997), elastic spectral ordinates between periods 0.3-0.5 sec exceed about 1.7g, spectrum intensity for 5% damping is 456cm, and drift spectrum for 5% damping at 0.3-0.5 sec is between 1.5 and 2.26%. However, as mentioned before, the assigned damage index is low (Singhal and Kiremidjian, 1996) indicating no significant damage.

Consider, for example, spectrum intensity at RRS (456 cm) and that at the Van Nuys seven-story building (174 and 230 cm, for the motion at the building base and free-field record, respectively). Purely based on this parameter, more damage may be expected at the site of building #17 than the Van Nuys seven-story building. This is due to the fact that strength, deformation and energy dissipation capacities of the structures are important factors in controlling the response, and therefore the damage. These factors, however, do not have any influence on the computed values of, e.g., elastic spectral ordinates or spectrum intensity. Hence, such parameters alone cannot accurately predict the observed damage.

CONCLUDING REMARKS

In this study several ground shaking, response and damage parameters were computed and examined. Two improved damage spectra and their characteristics were also examined. The parameters considered in this study can be classified into the following categories:

- *Parameters that are purely measures of free-field ground motion*. These include PGA and PGV, which are amongst the most important parameters measuring severity of the ground motion. However, they are independent of any data about the behavior of structural systems. Therefore, besides their other limitations, these parameters *alone* have limited capabilities to accurately predict damage.

- *Parameters that are related to the elastic response of SDOF and shear-beam models*. These include elastic spectral ordinates, spectrum intensity, and drift spectrum. Although these are also very important measures and their applications have been extensive, they do not include effects of inelastic structural response and repeated cycles of inelastic deformations, which are generally associated with damage.

- *Inelastic response spectra in the forms of displacement ductility, interstory drift ratio, and strength spectra*. These parameters reveal some fundamental features of inelastic response; however, the effects of number of cycles of inelastic response and duration of strong ground motion are not included.

- *Spectrum of hysteretic energy dissipation due to plastic deformations, and its associated equivalent hysteretic velocity spectra*. These parameters include some fundamental features of inelastic response as well as the effects of repeated cycles of inelastic deformations and strong ground motion duration. However, in order to use these parameters for rapid damage assessments and post-earthquake applications, they have to be normalized with the energy dissipation capacity of the structure.

- *Damage spectrum*. It is based on normalized response quantities of a series of inelastic SDOF systems. The improved damage spectra presented here are based on promising damage indices (DIs). The proposed damage spectra explicitly satisfy two important conditions: They will be zero if the response remains elastic, i.e., no significant damage is expected; and will be unity when the maximum deformation capacity is reached under monotonically increasing lateral deformation. Larger damage spectral ordinates conceptually correspond to larger damage. Another characteristic of the proposed damage spectra is that by varying a coefficient (a_1 in DI_1, or a_2 in DI_2), they are reduced to the commonly used normalized hysteretic energy and displacement ductility spectra. Also, the damage spectra, in their general form, are influenced by the repeated cycles of inelastic deformations and strong-motion duration. Although the proposed DIs may be further improved to include other features of inelastic response, they are more reliable indices than other commonly used DIs such as DI_{PA}.

The proposed damage spectra can be used to quantify the damage potential of the recorded ground motion and relate that to seismic structural performance categories. They are also effective quantities for post-earthquake applications and rapid identification of the damaged areas based on the recorded ground motions and the type of construction. Utilization of an up-to-date inventory of existing structures enhances the reliability of spatial distribution of the damage spectra.

ACKNOWLEDGEMENTS

This study was supported by the California Department of Conservation, Division of Mines and Geology, Strong Motion Instrumentation Program, Contract 1099-733. The support is gratefully acknowledged. The authors are grateful to Dr. Ken Campbell for providing soil and ground motion information at the sites of low-rise concrete buildings affected by the Northridge earthquake, and Dr. Ajay Singhal for extracting the construction dates of the same set of buildings. The authors also wish to thank Prof. Bill Iwan for providing the routine for computation of the drift spectrum, and Prof. Mustafa Erdik for supplying the ground motion records at Duzce, Turkey. Constructive comments by the members of California Strong-Motion Instrumentation Advisory Subcommittees are fully appreciated.

REFERENCES

Ang, A.H-S., and D. de Leon (1994). “Reliability and response control of R/C buildings,” *Proceedings, ASCE Structures Congress XII*, Vol. 2, pp. 1593-1599.

Arias, A. (1970). “A measure of earthquake intensity,” in *Seismic Design for Nuclear Power Plants*, R.J. Hansen, Editor, MIT Press.

Banon, H., and D. Veneziano (1982). “Seismic safety of reinforced concrete members and structures,” *Earthquake Engineering and Structural Dynamics*, Vol.10, pp.179-193.

Bertero, V.V., S.A. Mahin, and R.A. Herrera (1978). “Aseismic design implications of near-fault San Fernando earthquake records,” *Earthquake Engineering and Structural Dynamics*, Vol.6, pp.31-42.

Bertero, V.V., E.P. Popov, T.Y. Wang, and J. Vallenas (1977). “Seismic design implications of hysteretic behavior of reinforced concrete structural walls,” *Proceedings, 6th World Conference on Earthquake Engineering*, India, Vol. II, pp.1898-1904.

Bertero, V.V., and C-M Uang (1992). “Issues and future directions in the use of an energy approach for seismic-resistant design of structures,” in *Nonlinear Seismic Analysis and*

Design of Reinforced Concrete Buildings, Edited by P. Fajfar and H. Krawinkler, pp. 3-22.

Bolt, B.A. (1973). "Duration of strong ground motion," *Proceedings, 5th World Conference on Earthquake Engineering*, Rome, pp. 1304-1313.

Bozorgnia, Y., and V.V. Bertero (2001). "Evaluation of damage potential of recorded earthquake ground motion," *96th Annual Meeting of Seismological Society of America*, San Francisco, CA, April 17-21, 2001.

Bozorgnia, Y., K.W. Campbell, and M. Niazi, M.(1999). "Vertical ground motion: Characteristics, relationship with horizontal component, and building code implications," *Proceedings, SMIP99 Seminar on Utilization of Strong-Motion Data*, San Francisco, pp. 23-49.

California Seismic Safety Commission (1996). "1994 Northridge Earthquake Building Case Studies Project." *Report SSC 94-06*, Proposition 122, Product 3.2, State of California Seismic Safety Commission, Sacramento, CA.

Campbell, K.W., and Y. Bozorgnia (2000). "New empirical models for predicting near-source horizontal, vertical, and V/H response spectra: Implications for design," *Proceedings, 6th International Conference on Seismic Zonation*, Palm Springs, CA.

Chai, Y.H., K.M. Romstad, and S.M. Bird (1995). "Energy-based linear damage model for high-intensity seismic loading," *ASCE Journal of Structural Engineering*, Vol. 121, No.5, pp. 857-864.

Cosenza, E., G. Manfredi, and R. Ramasco (1993). "The use of damage functionals in earthquake engineering: A comparison between different methods," *Earthquake Engineering and Structural Dynamics*, Vol. 22, pp.855-868.

EERI (2000). "1999 Kocaeli, Turkey, earthquake reconnaissance report," *Earthquake Spectra*, Supplement to Vol. 16.

Fajfar, P. (1992). "Equivalent ductility factors, taking into account low-cycle fatigue," *Earthquake Engineering and Structural Dynamics*, Vol. 21, pp.837-848.

Goel, R.K., and A.K. Chopra (1997). "Period formulas for moment-resisting frame buildings." *ASCE Journal of Structural Engineering*, Vol. 123, No. 11, pp. 1454-1461.

Housner, G.W. (1952). "Spectrum intensities of strong-motion earthquakes," *Proceedings, Symposium on Earthquake and Blast Effects on Structures*, Edited by C.M. Duke and M. Feigen.

Housner, G.W. (1975). "Measures of severity of earthquake ground shaking," *Proceedings, U.S. National Conference on Earthquake Engineering*, Ann Arbor, Michigan, pp.25-33.

Iwan, W.D. (1995). "Drift demand spectra for selected Northridge sites," *Report No. 95-07*, Earthquake Engineering Research Lab., California Inst. of Technology.

Iwan, W.D. (1997). "Drift spectrum: Measure of demand for earthquake ground motions," *ASCE Journal of Structural Engineering*, Vol.123, No.4, pp.397-404.

Krawinkler, H., and M. Zohrei (1983). "Cumulative damage in steel structures subjected to earthquake ground motion," *Computers and Structures*, Vol. 16, pp.531-541.

Mahin, S.A., and V.V. Bertero (1976). "Problems in establishing and predicting ductility in aseismic design," *Proceedings, International Symposium on Earthquake Structural Engineering*, St. Luis, Missouri, August 1976, pp 613-628.

Mahin, S.A., and V.V. Bertero (1981). "An evaluation of inelastic seismic design spectra," *ASCE Journal of Structural Division*, Vol. 107, No. ST9, pp. 1777- 1795.

Mahin, S.A, and J. Lin (1983). "Construction of inelastic response spectra for single-degree-of-freedom systems" *Report UCB/EERC-83/17*, Earthquake Engineering Research Center, University of California, Berkeley.

Moehle, J.P., Y.R. Li, A. Lynn, and J. Browning (1997). "Performance assessment for a reinforced concrete frame building," *Proceedings, NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, Vol. III-A, pp.140-156.

Newmark, N.M., and W.J. Hall (1982). "Earthquake spectra and design," *Monograph*, Earthquake Engineering Research Institute (EERI).

Park, Y.J., and A.H-S. Ang (1985). "Mechanistic seismic damage model for reinforced concrete," *ASCE Journal of Structural Engineering*, Vol. 111, No.4, pp.722-739.

Park, Y.J., A.H-S. Ang, and Y.K. Wen (1987). "Damage-Limiting aseismic design of buildings," *Earthquake Spectra*, Vol. 3, No.1, pp.1-26.

Powell, G.H. and R. Allahabadi (1988). "Seismic damage prediction by deterministic methods: Concepts and procedures," *Earthquake Engineering and Structural Dynamics*, Vol. 16, pp.719-734.

SEAOC (1999). "Recommended Lateral Force Requirements and Commentary," *Report*, Seismology Committee, Structural Engineers Association of California, 7th Edition.

Singhal, A., and A.S. Kiremidjian (1996). "A method for earthquake motion-damage relationships with application to reinforced concrete frames." *Report No. 119*, The John A. Blume Earthquake Engineering Center, Stanford University.

Trifunac, M.D., and A.G. Brady (1975). "A study on the duration of strong earthquake ground motion." *Bulletin of Seismological Society of America*, Vol. 65, No. 3, pp.581-626.

Uang, C-M, and V.V. Bertero (1988). "Implications of recorded earthquake ground motions on seismic design of building structures," *Report No. UCB/EERC-88/13*, Earthquake Engineering Research Center, University of California, Berkeley.

Uang, C-M, and V.V. Bertero (1990). "Evaluation of seismic energy in structures," *Earthquake Engineering and Structural Dynamics*, Vol. 19, pp.77-90.

Uniform Building Code (1997). International Conference of Building Officials, Whittier, CA, Volume 2.

Wald, D., J., V. Quitoriano, T.H. Heaton., H. Kanamori, C.W. Scrivner, and C.B. Worden (1999). "TriNet "ShakeMaps": Rapid generation of peak ground motion and intensity maps for earthquakes in southern California," *Earthquake Spectra*, Vol. 15, No.3, pp.537-555.

Table 1—Results of Regression Analyses to Estimate a_1 and a_2

ß	**μ_{mon}**	**a_1 Northridge EQ**	**a_2 Northridge EQ**	**a_1 Landers EQ**	**a_2 Landers EQ**
0.10	8	0.206	0.273	0.238	0.280
0.15	8	0.286	0.332	0.316	0.331
0.20	8	0.364	0.385	0.378	0.380
0.10	10	0.185	0.243	0.231	0.245
0.15	10	0.269	0.302	0.296	0.297
0.20	10	0.350	0.354	0.357	0.344

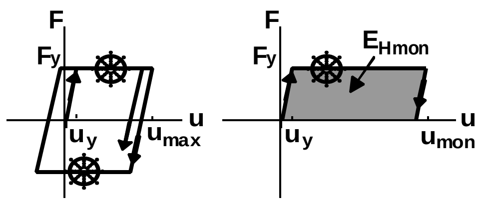
Table 2—Summary of the Recorded and Computed Data, Van Nuys Seven-Story Hotel, Northridge Earthquake

Peak Accel. (g)	**Elastic Spectrum (g) at 1.5 sec**	**Damage Spectrum at 1.5 sec**	**μ_{mon}**	**Interstory Drift Ratio (%)(*)**	**Rel. Roof Disp. / Bldg Height (%) Based on Recorded Bldg Accelerations**	**Drift: 3^{rd}-2^{nd} Flrs (%) Based on Recorded Bldg Accelerations**	**Drift Spectrum at 1.5 sec (%)(**)**	**Spectrum Intensity (cm)(***)**
0.45	0.46	0.8	4.2 – 5.6	1.3	1.2	1.9	1.3	174

(*) Computed using SDOF response
(**) At Base level, for 5% damping
(***) Using the recorded accelerations at the ground level of the building (EW). From free-field contours: 230 cm

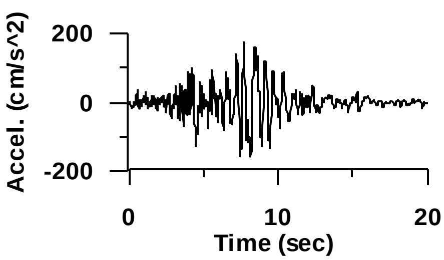
DAMAGE SPECTRUM

Given: A series of single-degree-of-freedom systems with:
- Period T (sec)
- Damping ratio ξ
- Site soil condition "S" (soil category)
- Strength; specified according to a seismic code: $(F_y/W) = (S_a/g)/R_d$
- A force-deformation relationship:



- E_{Hmon} ("monotonic hysteretic energy capacity") or, for elastic-perfectly-plastic (EPP): μ_{mon} ("monotonic ductility capacity")

Subjected to an earthquake ground acceleration record:



Compute:
- Ductility spectrum (μ)
- Hysteretic energy spectrum (E_H)

Develop Damage Spectrum:
- By combining μ and E_H spectra:

$$DI_1 = [(1 - \alpha_1)(\mu - \mu_e)/(\mu_{mon} - 1)] + \alpha_1 (E_H/E_{Hmon})$$

For special case of EPP systems:

$$DI_1 = [(1 - \alpha_1)(\mu - \mu_e)/(\mu_{mon} - 1)] + \alpha_1 (E_H/F_y{*}u_y)/(\mu_{mon} - 1)$$

where $0 \le \alpha_1 \le 1$ is a constant; μ_e= max. elastic deformation/u_y

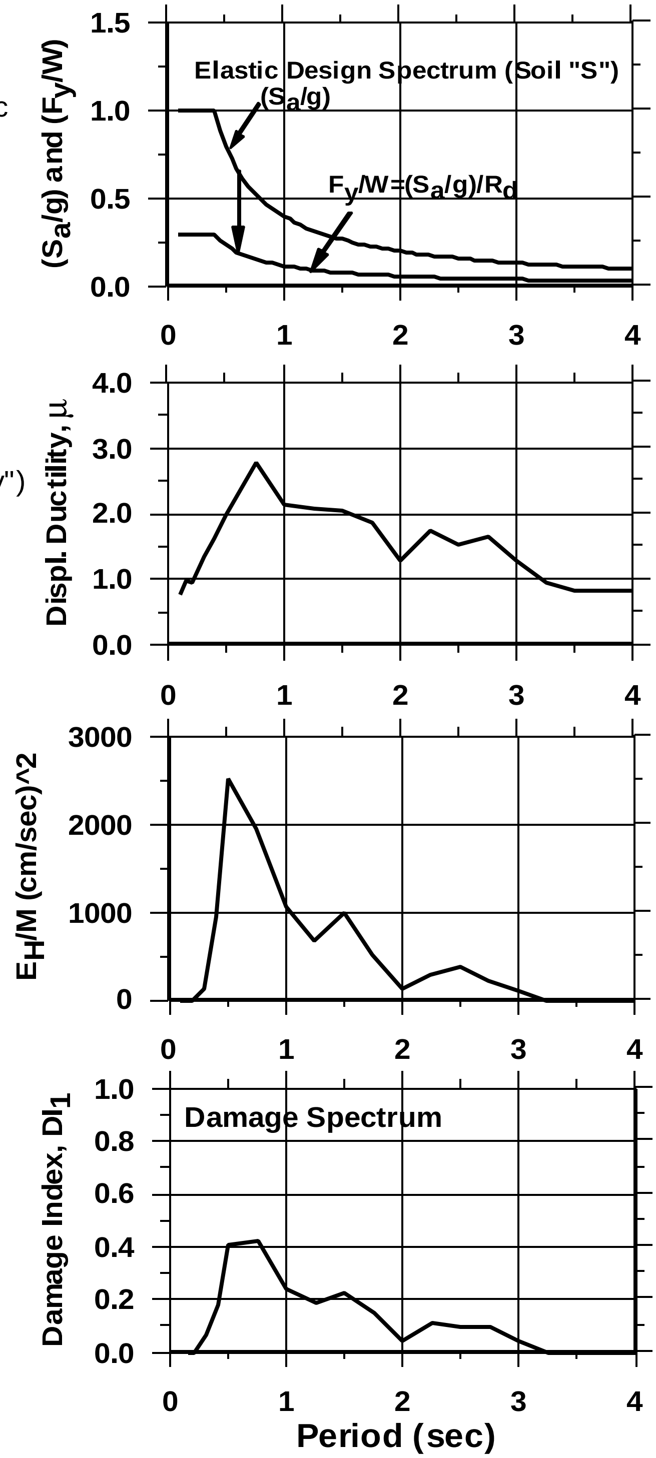


Figure 1: Summary of steps involved in developing *Damage Spectrum*

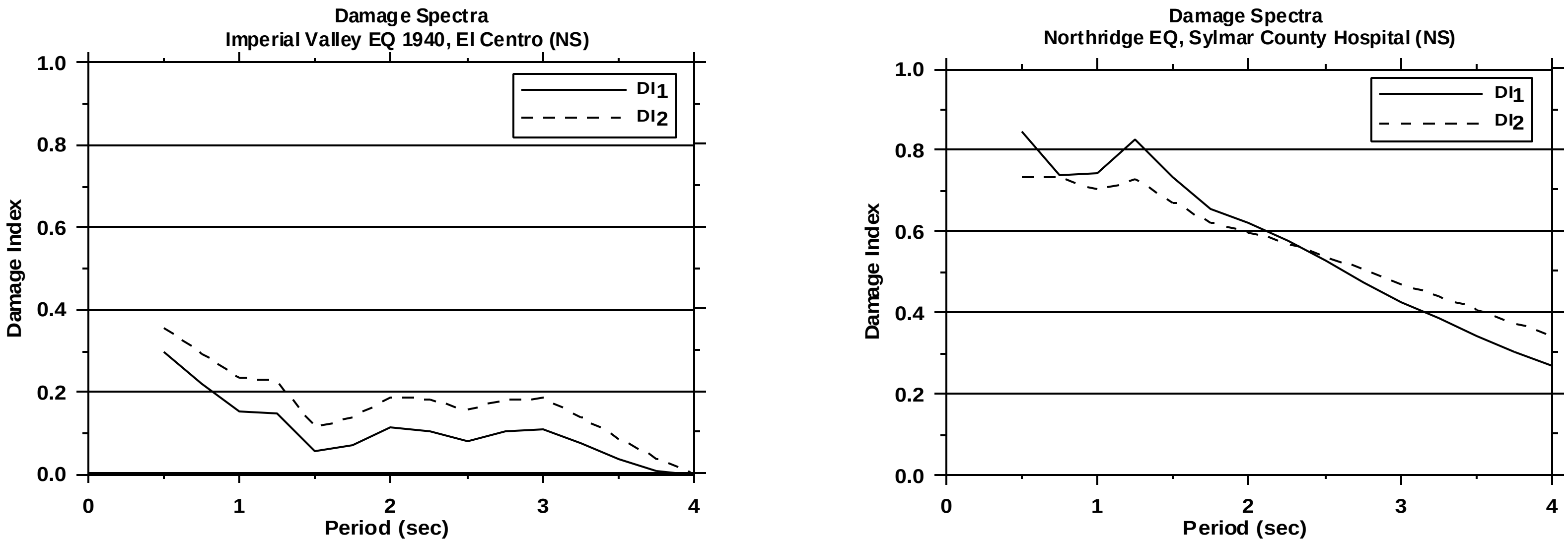


Figure 2: Examples of damage spectra, considering ξ=5%, μ_{mon}=10, and EPP behavior.

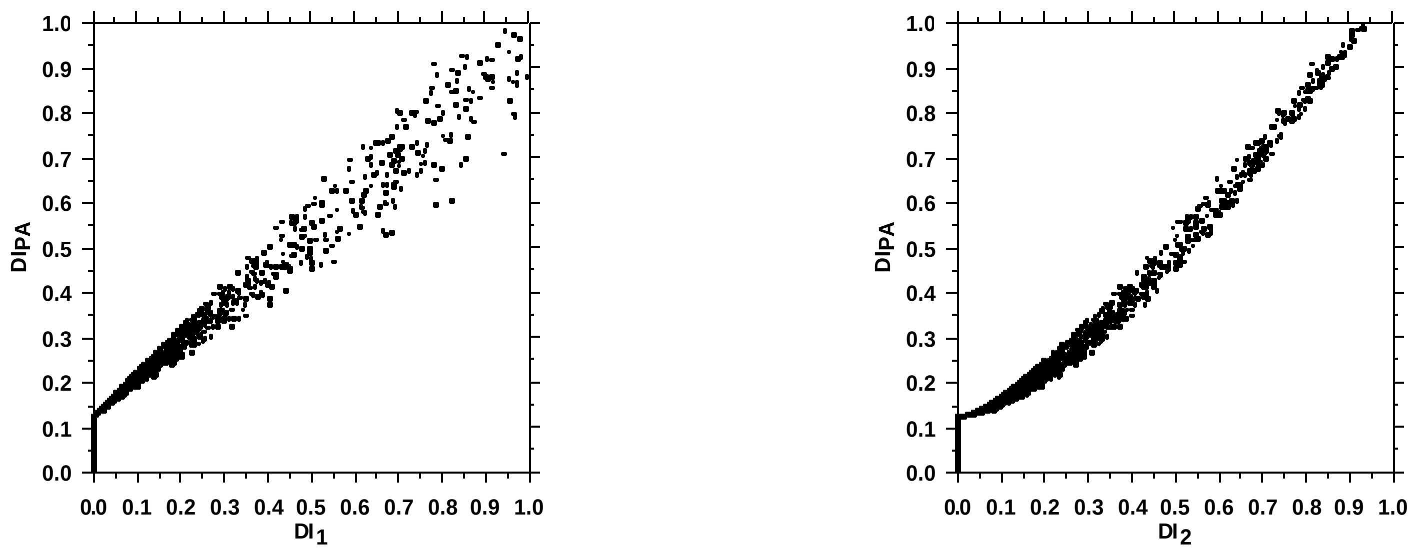


Figure 3: Example of correlation between damage indices (DI_1, DI_2) and DI_{PA}: Northridge EQ records, with β=0.15, α_1=0.286, α_2=0.332, μ_{mon}=8, ξ=5%.

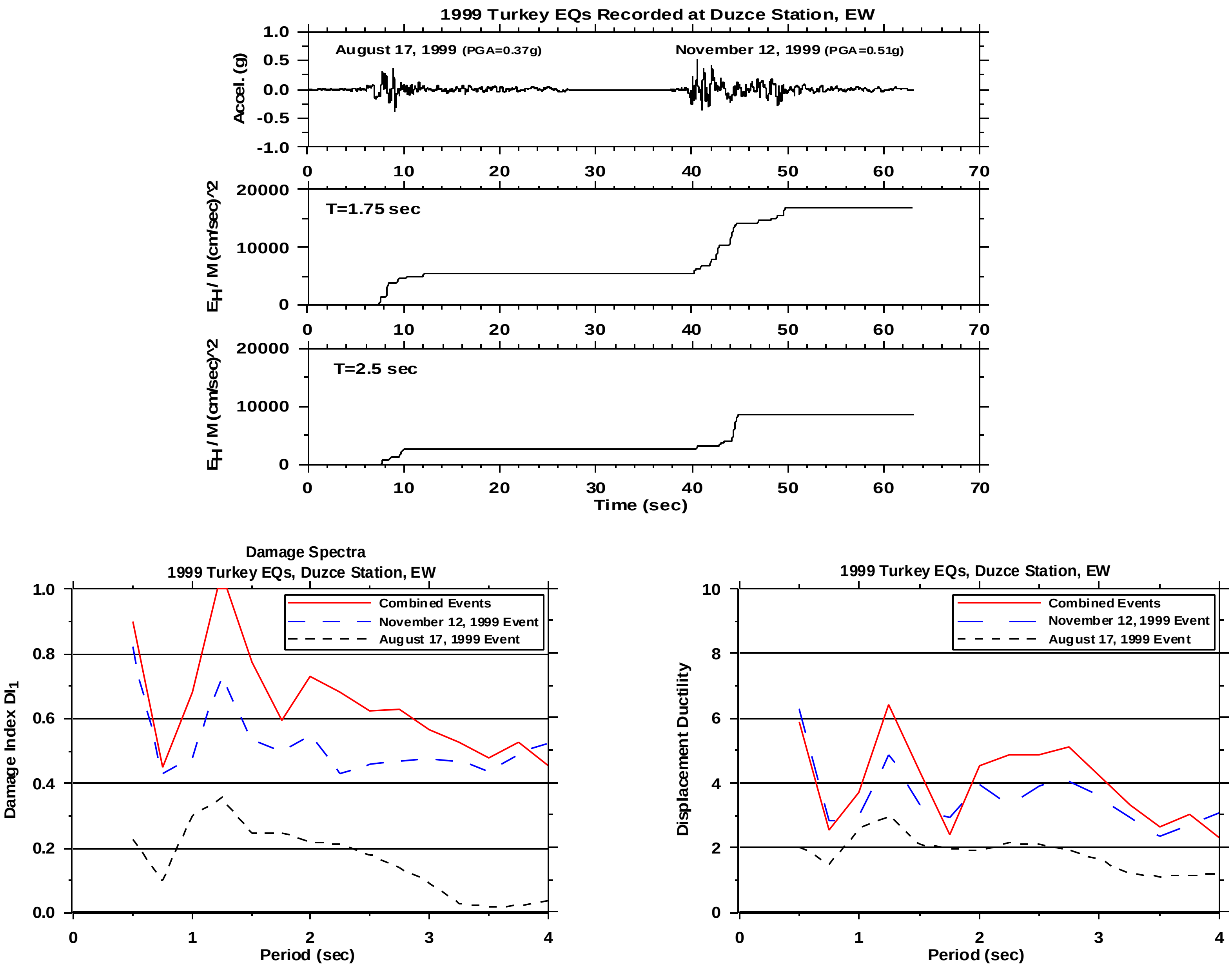


Figure 4: Ground accelerations at Duzce (Turkey); hysteretic energy demands; damage spectra; and displacement ductility.

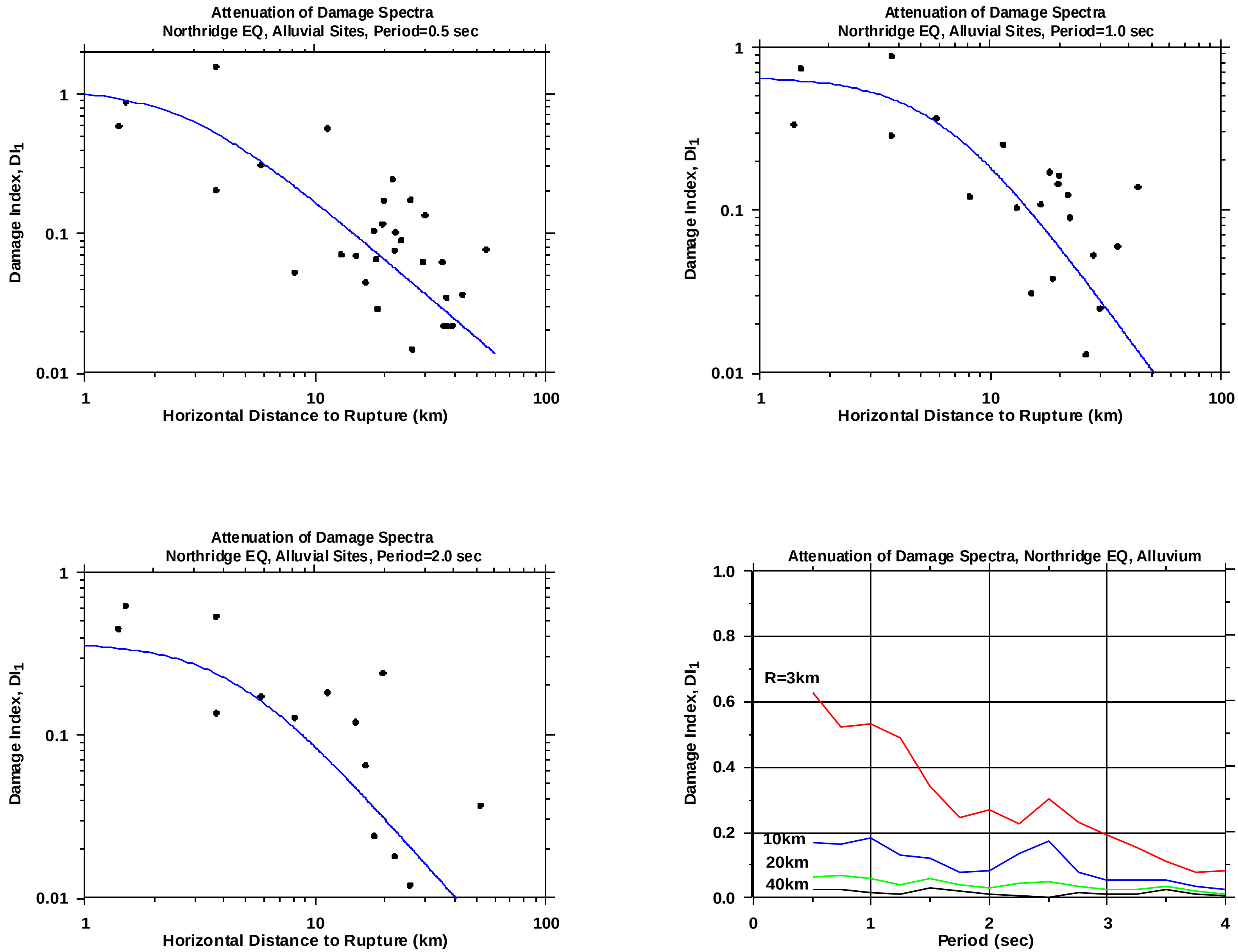


Figure 5: Distance scaling of damage spectral ordinates for the Northridge earthquake at alluvial sites.

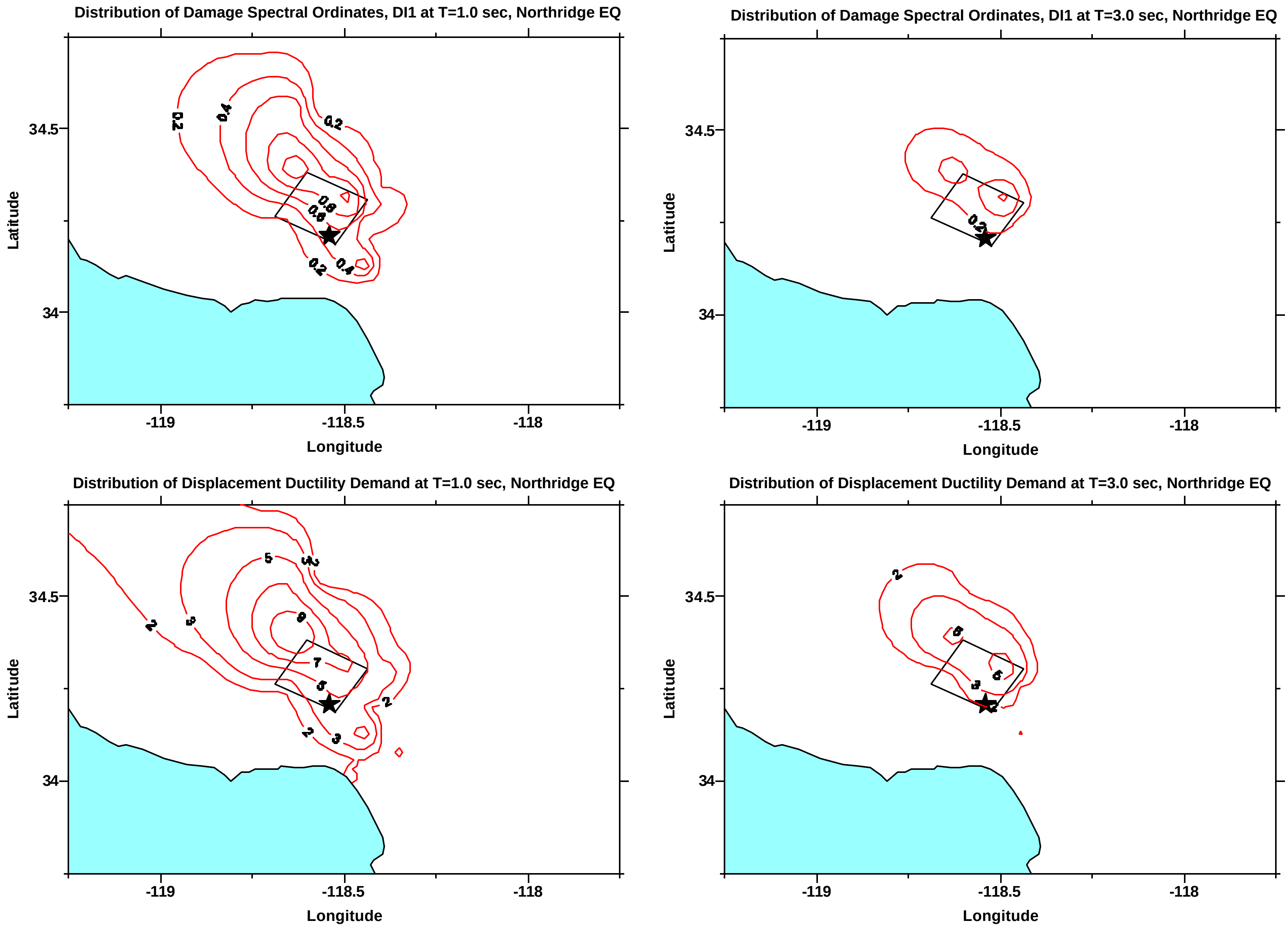


Figure 6: Distribution of damage spectral ordinates and displacement ductility demands of the ground motions recorded during the Northridge earthquake, T=1 and 3 sec.

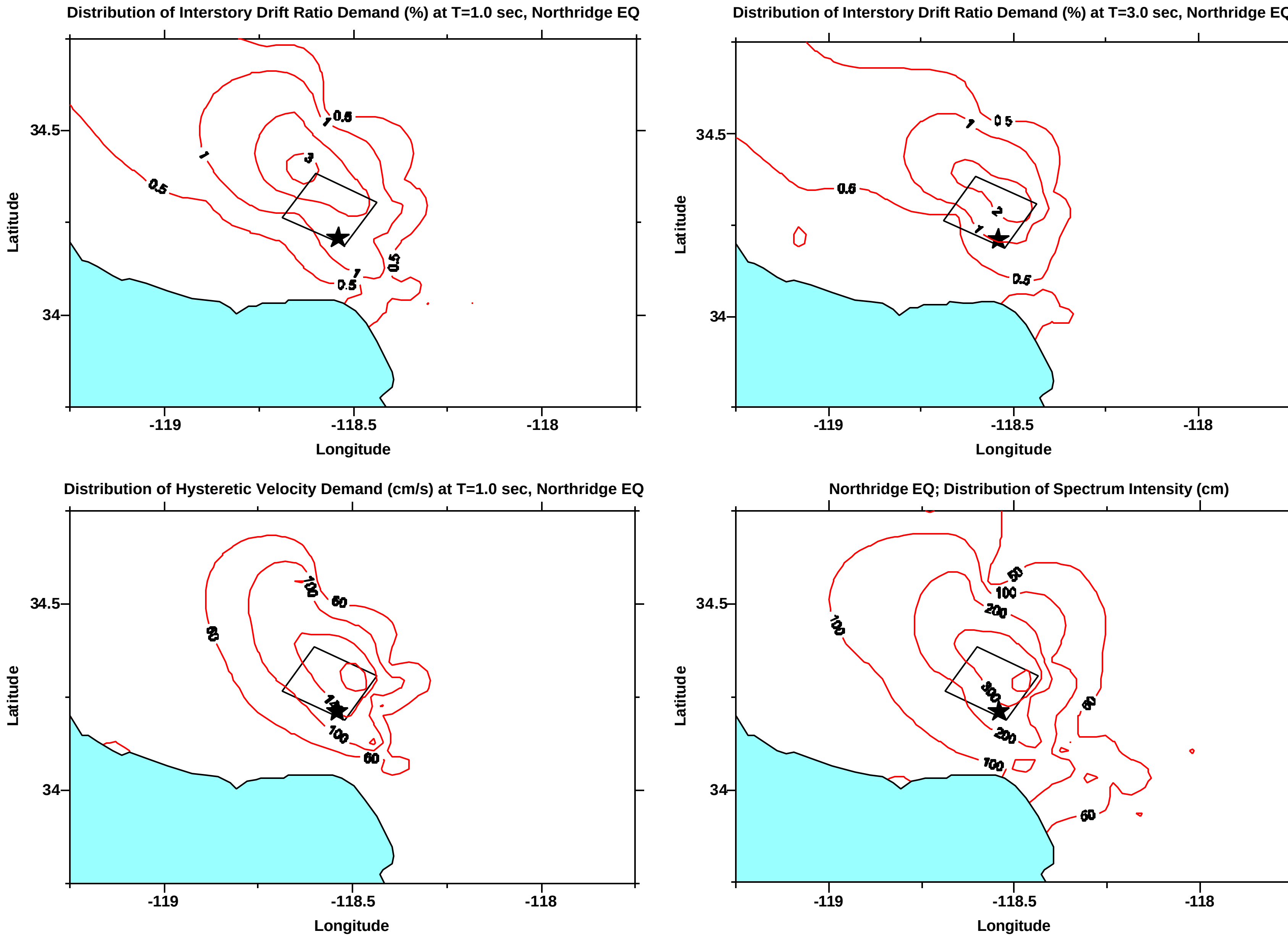


Figure 7: Distribution of interstory drift ratio demand (T= 1, 3 sec); hysteretic velocity demand (T=1 sec) and spectrum intensity, Northridge earthquake.

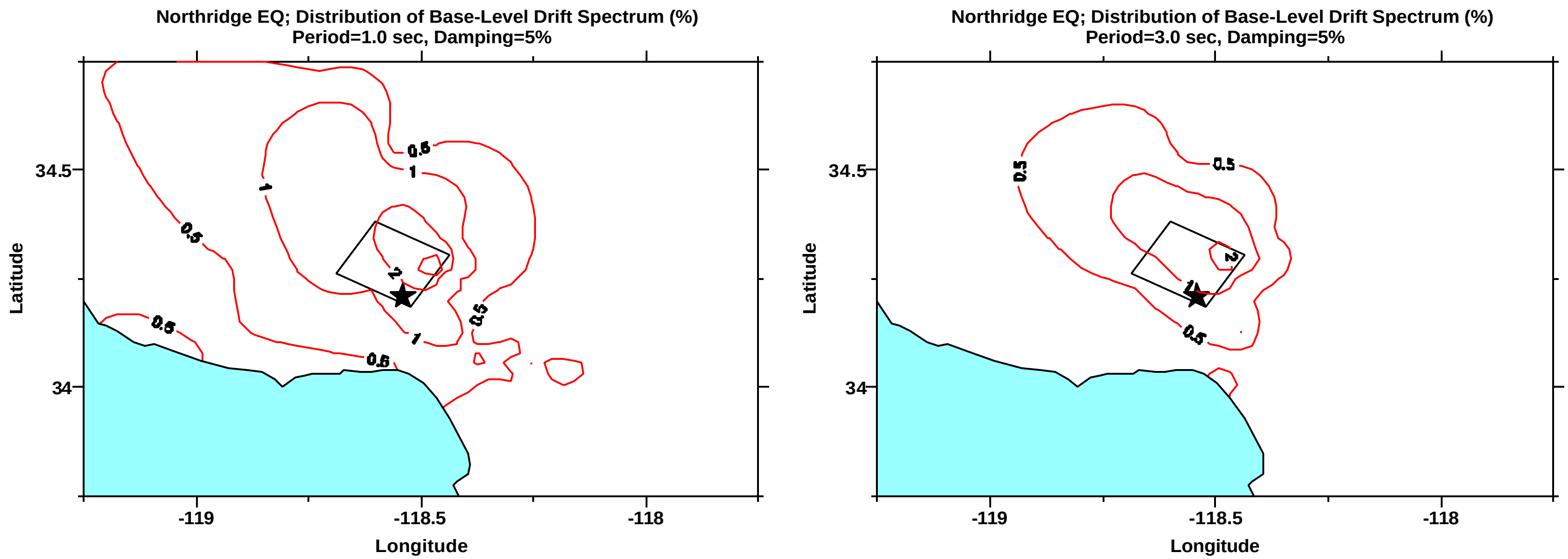


Figure 8: Distribution of drift spectral ordinates at base-level, Northridge earthquake, T=1, and 3 sec.

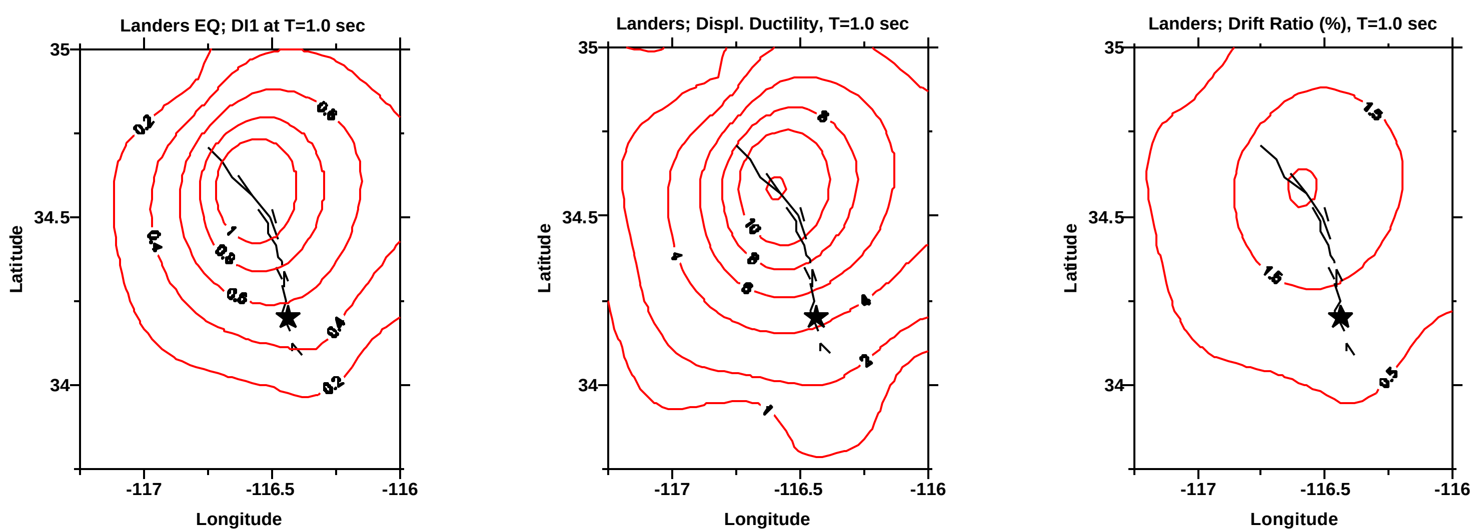


Figure 9: Distribution of damage spectral ordinates, displ. ductility and interstory drift ratio demands, Landers earthquake, T=1 sec.

Implications of Ground Motion Data Recorded in the M7.6 Chi-Chi, Taiwan Earthquake of September 21, 1999

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ABSTRACT

A disastrous earthquake took place in central Taiwan at 01:47 of September 21, 1999 (Taiwan local time). The Seismology Center of the Central Weather Bureau (CWB) located the epicenter near the town of Chichi, Nantou County . The magnitude of this earthquake was M_L 7.3 (CWB) and M_W 7.6 (NEIC). The earthquake has caused heavy casualties and building damages: 2,539 people killed or missing, 11,306 people injured; 51,751 household units totally collapsed, 54,406 household units partially collapsed. In addition, there were widespread destruction and disruption of lifelines, including roads and bridges, water supply, gas supply, communication and electricity. The Chi-Chi, Taiwan earthquake produced a rich set of 441 strong ground motion recordings. In this paper we present some results from analysis of these recordings.

First, we found that the overall level of the observed horizontal peak ground acceleration (PGA) values was relatively low (about 50% less) when compared with what would be predicted for an earthquake of the same magnitude by existing attenuation models based on worldwide data. High horizontal PGA values at sites on the hanging wall and within 20 km of the surface fault ruptures are notable exceptions. The horizontal PGA values are indistinguishable among the four different site classes. However, the horizontal PGA values in Taipei Basin, Ilan Plain, and Hwalien areas are significantly higher than the average at similar distances. Unlike the horizontal PGA, the observed horizontal peak ground velocity (PGV) values are relatively high (at least 100% higher) when compared with what would be predicted for an earthquake of the same magnitude by an existing PGV attenuation model based on worldwide data. Thus, as far as peak ground motion parameters are concerned, the Chi-Chi earthquake may be called a high-PGV, low-PGA earthquake.

Next, we analyzed the 5% damped acceleration response spectrum shapes for the four different site classes B, C, D, and E, in order to study possible dependence of the response spectrum shape on local site conditions. It is found that the peak spectral amplification factor ranges between 2.3 and 2.5 for all four classes of site conditions. In general, the response spectrum shape for Class B sites on soft rocks older than the Pliocene age has spectral amplification for periods up to about 1.5 seconds. The spectral amplification of Classes C and D sites on stiff soils occurs over periods up to about 2.0 seconds. The spectral amplification of Class E sites on soft soils occurs over periods up to about 3.0 seconds. The response spectrum shapes for Taipei Basin and Ilan Plain are quite similar to Class E sites, whereas Hwalien area is similar to Class C or D sites.

Finally, we analyzed the observed characteristics of acceleration response spectra from 44 near-fault sites. For the eight sites within 2 km from the surface fault ruptures, the median horizontal PGA value is about 0.5 g. The corresponding spectral peak is about 1.0 g. The median-plus-one-standard-deviation horizontal PGA value is about 0.7 g and the corresponding spectral peak is

about 1.8 g. Thus, for sites within 2 km from the surface fault ruptures, application of a scaling factor of 1.5 to the current seismic design spectrum anchored at a PGA value of 0.33 g for Zone 1A appears to be appropriate. For the 18 sites located at 2 to 10 km from the surface fault ruptures, the median horizontal PGA value is about 0.25 g. The corresponding peak spectral value is about 0.6 g. The median-plus-one-standard-deviation horizontal PGA value is about 0.4 g and the corresponding peak spectral value is about 0.8 g. Thus, for sites between 2 and 10 km from the surface fault ruptures, the current seismic design spectrum anchored at a PGA value of 0.33 g for Zone 1A appears to be adequate. For the 33 sites at 10 to 20 km from the surface fault ruptures, the median horizontal PGA value is about 0.18 g and the corresponding peak spectral value is about 0.45 g. The median-plus-one-standard-deviation horizontal PGA value is about 0.3 g and the corresponding peak spectral value is about 0.7 g. Thus, for sites located between 10 and 20 km from the surface fault ruptures, the current seismic design spectrum anchored at a PGA value of 0.33 g for Zone 1A is more than adequate.

Introduction

On September 21, 1999 at 1:47 Taiwan local time (September 20, 17:47 GMT), the central Taiwan area was hit by a disastrous earthquake of M_L magnitude 7.3 (the Seismology Center of the Central Weather Bureau (CWB). The Mw magnitude of the earthquake was 7.6 (NEIC). The epicenter of the event was located at 120.82^{o}E, 23.85^{o}N. The focal depth was about 8 km (Shin et al., 2000). This was the largest earthquake to strike central Taiwan in this century.

This earthquake was caused by sudden rupture of the Chehlungpu fault. Both the unusually large surface fault displacements and the very strong ground shakings caused enormous destruction. The most severely devastated areas were in Nantou and Taichung Counties as well as Taichung City in central Taiwan. The most strongly shaken area has about 1.2 million residents. It also caused significant casualties and damages in other cities and counties both in central and northern Taiwan. According to latest official reports, a total of 2,489 people were killed, 11,306 injured, 51,751 household units totally collapsed, 54,406 houldhold units partially collapsed. There were 50 people still missing. This was the second most disastrous earthquake in Taiwan history, after the April 21,1935 earthquake of M_L 7.1 which occurered just north of the Chi-Chi earthquake and killed 3,276 people in Taichung and Miaoli counties.

Values Of Rapid Earthquake Information

At 102 seconds after the earthquake, the Taiwan Rapid Earthquake Information Release System (TREIRS) operated by the Seismology Center of the Central Weather Bureau recorded and located automatically the time, location magnitude of the earthquake. The information provided to the public also included recorded intensity data at many locations throughout Taiwan (Wu et al., 1998, 1999). The availability of rapid and reliable earthquake information was instrumental to the formation of the National Emergency Operation Center immediately to mobilize and deploy search-and-rescue personnel and relief materials to the impacted areas even in the middle of the night.

Figure 1 shows the locations of seismic stations in the Taiwan Rapid Earthquake Information Release System. Figure 2 shows the target times, modes, and intended recipients of rapid earthquake information. It aimed to have intensity information available in one minute, location and magnitude information available in three minutes. The information is disseminated by Pager, e-mail, fax, internet and ftp. The information is sent to the Central Fire Administration, City and County Fire departments, other government agencies and officials, and news media. Figure 3 shows the actual CWB earthquake report for the Chi-Chi earthquake. The system was also extremely valuable in providing rapid and reliable information about strong aftershocks and earthquakes in other areas in the days following the Chi-Chi earthquake. The people, both inside and outside the disaster areas, were very frightened by then. Timely and reliable earthquake information greatly helped to calm people and to prevent rumors.

Surface Ruptures Of The Causative Chehlungpu Fault

By dawn in the morning immediately following the earthquake, many geologists rushed to the epicenter areas to make reconnaissance surveys of possible surface fault ruptures. It was soon discovered that the Chehlungpu fault was the culprit of the earthquake. It slipped almost continuously, although sinuously, along its whole length extending southward from Fengyuan in the northern end to Tongtou in the southern end. Soon later, splays of NE-trending surface fault ruptures were found extending northeastward from Fengyuan toward Shihkang. Total length of the surface fault ruptures was estimated at about 100 km (Central Geological Survey, 1999). Figure 4 shows the location of the Chehlungpu fault and the amount of slips along the fault. Photos 1 to 4 show destruction of some structures caused by the fault ruptures. The structures destroyed included a dam (photo 1), bridges (photo 2), schools (photo 3), houses (photo 4), etc.

Both uplift and left-lateral strike-slip displacements were observed at most outcrop locations. It is clear that the Chehlungpu fault was an oblique thrust fault. This was consistent with the fault-plane solution obtained by the first motion polarities and moment tensor inversions as shown in Figure 4. It is remarkable that the amount of slips increased persistently from a little over one meter in the southern end and to almost ten meters observed near the northern end of the fault. Figure 5 shows the regional geology of the surrounding areas (Lee et al., 1999). The Chehlungpu fault clearly marks the boundary between the Pliocene and Quaternary formations. An E-W section across the fault at the bottom of the figure shows a series of imbricated thrust faults dipping to the east. The Chehlungpu fault is just one of them. Figure 4 also shows the locations of background seismicity and strong aftershocks of the Chi- Chi earthquake. It is seen that most aftershocks took place far away from the Chehlungpu fault in the zones of active background seismicity east of the Chelnungpu fault. The zones of active background seismicity appeared to define the boundaries of the displaced crustal block. Figure 4 additionally shows the velocity waveforms of the E-W component integrated from original acceleration records at seven stations happened to align along the fault trace. It is seen from the differential timings among the big pulses that the fault rupture started from the hypocenter first and then propagated toward the north and south. The rupture velocity can be estimated at about 2 km/sec. The big pulse near the northern end was significantly enhanced due to rupture directivity.

The Chehlungpu fault was a product of plate collision in Taiwan area. Figure 6 shows the configurations of the Philippine Sea plate and the Eurasian plate in Taiwan area. It is seen from the figure that the two plates collide with each other along the Taitung Longitudinal Valley. The Philippine Sea plate subducts northward under the Eurasian plate in northeastern Taiwan. In the meantime, The Eurasian plate is subducting eastward under the Philippine Sea plate in southeastern Taiwan.

Figure 7 shows the GPS measurement results on the velocity of crustal movement in Taiwan (Yu et al., 1997). The Philippine Sea plate is seen to move northwestward toward Taiwan at a velocity of more than 8 cm/year. It is noted that the crustal velocity decreases progressively westward, causing compression across most of the island of Taiwan and resulted in series of imbricated faults, as shown previously in Figure 5.

Strong Ground Motion Peak Values And Permanent Displacements

The Chi-Chi earthquake was well recorded by 441 high-quality free-field strong-motion accelerographs. Figure 8 shows the locations of these recording instruments at different geologic site conditions. The recording sites were classified into four classes, namely B, C, D, and E, according to geologic age (Lee, et al., 2001). Figure 9 shows distributions of the recorded horizontal peak ground acceleration (PGA) values along with the total fatalities of each county or city. It can be seen that the PGA values are significantly higher at sites along the Chehlungpu fault and in the areas to the east of the fault than other areas. This was due to its thrust faulting mechanism that often caused stronger ground motions on the hanging wall block (Abrahamson and Somerville, 1996). This ground motion feature was closely correlated with the distribution of fatality rates in the meizoseismal area, as shown in Figure 10 below.

Figure 10 shows the total fatalities and fatality rates in individual townships, as well as the seismic intensity distribution in the near-fault areas in central Taiwan. It is apparent that all large fatalities took place in the towns experiencing seismic intensity greater than 250 gals. This pattern becomes even clearer when we look at the distribution of the fatality rate. We use the necessary population data from the demographic summary for 1999 (National Office of Statistics, 2000b). The fatality rates in towns experiencing more than 400 gals ranged from 0.054% to 1.112%, whereas the fatality rates were all below 0.002% in towns experiencing less than 250 gals. The only notable exception in this lower intensity zone was the town of Yuanlin in Changhua County where a fatality rate of 0.019% occurred. It was found that severe liquefaction had caused collapse of many buildings in this town (National Center for Research in Earthquake Engineering, 1999).

Figure 11 shows the plot of horizontal PGA values as function of the closest distance to the seismogenic zone, according to Campbell's definition (Campbell, 1997). The data points are plotted according to the four site classes. In addition, the data points from the Taipei Basin, Ilan Plain, and Hwalien areas are plotted separately. In the figure we also plot the Campbell's median and median +/- one standard deviation PGA curves for M_W 7.6 that are modified by multiplying a factor of 0.55 to fit the data points. From the figure we can see the slope of Campbell's curve fit quite well with the data points from the Chi-Chi earthquake. However, the Campbell's curves would significantly overestimate relative to the actual PGA values. It is noted that the PGA values from the Taipei Basin, Ilan Plain, and Hwalien area are significantly higher than the rest of the data set. This was probably due to the basin amplification effects.

Figure 12 shows the integrated horizontal peak ground velocity (PGV) values in cm/sec. It can be seen that the PGV values are significantly higher at sites along the Chehlungpu fault and in the areas to the east than in other areas. This was again due to its thrust faulting mechanism that often caused stronger ground motions on the hanging wall block.

Figure 13 shows the plot of horizontal PGV values as function of the closest distance to the seismogenic zone, according to Campbell's definition (Campbell, 1997). The data points are plotted according to the four site classes. In addition, the data points from the Taipei Basin, Ilan Plain, and Hwalien areas are plotted separately. In the figure we also plot the Campbell's median and median +/- one standard deviation PGV curves for M_W 7.6 that are modified by multiplying a factor of 2.18 to fit the data points. From the figure we can see the slope of Campbell's curve fit quite well with the actual data points from the Chi-Chi earthquake. However, the Campbell's curves would significantly underestimate relative to the actual PGV values. It is noted that the PGV values from the Taipei Basin, Ilan Plain, and Hwalien areas are significantly higher than the rest of the data set. This was probably due to basin amplification effects.

Figure 14 shows the distribution of integrated horizontal permanent displacement (PD) in meters. In the figure we also show the displacement values measured by GPS (Yu, 1999). It is found that the two sets of measurements are highly consistent with each other. This is the first time that permanent co-seismic ground displacements were observed by so many accelerographs. From the figure we can see very clearly the horizontal displacement vectors of the hanging wall block rotate clockwise in direction from south to north and increase in magnitude from about 2 meters in the south to almost 10 meters in the north. These displacement vectors are also consistent with the dislocations observed from the surface fault ruptures. Figure 15 shows the original accelerograms and the integrated velocity and displacement waveforms observed at the Shihgang station (TCU068). The records indicate the fault displaced smoothly and quickly near its northern end.

Figure 16 shows the first-order estimation of the dip-slip and strike-slip displacements in the southern, central and northern segments of the Chelungpu fault. Figure 17 compares the observed and calculated horizontal and vertical displacements across the southern, central and northern segments of the fault. The fittings are reasonably close.

Dependence Of Response Spectrum Shape On Local Site Conditions

In the following we analyzed the 5% damped acceleration response spectrum shapes for four different site classes B, C, D, and E in order to study possible dependence of response spectrum shape on local site conditions. For the sake of easy comparison, we use four modified seismic design spectrum shapes for soil Types 1,2,3 and Taipei Basin sites, respectively. They are obtained by replacing the constant value of 1.0 at long periods (T) on current seismic design spectra in the Taiwan Building Code (TBC) with a 1/T function. In addition, the amplification factor is increased from 2.0 to 2.5 for the modified design spectrum for Taipei Basin in current Taiwan Building Code (TBC).

Figure 18 shows the normalized response spectrum shape for Class B sites on rocks of Miocene age or older, as well as the four modified seismic design spectrum shapes. The observed median curve has spectral amplification over periods up to about 1.5 seconds. It is similar to the modified seismic design spectrum for Type 2 sites in the current Taiwan Building Code (TBC). For periods greater than 1 second the observed median curve is clearly below the modified TBC spectrum level. The peak spectral amplification factor is about 2.3.

Figure 19 shows the normalized response spectrum shape for Class C sites on soft rocks of Pliocene or early Pleistocene ages, as well as the four modified seismic design spectrum shapes. The observed median curve has spectral amplification over periods up to about 2.0 seconds. It is similar to the modified seismic design spectrum for Type 3 sites in the current Taiwan Building Code (TBC). For periods shorter than 5 seconds the observed median curve follows closely with the modified Type 3 spectrum. The peak spectral amplification factor is about 2.4.

Figure 20 shows the normalized response spectrum shape for Class D sites on stiff soils of late Pleistocene age or younger, as well as the four modified seismic design spectrum shapes. The observed median curve has spectral amplification over periods up to about 1.7 seconds. It is similar to the modified seismic design spectrum for Type 3 sites in the current Taiwan Building Code (TBC). For periods greater than 1.5 seconds the observed median curve is clearly below the modified TBC Type 3 spectrum level. The peak spectral amplification factor is about 2.3.

Figure 21 shows the normalized response spectrum shape for Class E sites on soft soils of Holocene age or younger, as well as the four modified seismic design spectrum shapes. The observed median curve has spectral amplification over periods up to about 3.0 seconds. It follows closely but falls slightly below the modified seismic design spectrum for Taipei Basin sites in the current Taiwan Building Code (TBC). For periods greater than 4.0 seconds the observed median curve deviates more below the modified TBC Taipei Basin spectrum level. The peak spectral amplification factor is about 2.4.

In summary, we have seen clear dependence of the response spectrum shape on local site conditions from the recordings of the Chi-Chi earthquake. The median spectrum shape of Class B sites is similar to the modified Type 2 seismic design spectrum in current TBC. The median spectrum shapes of Classes C and D sites are similar to the modified Type 3 seismic design spectrum in current TBC. Finally, the median spectrum shape of Class E sites is similar to the modified Taipei Basin seismic design spectrum in current TBC.

Near-Fault Ground Acceleration Response Spectra

Finally, we analyzed the observed acceleration response spectra from 64 near-fault sites to study their characteristics. Figure 22 shows the response spectra for the 9 sites within 2 km from the surface fault ruptures. The observed median response spectrum has a horizontal PGA value of about 0.5 g and a corresponding spectral peak of about 1.0 g. The median-plus-one-standard-deviation horizontal PGA value is about 0.7 g and the corresponding spectral peak is about 1.8 g. In the figure are shown the three modified TBC seismic design spectra anchored at a PGA of 0.33 g. It is found that the observed median curve for sites located within 2 km of the surface fault ruptures matches well with the Type 3 design spectrum, except at very short periods. After multiplied by a scaling factor of 1.5, the modified Type 3 seismic design spectrum anchored at a PGA value of 0.33 g for Zone 1A will almost match the median-plus-one-standard-deviation curve, as shown in Figure 23.

Figure 24 shows the response spectra for the 21 sites located at 2 to 10 km from the surface fault ruptures. The median horizontal PGA value is about 0.25 g. The corresponding peak spectral value is about 0.6 g. The median-plus-one-standard-deviation horizontal PGA value is about 0.4 g and the corresponding peak spectral value is about 0.8 g. Thus, for sites located between 2 and 10 km from the surface fault ruptures the current seismic design spectrum anchored at a PGA value of 0.33 g for Zone 1A would be more than adequate.

Figure 25 shows the response spectra for the 34 sites located at 10 to 20 km from the surface fault ruptures. The median horizontal PGA value is about 0.18 g with a corresponding peak spectral value of about 0.45 g. The median-plus-one-standard-deviation horizontal PGA value is about 0.3 g with a corresponding peak spectral value of about 0.7 g. Thus, for sites located between 10 and 20 km from the surface fault ruptures the current seismic design spectrum anchored at a PGA value of 0.33 g for Zone 1A would be much more than adequate.

Acknowledgements

The strong ground motion recordings were provided by the Central Weather Bureau. We sincerely thank the people who maintained the instruments. This research was supported by the National Science Council under Contract No.NSC 89-2625-2-008-007.

References

Abrahamson, N.A. and Somerville, P.G. (1996). Effects of the hanging wall and footwall on ground motions recorded during the Northridge Earthquake, Bull. Seism. Soc. Am.,86, S93-S99.

Campbell, Kenneth W.(1997). Attenuation relationships for shallow crustal earthquakes based on California strong motion data, Seism. Research Letters, 180-189.

Campbell, K. W.(1997). Empirical near-source attenuation relationships for horizontal and vertical components of peak ground acceleration, peak ground velocity, and pseudo-absolute acceleration response spectra, Seism. Res. Letter, 68, 154-179.

Central Geological Survey (1999). Report on geological investigations of the 921 earthquake (in Chinese), 315 pp.

Chang, C. H., Y. M. Wu, T. C. Shin, and C. Y. Wang (2000). Relocation of the 1999 Chi-Chi earthquake in Taiwan, TAO (Terrestrial, Atmospheric and Oceanic Sciences), vol. 11, no. 3, 581-590.

Institute of Building Research (1999). Preliminary report on surveys of damaged buildings from the great 921 Chi-Chi earthquake (in Chinese), 178 pp.

Lee, W. H. K., T. C. Shin, K. W. Kuo, and, K. C. Chen (1999). CWB free-field strong-motion data from the 921 Chi-Chi earthquake, Volume 1: Digital acceleration files on CD-Rom, Seismology Center, Central Weather Bureau, Taipei, Taiwan.

Liu, Kun-Sung, Shin, Tzay-Chyn and Tsai, Yi-Ben (1999). A free-field strong motion network in Taiwan: TSMIP, TAO, 10, 377-396.

Ma, K. F., C. T. Lee, Y. B. Tsai, T. C. Shin, and, J. Mori (1999). The Chi-Chi, Taiwan earthquake: Large surface displacements on inland thrust fault, EOS, v.80, 605-611.

Shin, T.C., K.W. Kuo, W.H.K. Lee, T.L. Teng, and Y.B. Tsai (1999). A preliminary report on the 1999 Chi-Chi (Taiwan) earthquake, Seism. Res. Lett., submitted.

Shin, T. C. (2000). Some seismological aspects of the 1999 Chi-Chi earthquake in Taiwan, TAO (Terrestrial, Atmospheric and Oceanic Sciences), vol.11, no.3, 555-566.

Tsai, Y. B. and M. W. Huang (2000). Strong ground motion characteristics of the Chi-Chi, Taiwan earthquake of September 21, 1999, Earthquake Engineering and Engineering Seismology, vol.2, no.1, 1-21.

Wu, Y. M., T. C. Shin, and Y. B. Tsai (1998). Quick and reliable determination of magnitude for seismic early warning, Bull. Seism. Soc. Am. Vol. 88, No5, 1254-1259.

Yih-Min Wu, Jen-Kuang Chung, Tzay-Chyn Shin, Yi-Ben Tsai, William H. K. Lee (1999). Development of seismic rapid reporting and early warning system in Taiwan, IUGG99 abstracts, A6 or A126.

Wu, Y. M., W. H. K. Lee, C. C. Chen, T. C. Shin, T. L. Teng, and Y. B. Tsai (2000). Performance of the Taiwan rapid earthquake information release system (RTD) during the 1999 Chi-Chi (Taiwan) earthquake, Seism. Res. Let., 71, 338-343.

Yu, S.B., Chen, H.Y. and Kuo, L.C. (1997). Velocity field of GPS stations in the Taiwan area, Tectonophysics 274, 41-59.

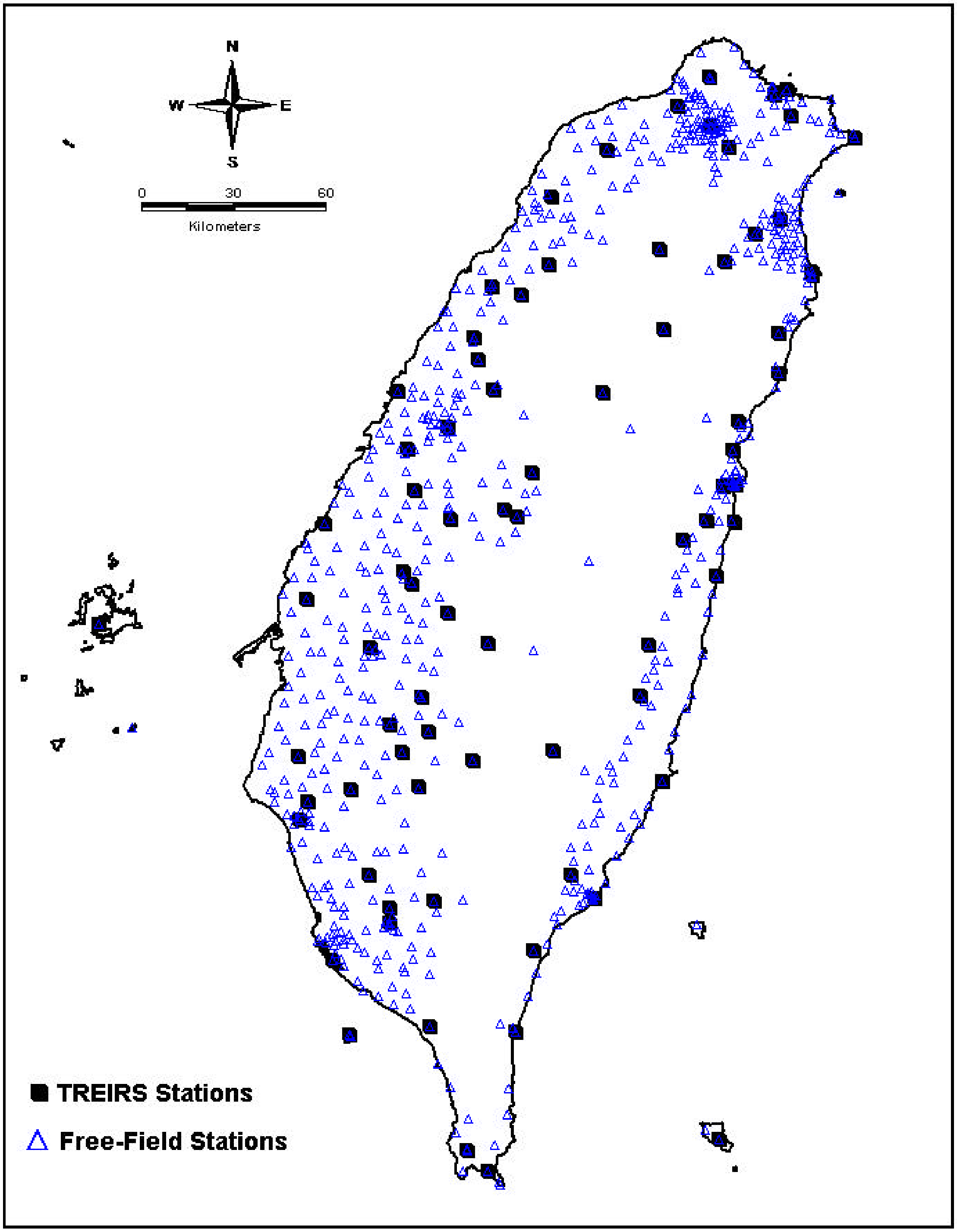

Figure 1. Locations of seismic stations for the Taiwan Rapid Earthquake Information System and the free-field strong motion network.

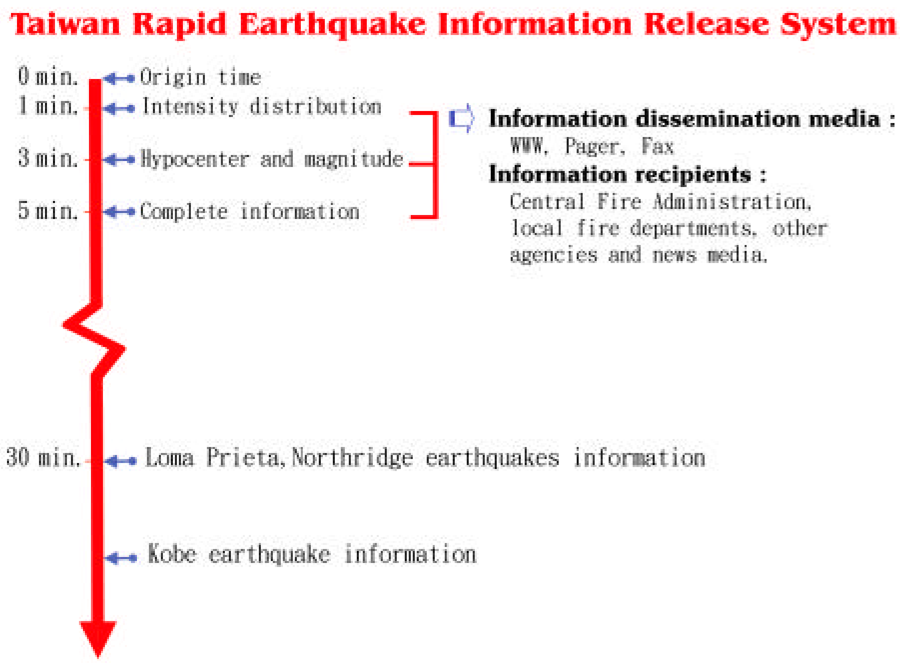

Figure 2. Target time schedule of Taiwan rapid Earthquake Information System

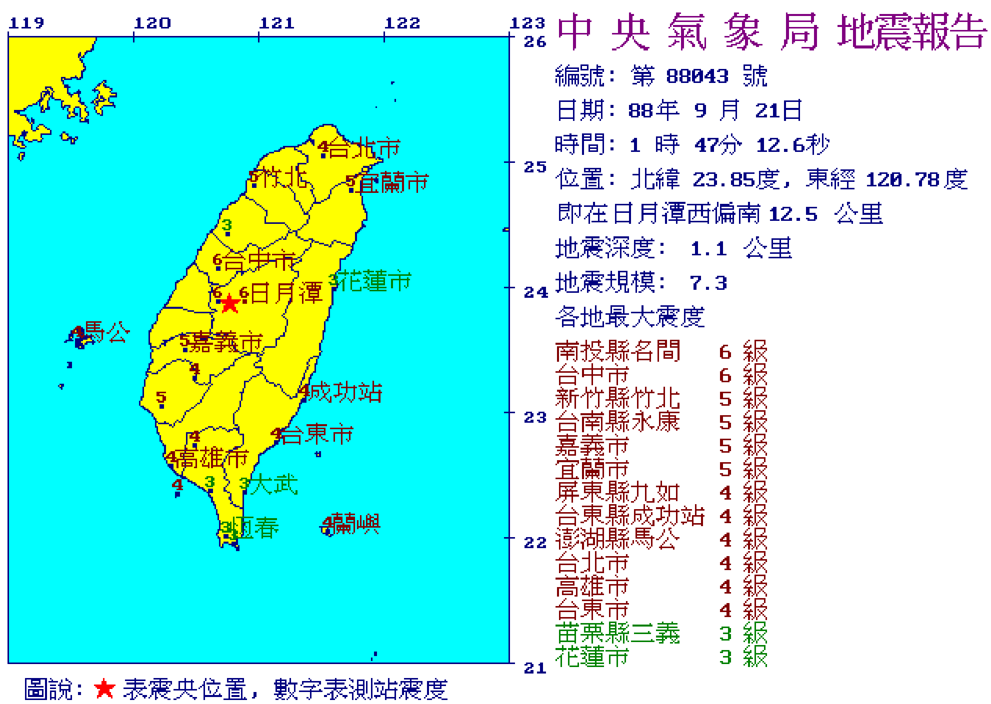

Figure 3. The Central Weather Bureau's Earthquake No.88043 on the Chi-Chi earthquake of September 21, 1999.

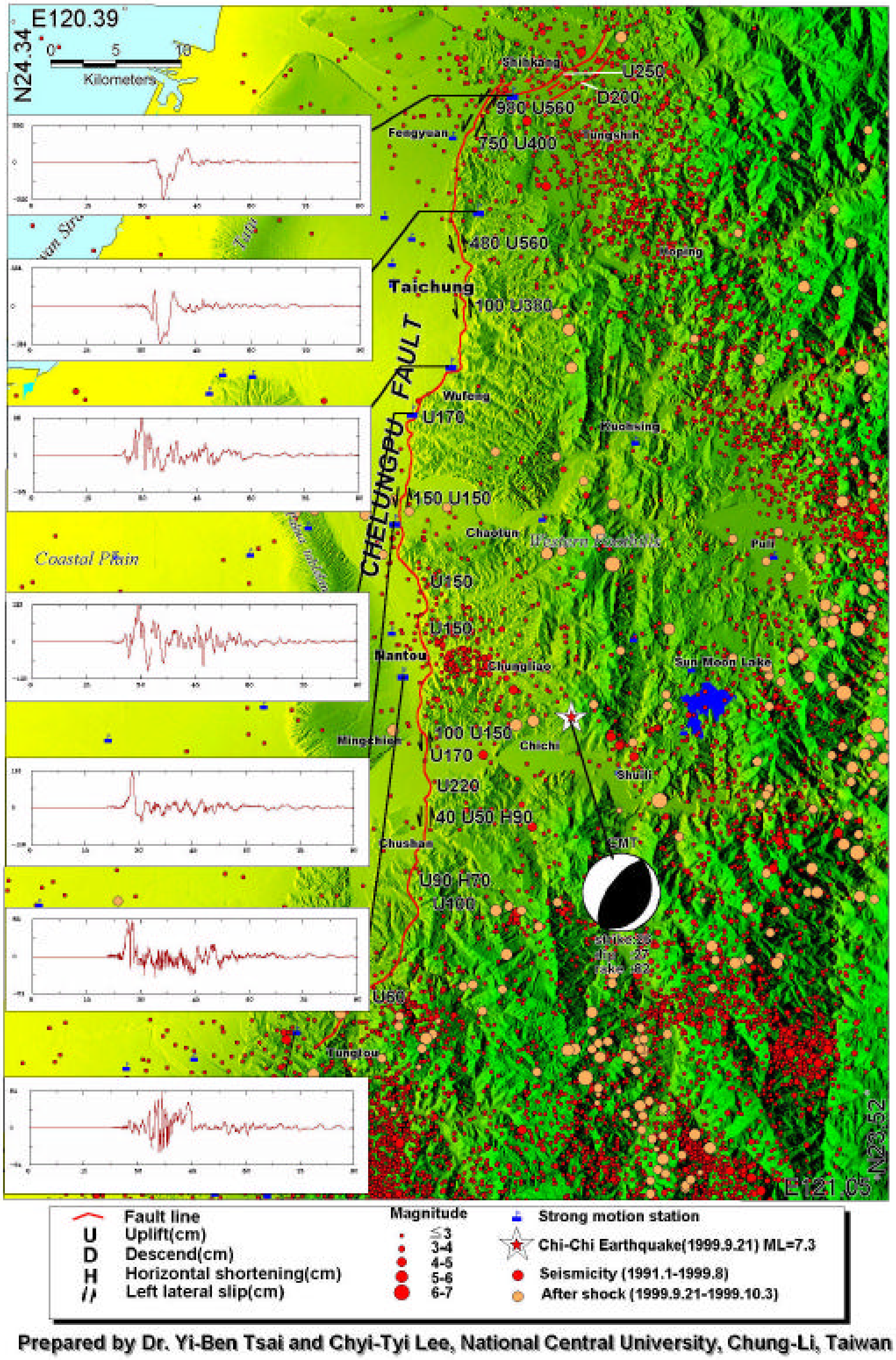

Figure 4. The Chehlungpu fault, and the epicenter of the Chi-Chi earthquake. Also shown are background seismicity (in red dots), strong aftershocks(orange dots), E-W component velocity waveforms along the fault line.

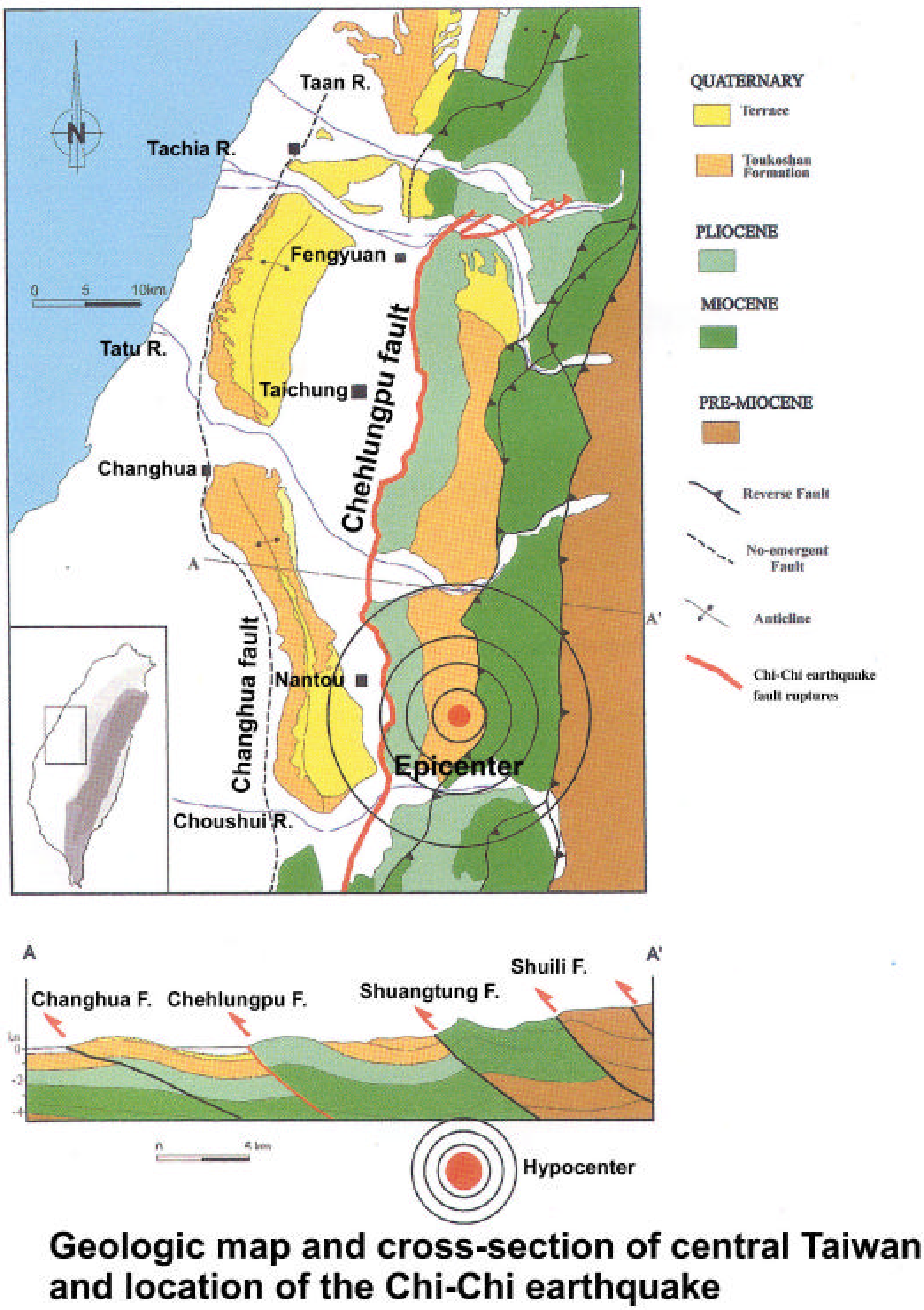

Figure 5. Regional geology surrounding the Chehlungpu fault and an E-W cross section.(After Lee et al, 1999)

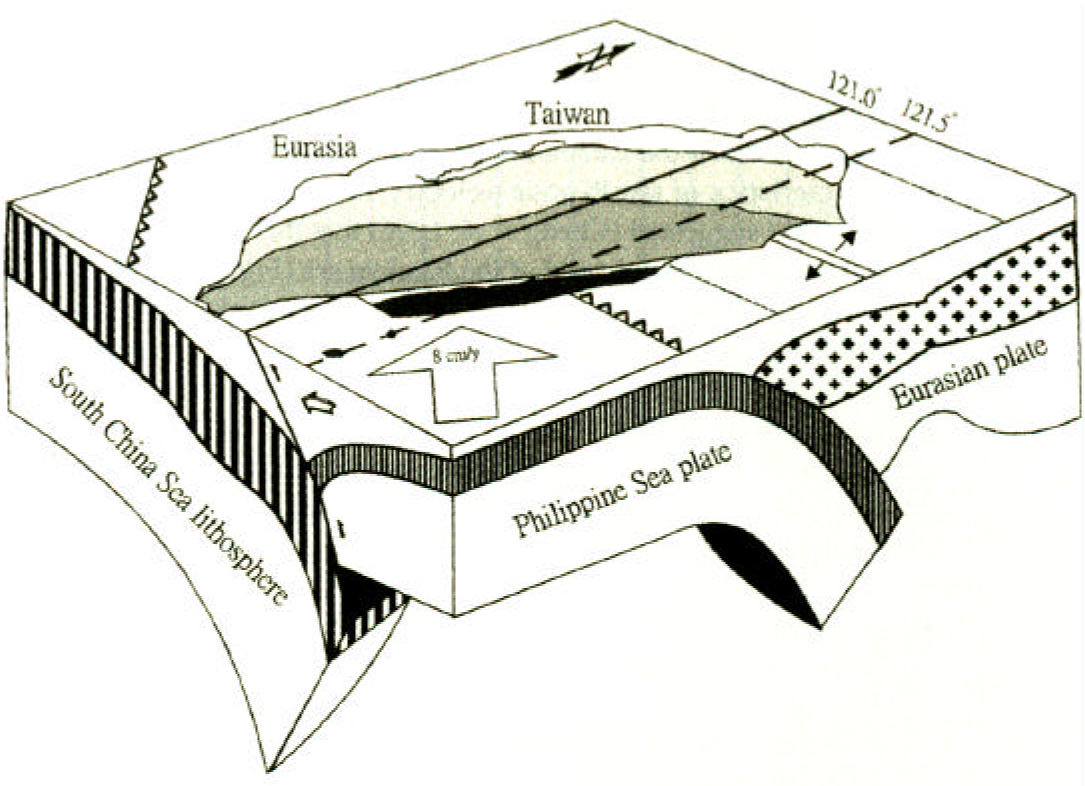

Figure 6. Plate configurations in Taiwan area (after Angelier, 1986).

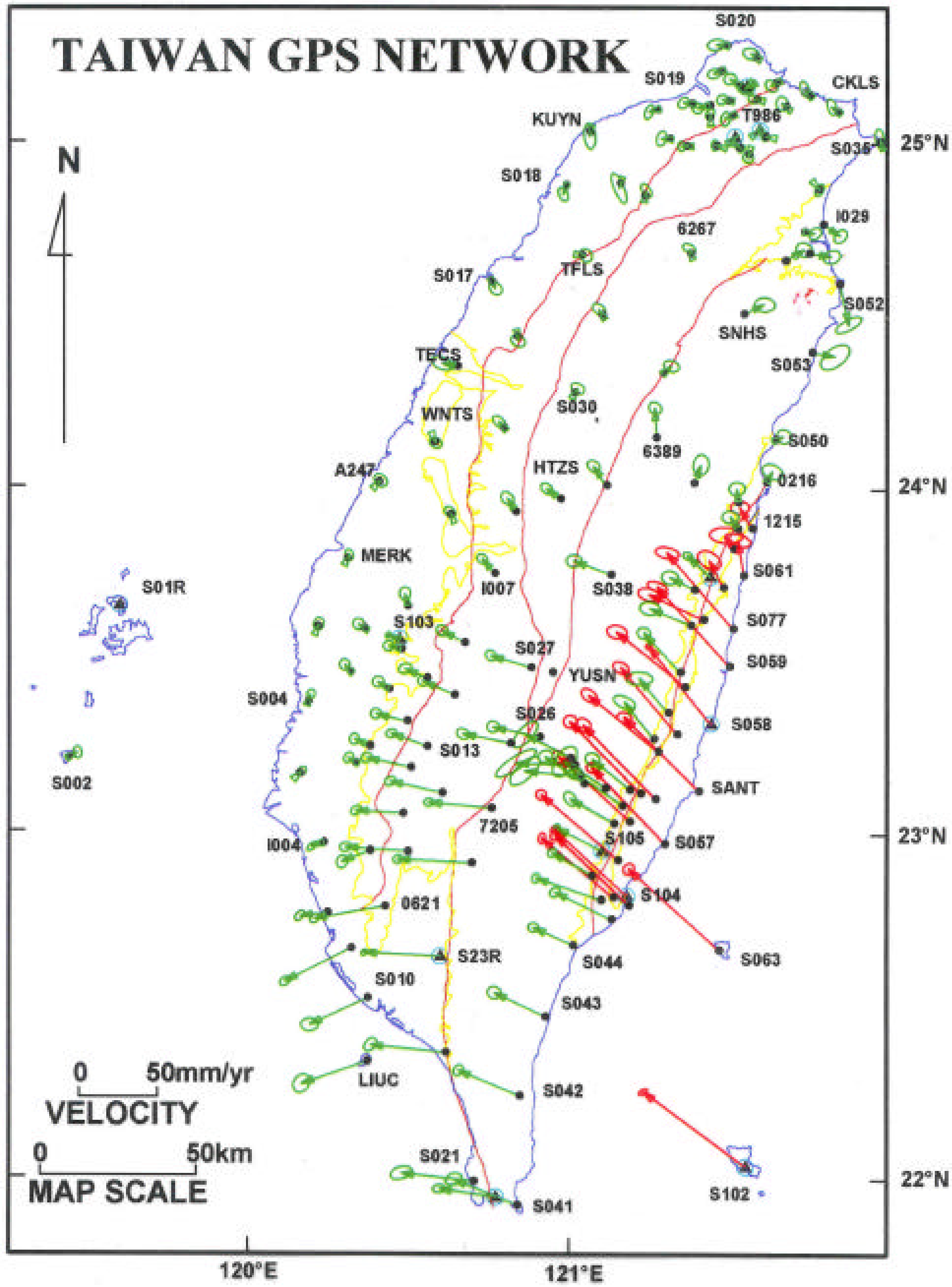

Figure 7. The velocity field of crustal movement measured by GPS (after Yu et al., 1997).

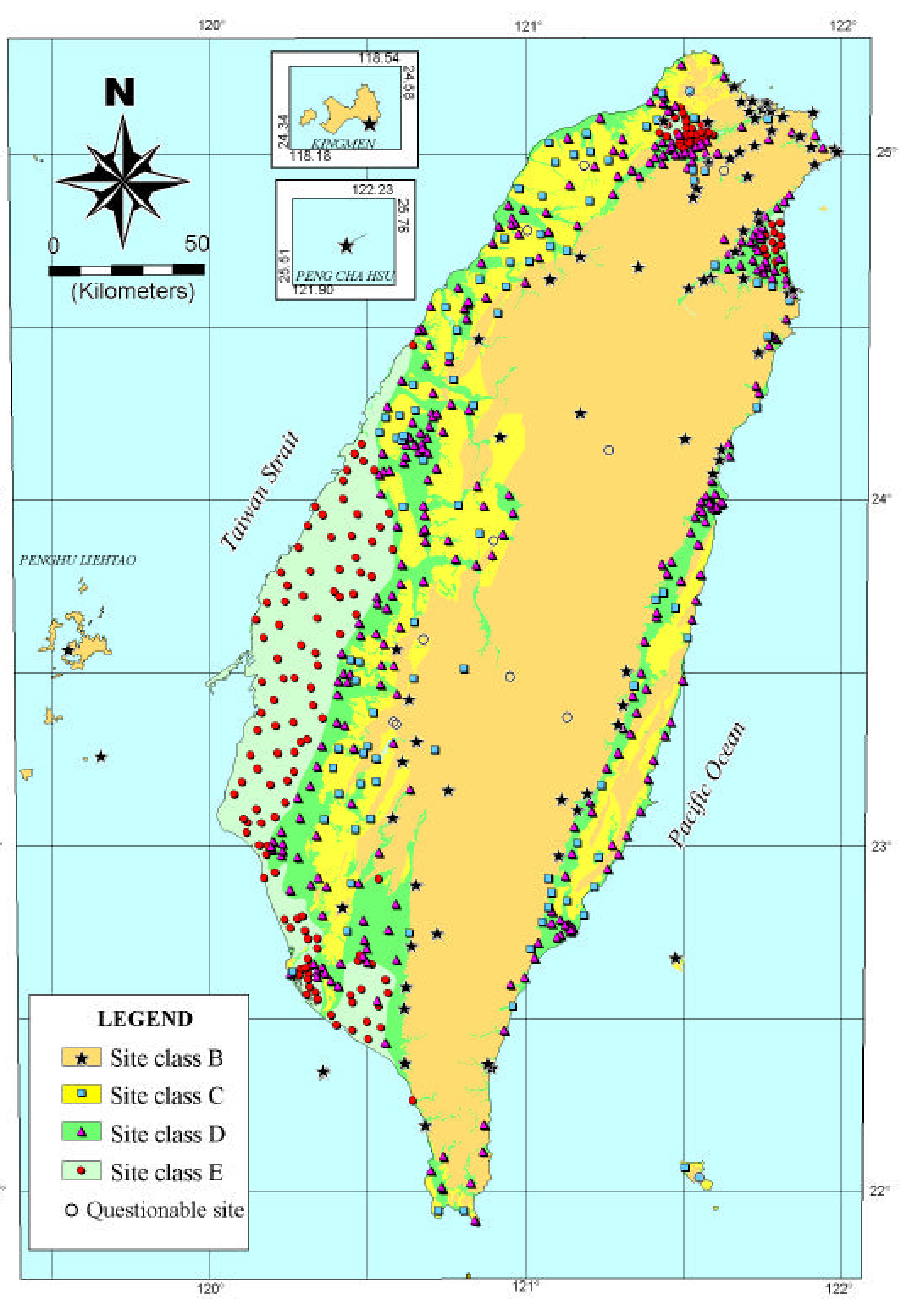

Figure 8. Free-field strong motion accelerograph sites and geologic conditions of Taiwan (Lee et al., 2001).

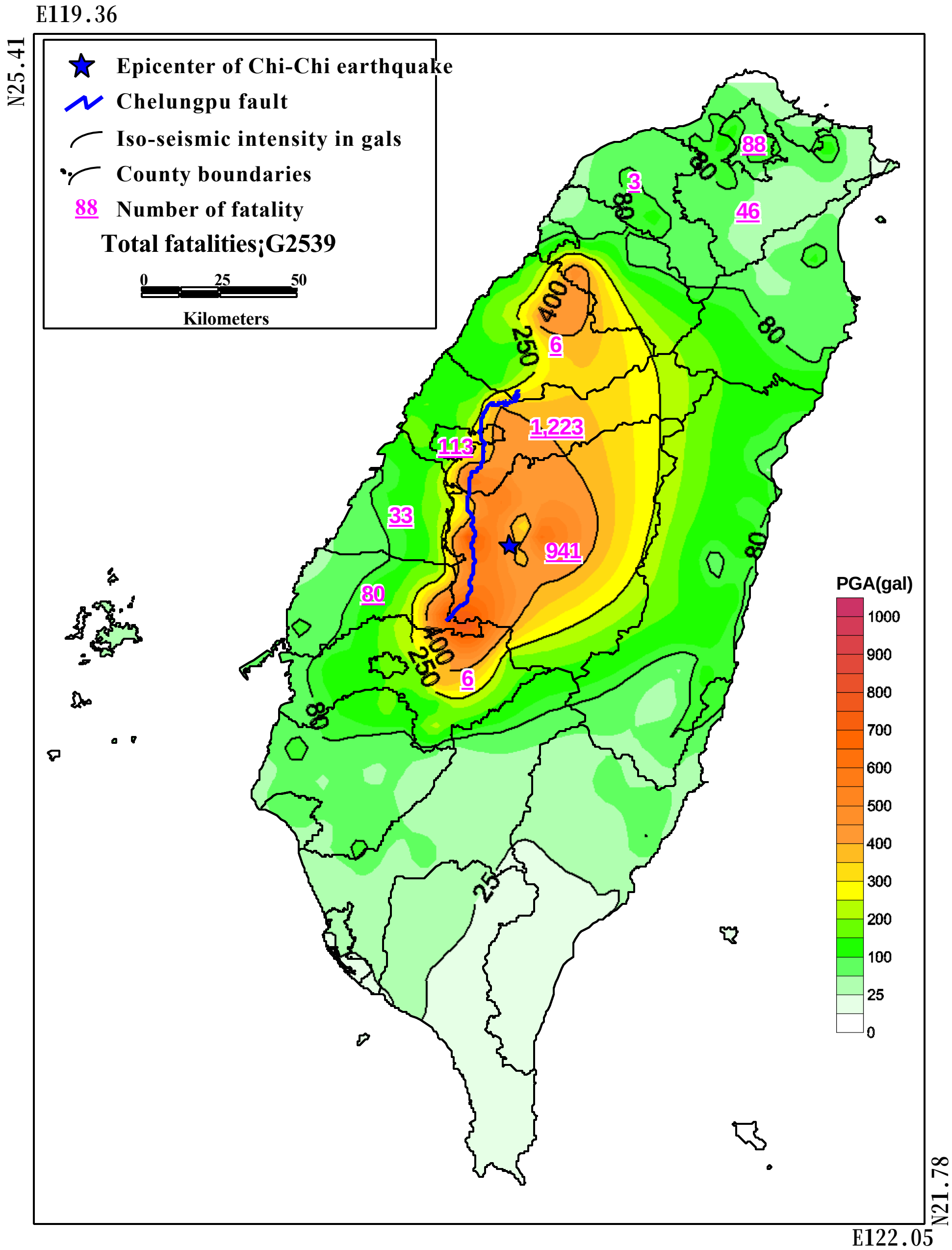

Figure 9. Contours of horizontal peak ground acceleration in gals and the total number of fatality in each county or city due to the Chi-Chi, Taiwan earthquake of September 21, 1999

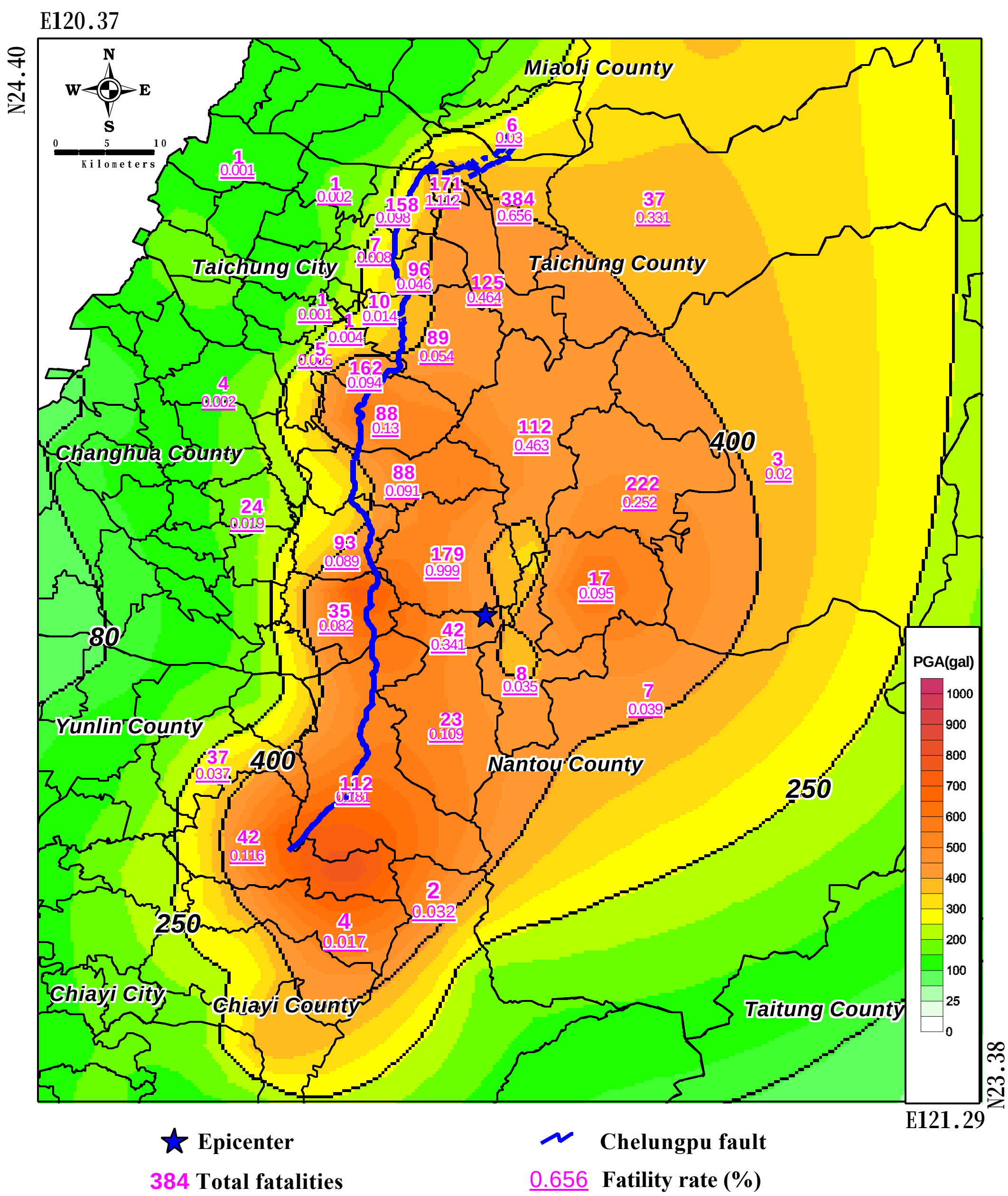

Figure.10 The total fatality and fatality rate (%) of each township. The thick dark curves are contours of horizontal peak ground acceleration in gals in central Taiwan due to the Chi-Chi, Taiwan Earthquake of September 21,1999.

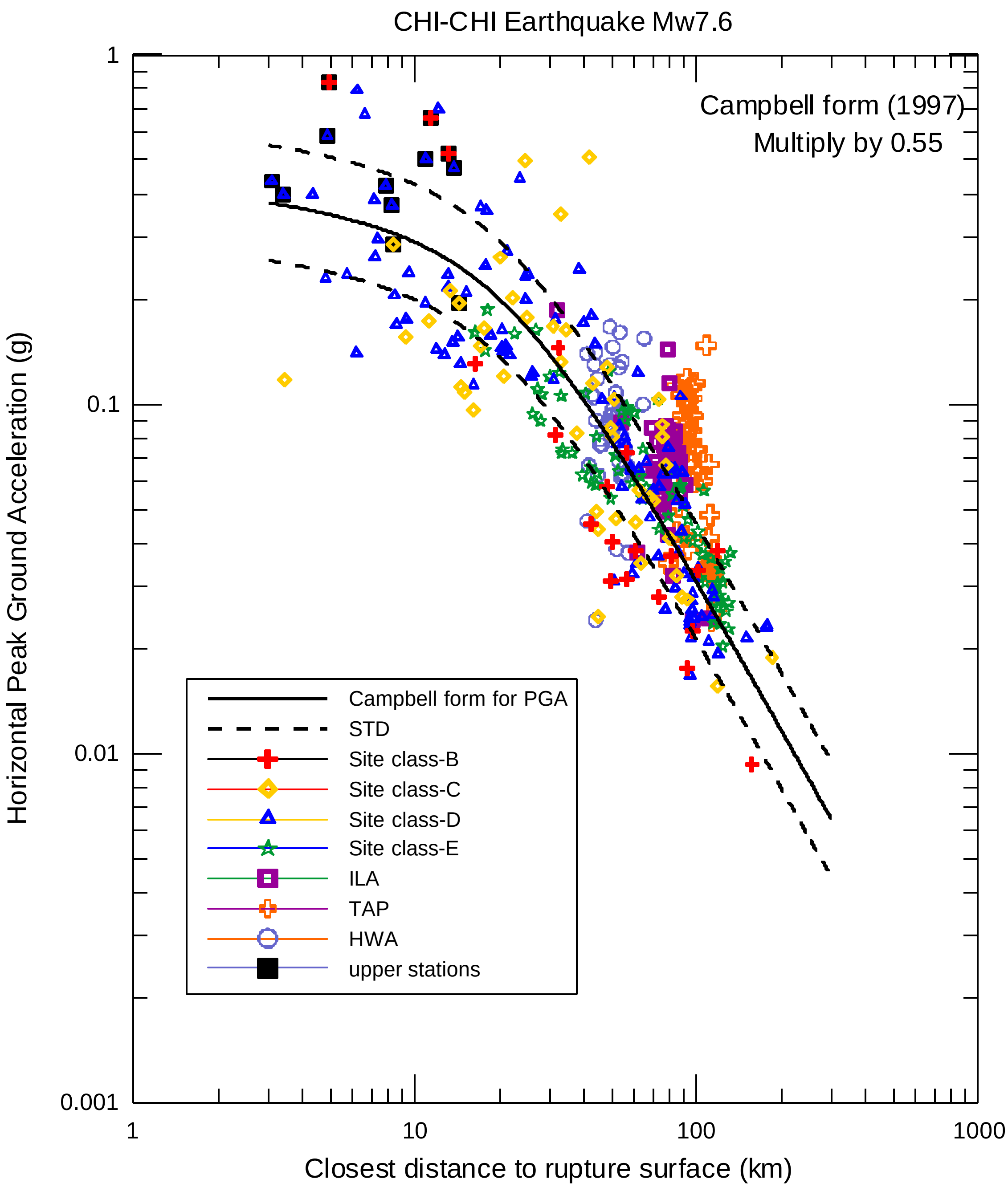

Figure 11. Attenuation of horizontal peak ground acceleration from the Chi-Chi earthquake.

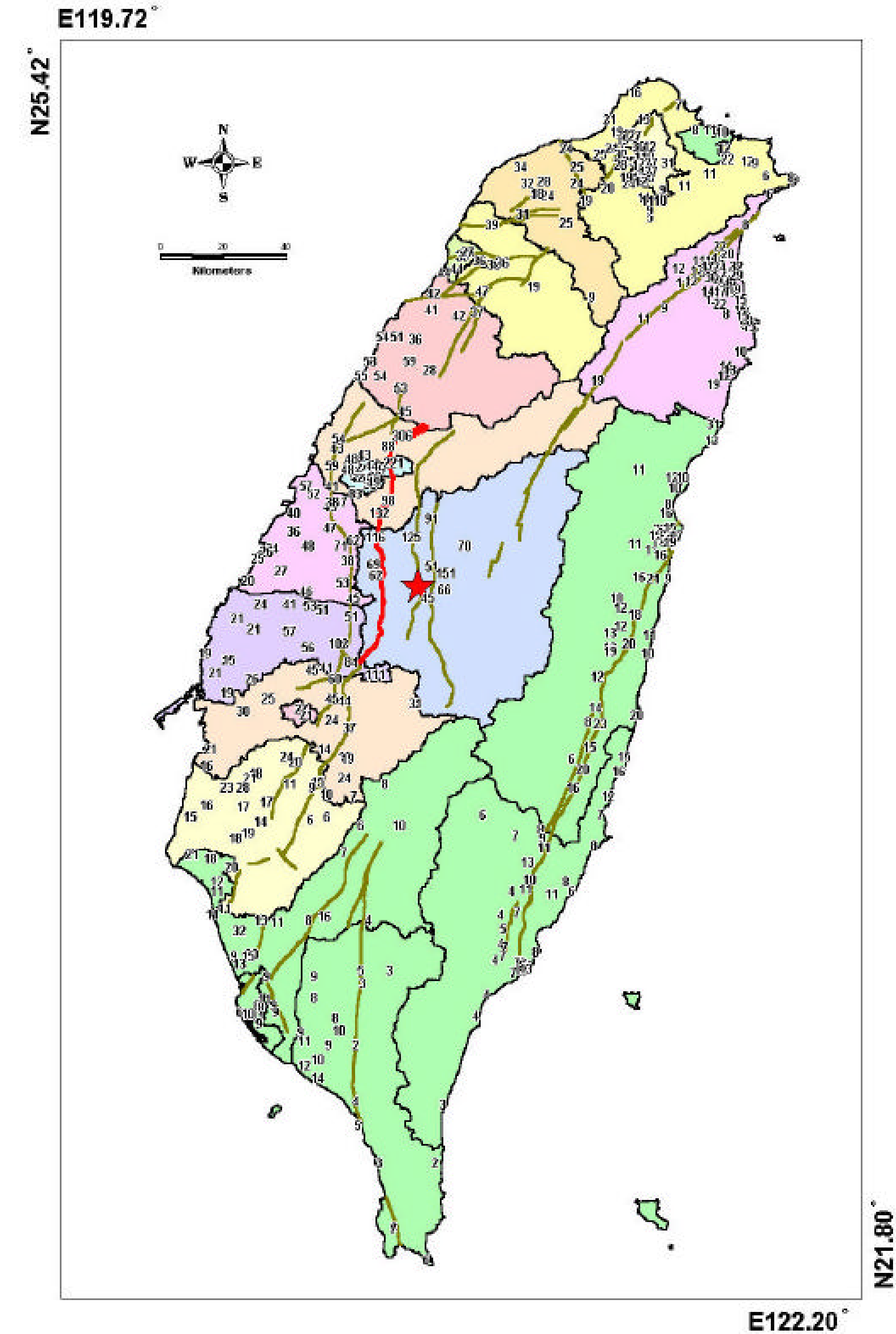

Figure 12. Distribution of integrated horizontal peak ground velocity (in cm/sec) from the Chi-Chi earthquake.

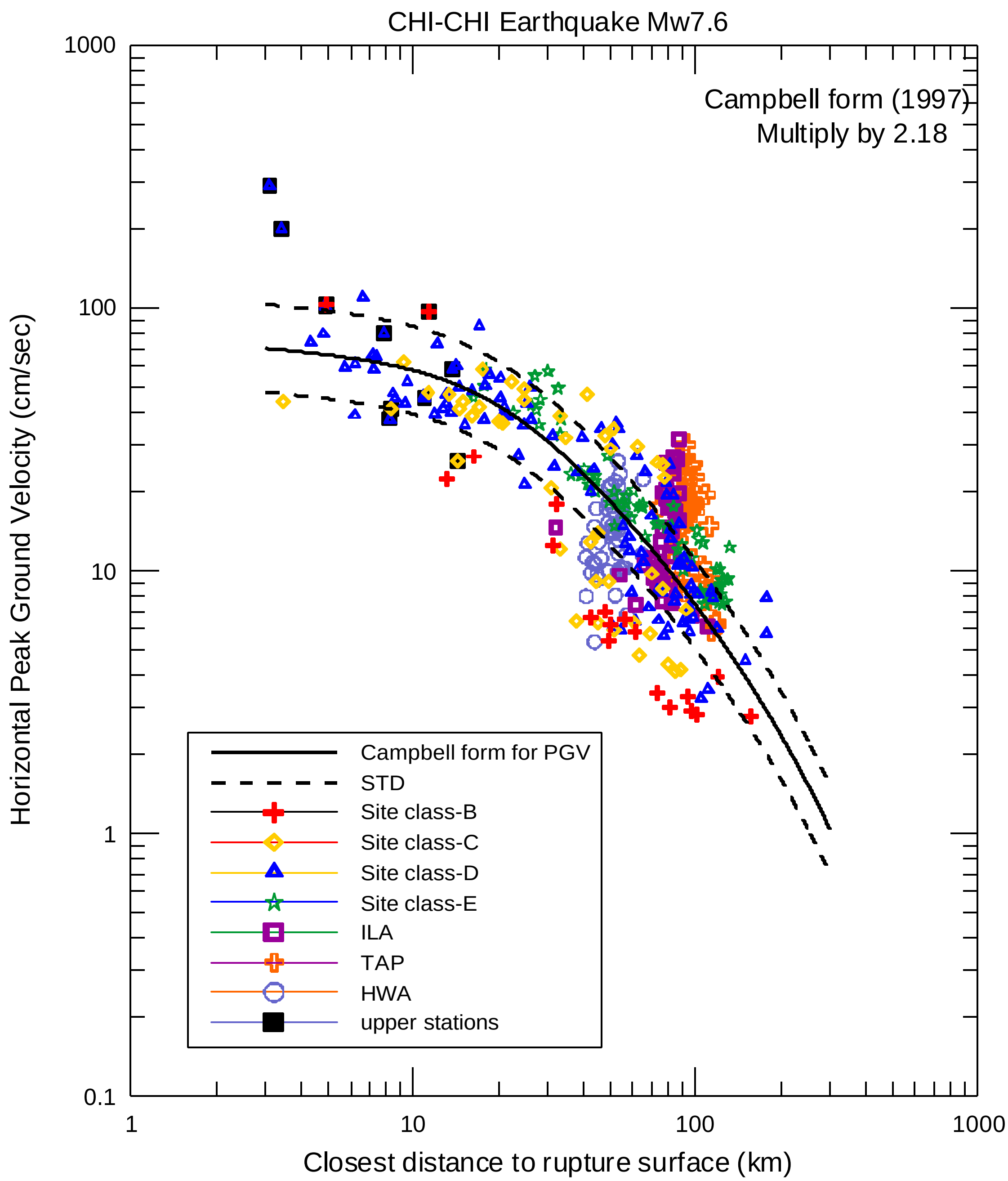

Figure 13. Attenuation of horizontal peak ground velocity from the Chi-Chi earthquake.

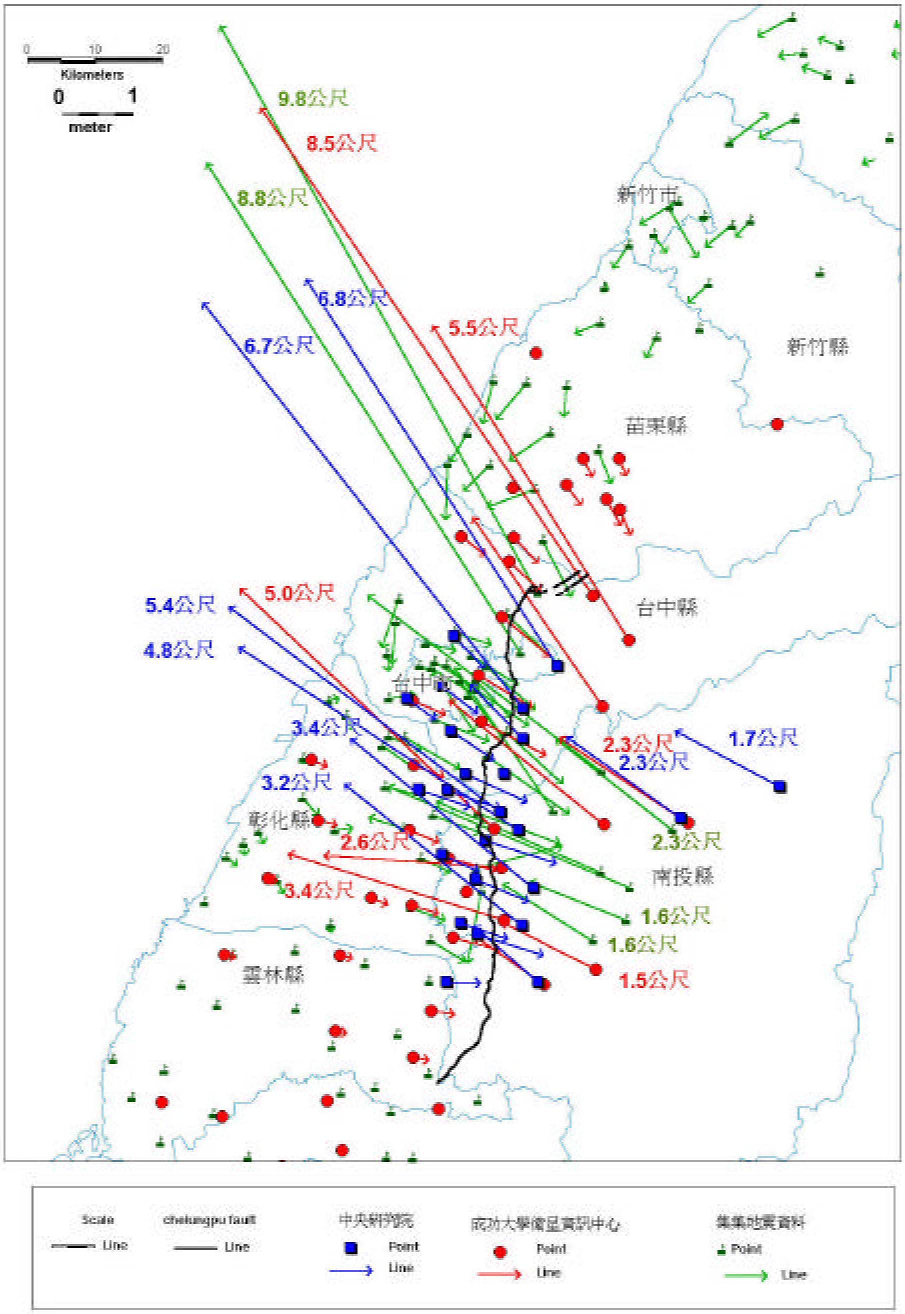

Figure 14. Distribution of integrated permanent horizontal ground displacement vectors from the Chi-Chi earthquake (in green). Also shown are he ground displacements from GPS measurements (in blue and red).

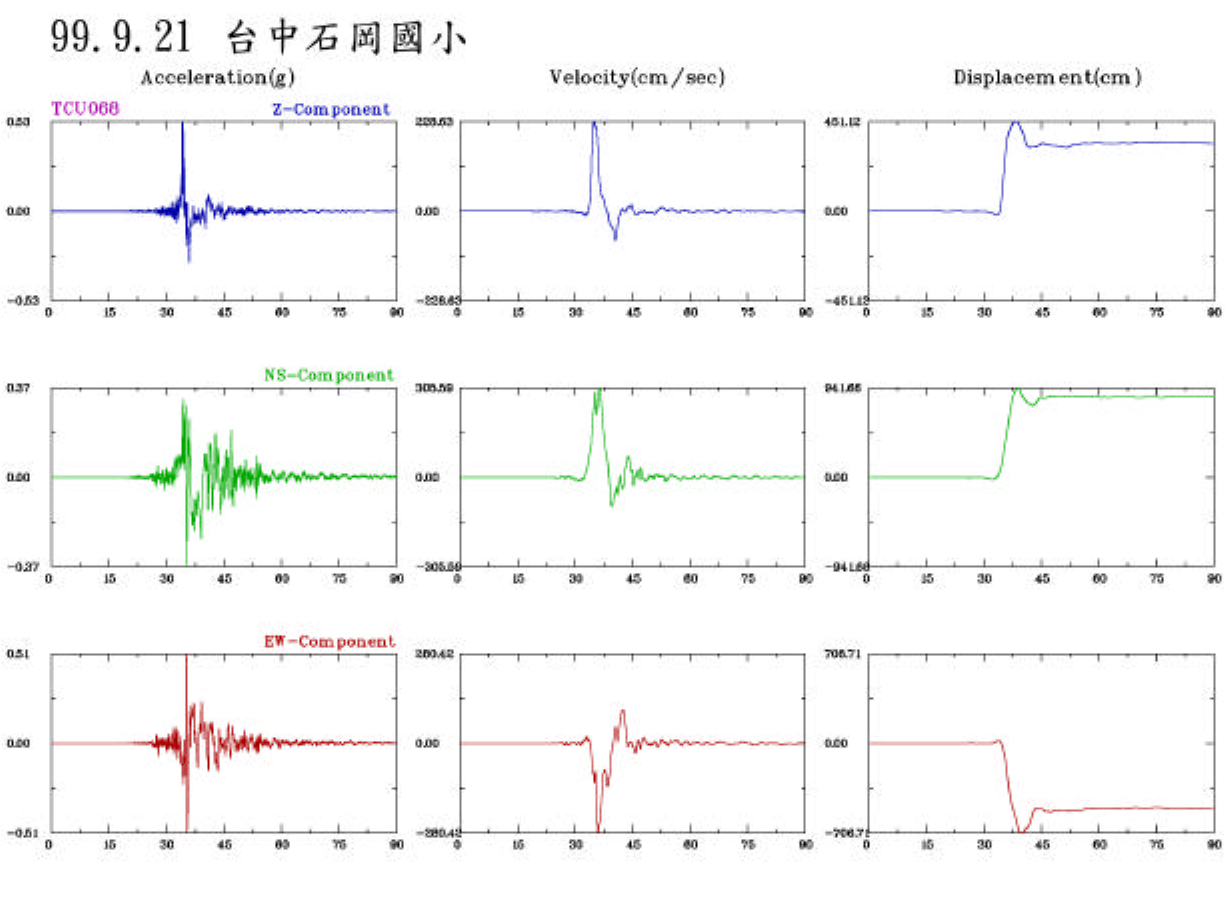

Figure 15. The recorded acceleration, integrated velocity and displacement waveforms at station TCU068 from the Chi-Chi earthquake.

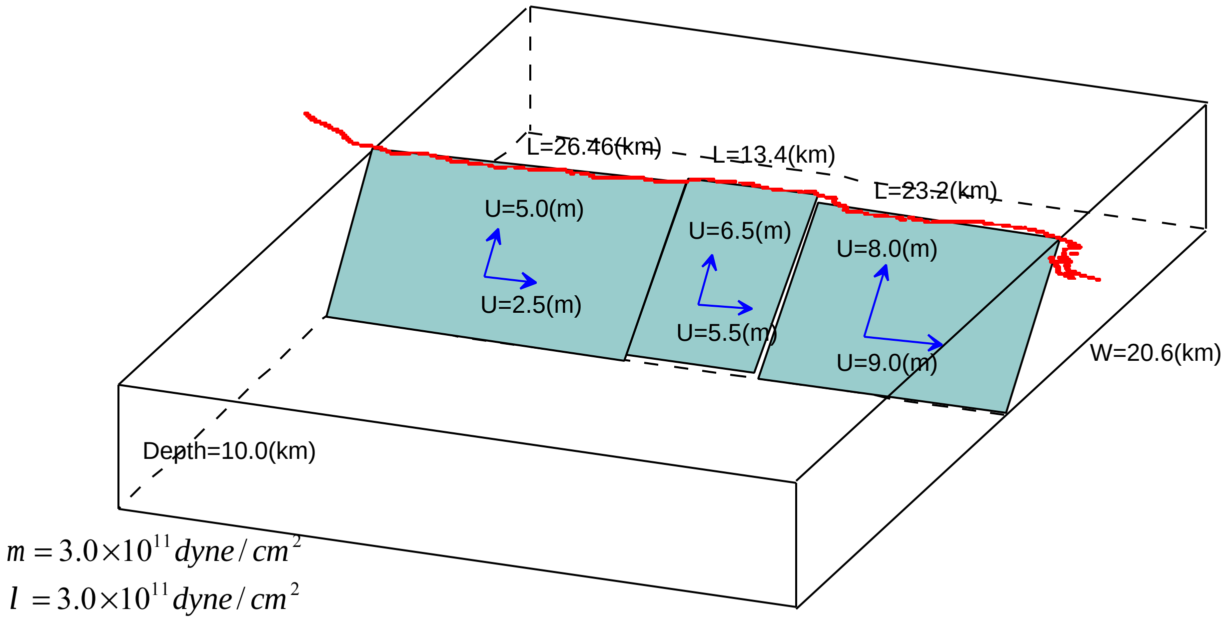

Figure 16. The first-order estimation of the dip-slip and strike-slip displacements in the southern, central and northern segments of the Chelungpu fault.

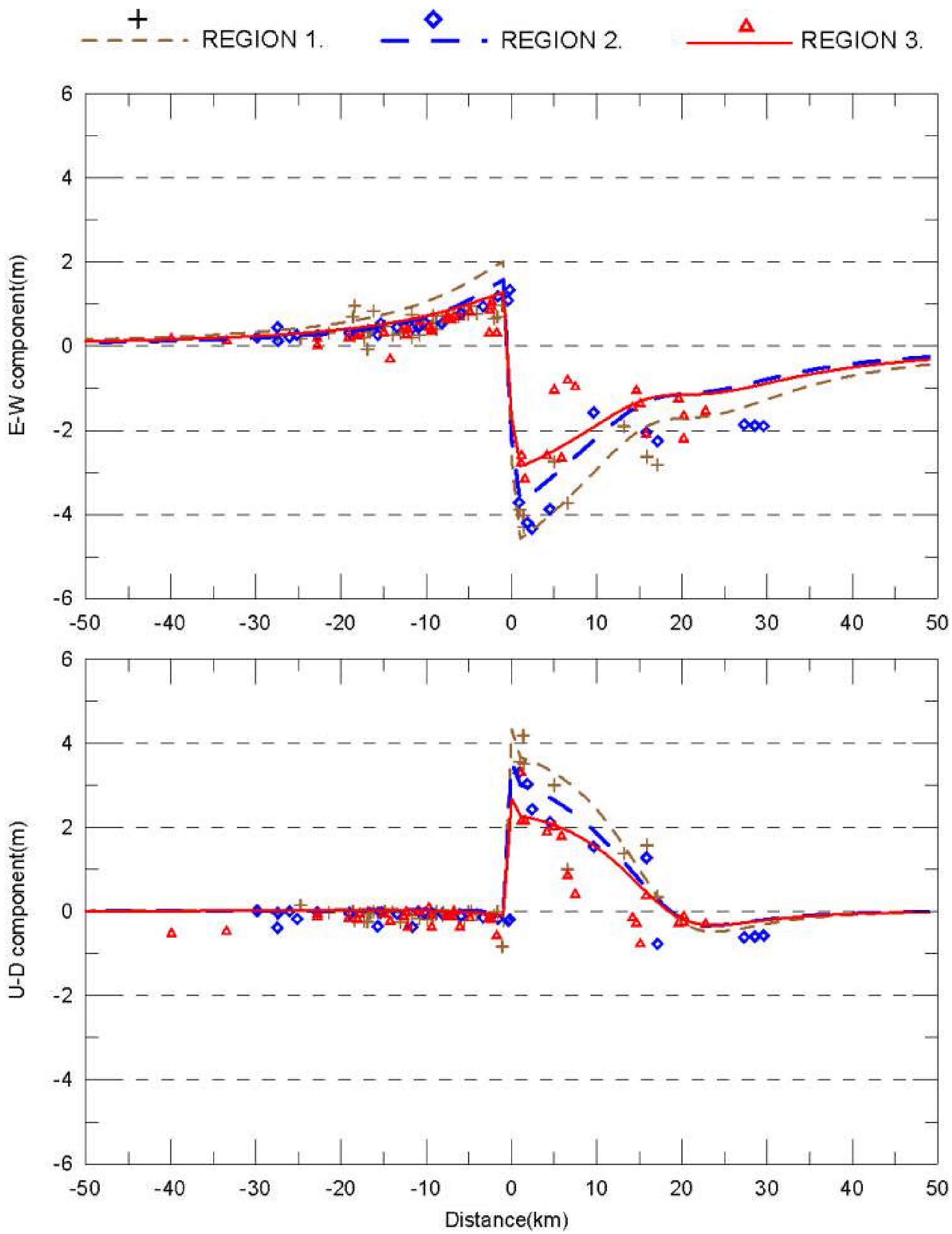

Figure 17. The observed and calculated vertical displacements across the southern, central and northern segments of the fault.

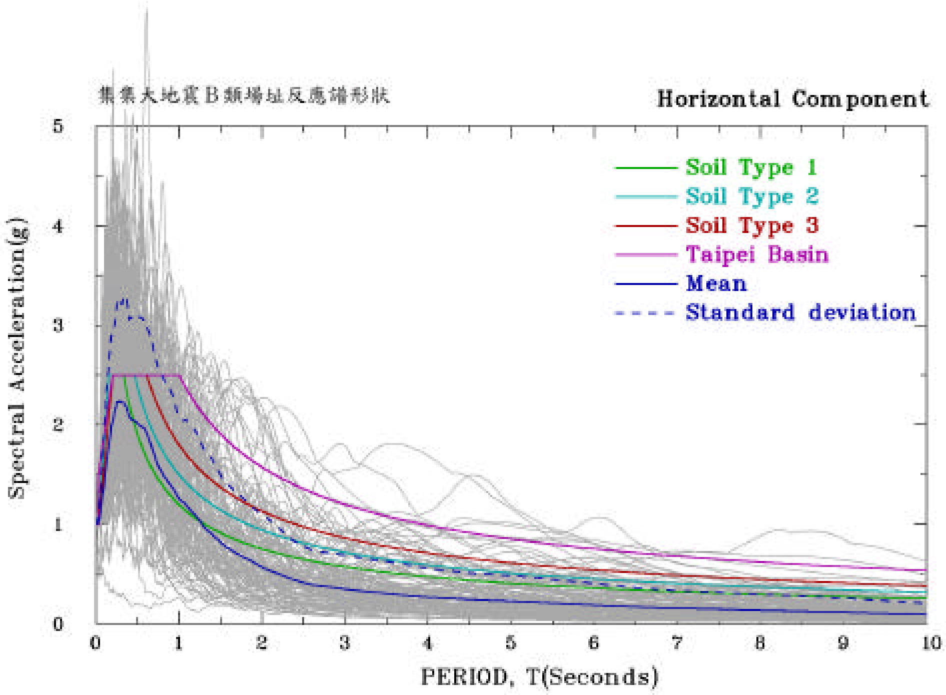

Figure 18. Comparison of the normalized 5% damped acceleration response spectra from Class B sites with the modified Type 1, 2, 3 and Taipei Basin seismic design spectra.

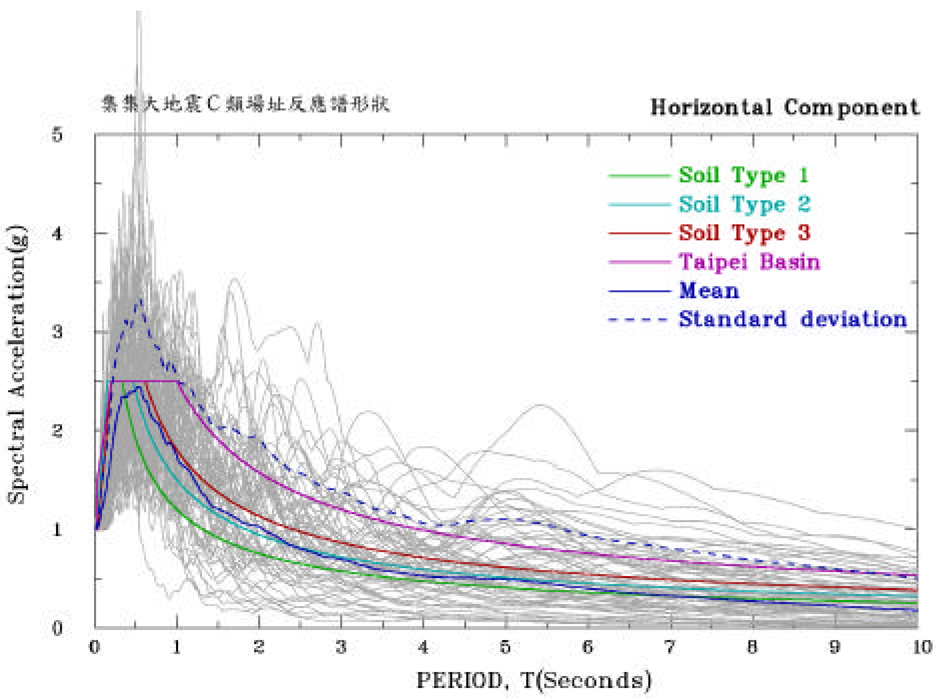

Figure 19. Comparison of the normalized 5% damped acceleration response spectra from Class C sites with the modified Type 1, 2, 3 and Taipei Basin seismic design spectra.

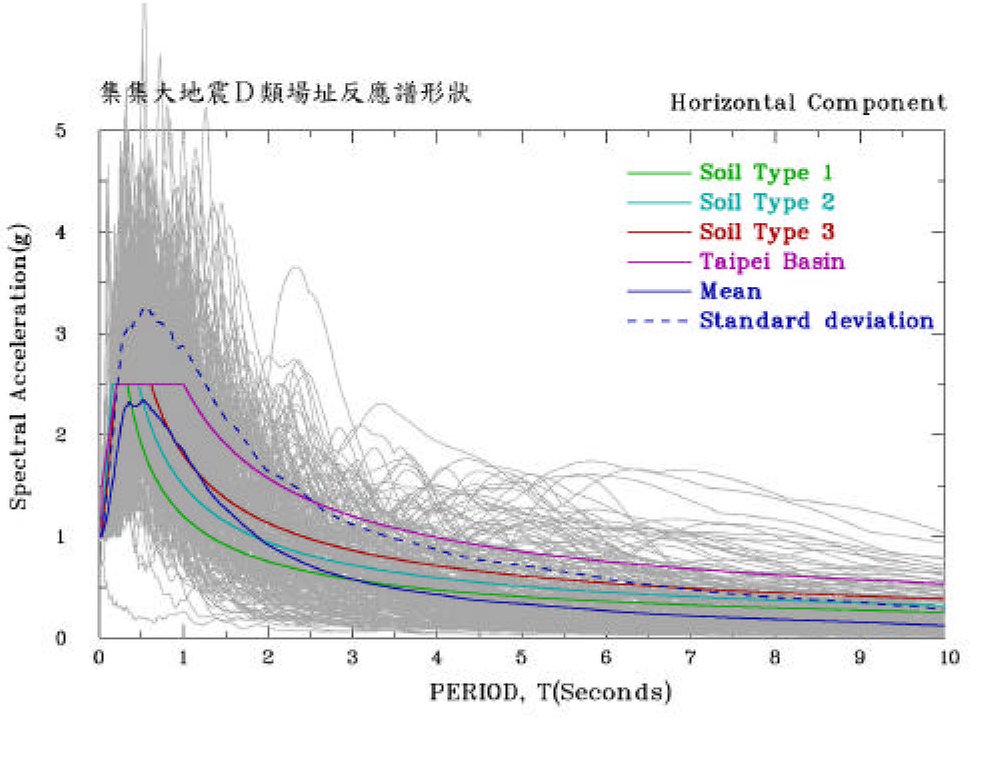

Figure 20. Comparison of the normalized 5% damped acceleration response spectra from Class D sites with the modified Type 1, 2, 3 and Taipei Basin seismic design spectra.

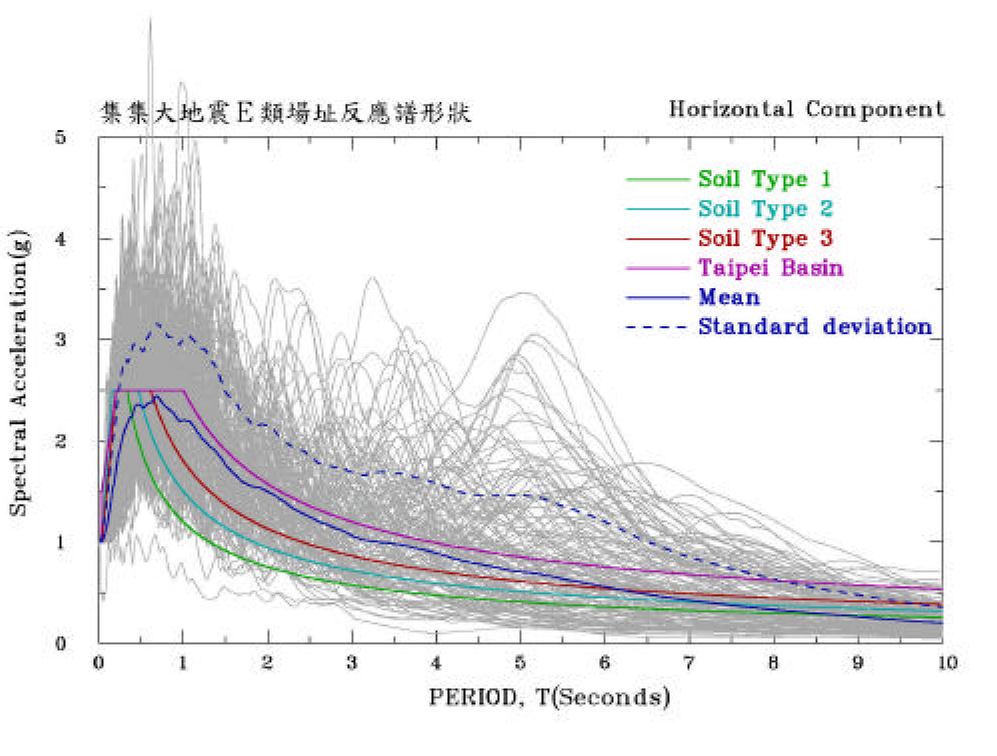

Figure 21. Comparison of the normalized 5% damped acceleration response spectra from Class E sites with the modified Type 1, 2, 3 and Taipei Basin seismic design spectra.

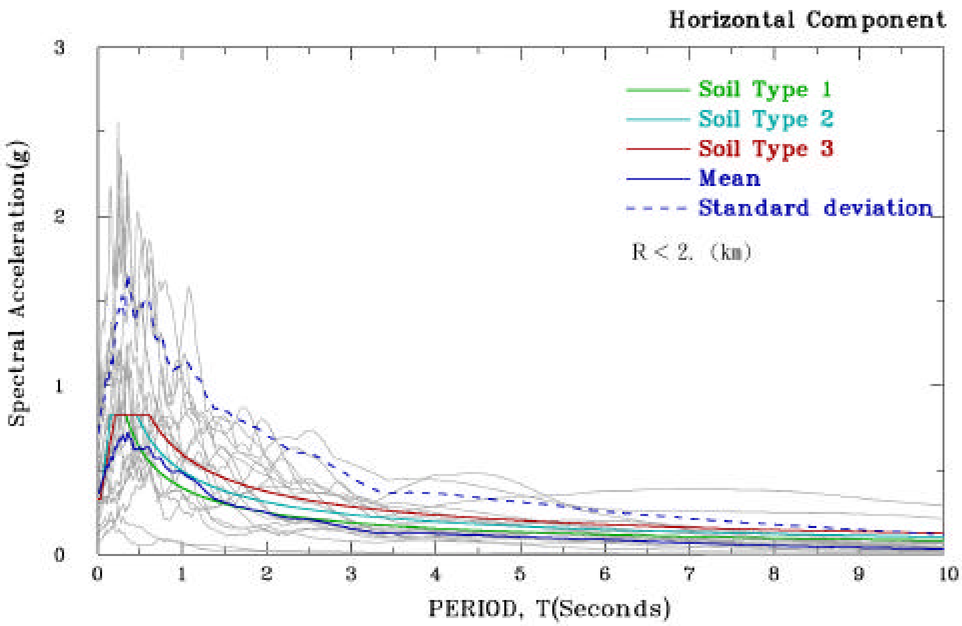

Figure 22. Comparison of 5% damped response acceleration spectra from the recording sites within 2 km of the Chehlungpu fault with the modified seismic design spectra anchored at 0.33g.

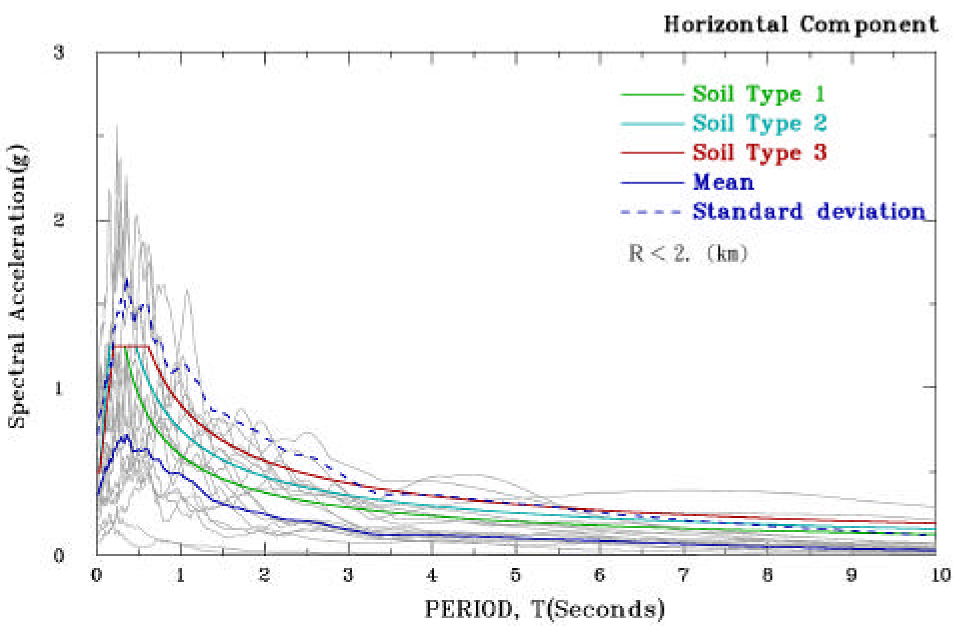

Figure 23. Comparison of 5% damped response acceleration spectra from the recording sites within 2 km of the Chehlungpu fault with the modified seismic design spectra anchored at 0.50g.

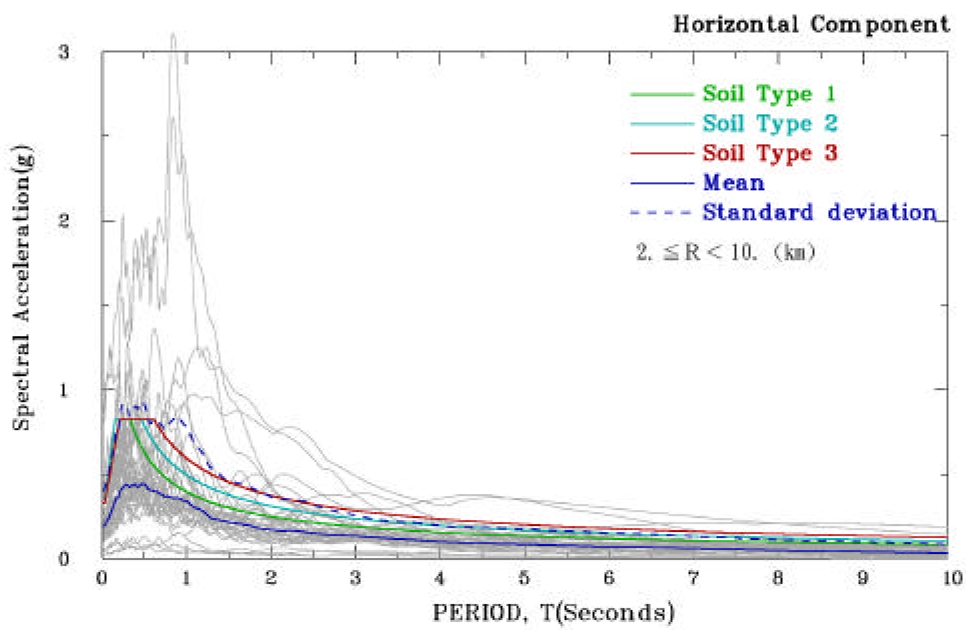

Figure 24. Comparison of 5% damped response acceleration spectra from the recording sites at 2-10 km of the Chehlungpu fault with the modified seismic design spectra anchored at 0.33g.

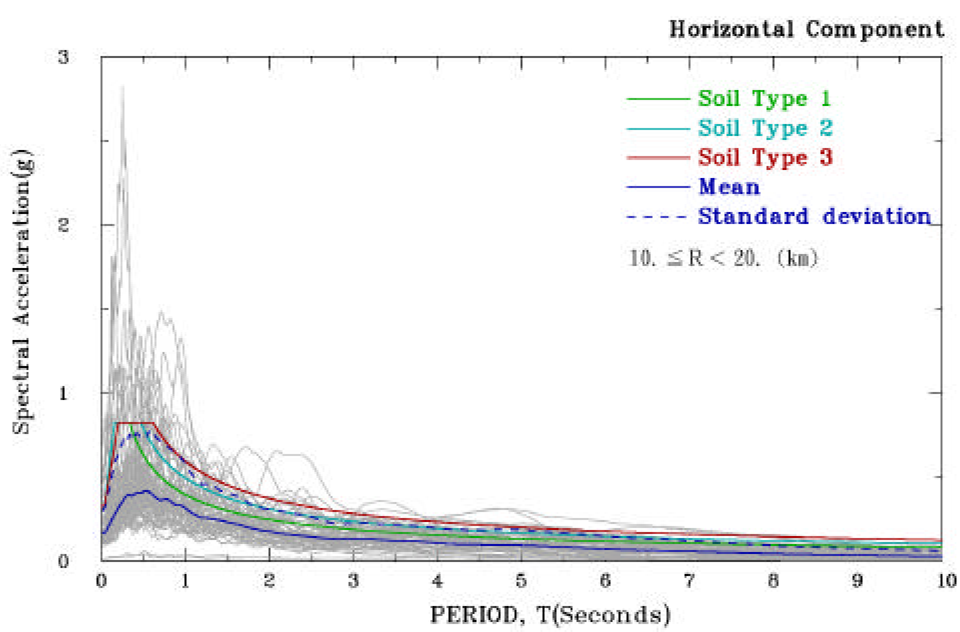

Figure 25. Comparison of 5% damped response acceleration spectra from the recording sites at 10-20 km of the Chehlungpu fault with the modified seismic design spectra anchored at 0.33g

Photo 1.

Photo 2.

Photo 3.

Photo 4.

TriNet/CISN Engineering Strong Motion Data Center and the Internet Quick Report

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and

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U.S. Geological Survey

Abstract

The development of the TriNet/CISN Engineering Data Center is in progress. As one part of the Engineering Data Center, the California Division of Mines and Geology's Strong Motion Instrumentation Program has developed a prototype Internet Quick Report (IQR) that uses Internet technology to distribute processed strong-motion data immediately after an earthquake. The IQR is dynamic and cumulative, containing an up-to-date table listing recorded peak ground and structural accelerations arranged in either epicentral distance or alphabetical order. Also, users will have direct access to processed strong-motion data and detailed information on instrumented stations from the IQR. The Engineering Data Center is in the process of compiling detailed structural information on instrumented stations to assist users in utilizing the strong-motion data and to allow users to search for data from specific structure types.

Introduction

Earthquake monitoring in California is a multi-institutional effort involving state, federal, and private agencies. The TriNet project, funded by the Federal Emergency Management Agency (FEMA) through the California Office of Emergency Services (OES), is a cooperative effort of three agencies, the California Division of Mines and Geology, the California Institute of Technology and the Pasadena Office of the U.S. Geological Survey.

Based on the TriNet project, the California Integrated Seismic Network (CISN) is a newly formed consortium of institutions engaged in earthquake monitoring and will extend to include statewide coverage with two additional core members, the Menlo Park Office of the U.S. Geological Survey and the University of California, Berkeley. The OES serves as an ex-officio participant in the CISN.

A key component of the CISN is the Engineering Strong Motion Data Center. The data center will be operated by the California Department of Conservation's Strong Motion Instrumentation Program (CSMIP) in cooperation with the USGS/National Strong Motion Program (NSMP). A primary goal of the Engineering Data Center as well as the other two Data Management Centers in CISN is to provide rapid information after an earthquake, ranging from the ShakeMap to distribution of the data and calculated parameters. Under the TriNet project the

CSMIP has established backup ShakeMap production in Sacramento. Currently it is in the process of expanding the coverage area of ShakeMap from southern California to statewide backup under the CISN project. In addition, the Engineering Data Center will assemble strong-motion data sets for the earthquake engineering community incorporating data from all CISN stations. To effectively disseminate strong-motion data for engineering applications right after major earthquakes, an Internet-based Quick Report has been developed, based on the concept of the traditional hardcopy Quick Report method.

Internet Quick Report

The purpose of the Internet Quick Report (IQR) is to rapidly distribute strong-motion data and related information in standard World Wide Web format by using advanced Internet technology. The design concept for the IQR not only transforms the traditional Quick Report into an Internet page for rapid, broad, and convenient distribution, but also streamlines the Quick Report production process in an automatic fashion. To accomplish this, a suite of computer utilities and modules have been developed that serve as an add-on capability to the CSMIP monitoring system.

Upon the occurrence of an earthquake, the IQR programs will be activated during a period of time after the event. While the IQR modules are active, they develop and maintain a list of triggered strong-motion stations and a list of processed strong-motion data that is available for download. Peak ground and structural acceleration values recorded at stations are parsed from a summary table of peak accelerations in the CSMIP monitoring system and from incoming data from partner CISN agencies. The immediate outputs of the IQR programs are two Internet pages such as shown in Figure 1 and 2. They list all data recorded up to that time in two tables, one sorted for user convenience in increasing epicentral distance order and the other in alphabetical order by station name/location. The contents of these two Internet pages are cumulative and are updated continuously as the number of call-in stations increases and more data has been processed and made available for public access.

Each IQR Internet page is based on an internal key table of peak acceleration values of strong-motion data recorded at stations. As shown in Figure 1, at the top of the IQR Internet page is the name and the date of the earthquake and links to earthquake related information at other CISN sites regarding location, magnitude, and the ShakeMap. The contents of the table are sorted in either alphabetical or epicentral distance order. Each row of the table represents one record entry including station name, station number, network, epicentral distance, and peak acceleration on the ground and the structure. The buttons that are linked for viewing and downloading processed strong-motion data are enabled when data becomes available at the Engineering Data Center. Since the list of the recorded stations is dynamic and cumulative, the IQR tables are expanded by insertion of new station data into the IQR tables when it is received, either from the CSMIP monitoring system or from the CISN partners. At the same time, the status of the View and the Download buttons for each record are also updated based on file availability through or at the Data Center.

Internet Pages for Strong-motion Stations

There are four general types of the strong-motion stations, ground response, building, lifeline (bridge and dam), and special (geotechnical array and other). To help users acquire site and structural information for the recording stations, the Engineering Data Center is preparing Internet pages for CISN strong-motion stations. At the time of this paper, we are still in the process of creating Internet pages for the CSMIP stations. For ground response stations, a total of more than 600 Internet pages have been completed. For each station, the page contains information on location, elevation, and site geology, and also a photograph of the station. Also included are the modification date of the Internet page and the source of the station data. Figure 3 shows an example of a typical page for a ground response station.

For the other station types, detailed information regarding the instrumented structure is included to describe the station. Shown in Figure 4 is an example of a building Internet page. In the figure, basic data as well as detailed design information and sensor layouts of the instrumented building are listed. Also, the image of the building sensor layout is available at full scale so that users can click on the link to view the image full size as shown in Figure 5. Figure 6 shows another example of a building Internet page for a building station instrumented by USGS/NSMP. Internet pages of lifeline and special station types such as bridges, dams and geotechnical arrays will have similar formats as the building page with changes in some field entries. An example for a dam station is shown in Figure 7. Creation of the Internet web pages for structural stations is in progress.

Once the Internet pages for the CISN strong-motion stations have been prepared, the contents of the station Internet pages will be updated when there are changes to station lists. A utility program module has been developed to automatically update the station Internet pages.

The TriNet/CISN Engineering Data Center and the COSMOS Virtual Data Center

The COSMOS virtual data center (Archuleta, 2000) is a web based virtual library of primarily ground response strong-motion data from networks and stations throughout the world. The primary features of the virtual data center are to allow users to search its database, to provide users easy access to the data, and to allow data collecting agencies to be the source of the data. In terms of functionality, the COSMOS virtual data center and the TriNet/CISN Engineering Data Center complement and will be linked to each other. The TriNet/CISN Engineering Data Center provides data immediately after earthquakes and provides detailed information on structural stations not available in the COSMOS data center. The large database search and access of ground motion records that the COSMOS data center has developed will not be duplicated in the TriNet/CISN Engineering Data Center.

Even though the TriNet/CISN Engineering Data Center will not support full database search and access features, it will allow users to search for recorded strong-motion data and information on various structures. The design of the search function of the TriNet/CISN Engineering Data Center is to provide engineers a tool to access strong-motion records based on structure system such as structure design type, structure height, and the level of ground accelerations, etc. Structural engineers will be able to quickly access records of structural response for the type of building of interest for different earthquakes without going through every event in the Data Center. The search function of the Engineering Data Center is currently in prototype stage development, and will be finalized with engineering staff of CSMIP and NSMP in conjunction with the compilation of structure design information for structure Internet pages of the CISN stations.

Future Plans

The Governor signed the California budget in July 2001, which includes funds for the CISN. The primary missions of the CISN are to operate statewide seismic monitoring and to provide tools for emergency responders and earthquake engineers to reduce damage from earthquakes. As to the Engineering Data Center, the development of the data center is continuing as planned and it will become fully operational under CISN. In terms of data exchange and communication, we plan to increase the interactions with the other CISN Data Centers and to improve robustness of established data communication pathways. Methods of data exchange for strong ground motion and station data with collaborative agencies, primarily NSMP, are in development. With integrated data, the IQR will be a key feature of the Engineering Data Center. Site and structural information of CISN instrumented stations will be compiled for Web access. When the compilation of site and structural information of stations is completed, the search feature of the TriNet/CISN Engineering Data Center will become available. The station data will be updated routinely as new stations are installed and/or existing stations are upgraded.

Summary

The TriNet/CISN Engineering Data Center will manage strong-motion data for applications in earthquake engineering and the development of the data center is summarized below:

- A prototype Internet Quick Report has been developed to provide earthquake engineering users rapid and easy access to strong-motion records and processed data for recent earthquakes recorded by all five CISN institutions. The prototype IQR is currently linked to the CSMIP web site and can be accessed via the Internet address:

  http://docinet3.consrv.ca.gov /csmip/iqr_dist.htm

- The Engineering Data Center will provide users rapid, detailed information on instrumented structures and other stations including location, site geology, structure system, sensor layouts, etc.

- Developing station information pages in web accessible format is continuing with more than 600 ground response station pages and eight structure pages completed.

- The Engineering Data Center will provide users a search function for accessing strong-motion data from various earthquakes based on the designs of instrumented stations instead of the sources of earthquakes.

References

Archuleta, R. (2000). "COSMOS Virtual Data Center", in SMIP2000 Seminar on Utilization of Strong-Motion Data, 2000, 97-114.

Shakal, A.F. and C.W. Scrivner (2000). "TriNet Engineering Strong Motion Data Center", in SMIP2000 Seminar on Utilization of Strong-Motion Data, 2000, 115-124.

Combined TriNet/CISN Strong-Motion Data Set

Internet Quick Report

Portola Earthquake of Aug 10, 2001

Information on Earthquake : Location, magnitude and TriNet/CISN ShakeMap

Stations listed in **Increasing Epicentral Distance** (Alternatively, select alphabetical listing)

Station Name	Station No./ID	Network	Dist. (km)	Horiz Apk (g)		View	Download
				Ground	Struct.		
Nevada City - New Bullards Bar Dam	77756	CDMG	65	.004	.061		- -
Martis Creek Dam	01133	ACOE	72	.017	.022	- -	- -
Reno - SP Power Co.	02023	USGS	85	.014	- -	- -	- -
Palermo - Fire Station	77350	CDMG	90	.011	- -		- -
Carson City - Nevada Community College	02019	USGS	103	.005	- -	- -	- -
Meyers - South Lake Tahoe	66038	CDMG	120	.007	- -	- -	- -
Silver Springs - Fire Station	02018	USGS	130	.010	- -	- -	- -
Sacramento - 801 K St Basement	67990	CDMG	157	.004	- -	- -	- -
Sacramento - State Capitol Bldg	67508	CDMG	158	Trig.	- -	- -	- -

Return to Home Page

Figure 1. An example of the prototype Internet Quick Report table sorted in epicentral distance order for the M5.5 earthquake near Portola, CA on Aug. 10, 2001. The two stations in the table with processed strong-motion records available for viewing have the View buttons enabled.

Combined TriNet/CISN Strong-Motion Data Set

Internet Quick Report

Portola Earthquake of Aug 10, 2001

Information on Earthquake : Location, magnitude and TriNet/CISN ShakeMap

Stations listed in **Alphabetical Order** (Alternatively, select increasing epicentral distance listing)

Station Name	Station No./ID	Network	Dist. (km)	Horiz Apk (g)		View	Download
				Ground	Struct.		
Carson City - Nevada Community College	02019	USGS	103	.005	- -	- -	- -
Martis Creek Dam	01133	ACOE	72	.017	.022	- -	- -
Meyers - South Lake Tahoe	66038	CDMG	120	.007	- -	- -	- -
Nevada City - New Bullards Bar Dam	77756	CDMG	65	.004	.061		- -
Palermo - Fire Station	77350	CDMG	90	.011	- -		- -
Reno - SP Power Co.	02023	USGS	85	.014	- -	- -	- -
Sacramento - 801 K St Basement	67990	CDMG	157	.004	- -	- -	- -
Sacramento - State Capitol Bldg	67508	CDMG	158	Trig.	- -	- -	- -
Silver Springs - Fire Station	02018	USGS	130	.010	- -	- -	- -

Return to Home Page

Figure 2. The Internet Quick Report table sorted in alphabetical order of station name/location for the M5.5 earthquake near Portola, CA on Aug. 10, 2001.

Los Angeles - Temple & Hope	**Sta.No. 24611**
Network:	**CDMG/CSMIP**

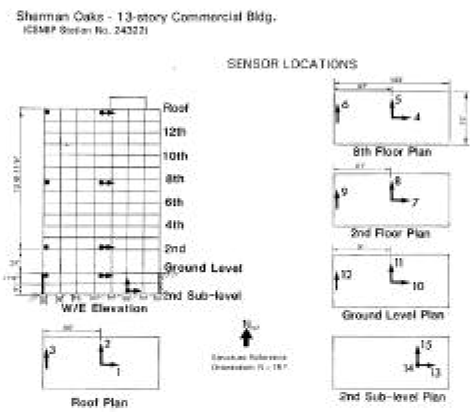
Latitude	34.059N
Longitude	118.246W
Elevation	117M
Site Geology	Rock (sedimentary)

Page Last Updated: 22 Aug 2001 16:38 Sta. List Ver. 3.9

Press* **[Back] *button in your web browser to return to the previous page.*

Figure 3. An example Internet page for a ground response station. In the page, basic information including location and site condition of the station as well as a photograph are included. The update date and the source of station data are shown at the bottom of the page.

Sherman Oaks - 13-story Commercial Bldg **(CSMIP Station No. 24322)**
Instrumented by: CDMG/SMIP



(Sensor Layout - click to enlarge)

Latitude	34.154N
Longitude	118.465W
Elevation	215M
Site Geology	Alluvium

No. of Stories above/below ground	13/2
Plan Shape	Rectangular
Base Dimensions	209 x 125 ft (63.7 x 38.1 m)
Typical Floor Dimensions	193 x 75 ft (58.8 x 22.9 m)
Design Date	1964
Instrumentation	1977, 15 accelerometers, on 6 levels

Vertical Load Carrying System	4.5 in. (11.4 cm) concrete slabs supported by concrete beams and columns.
Lateral Force Resisting System	Moment resisting concrete frames in both directions for the upper stories; concrete shear walls in the basements.
Foundation Type	Concrete piles.
Remarks	The building was retrofit with friction dampers after the 1994 Northridge Earthquake.

Sta. Last Updated: 16 Aug 2001 09:40 Sta. List Ver. 3.9

Press* *[Back]*** *button in your web browser to return to the previous page.*

Figure 4. An example Internet page for a building station. Details on the structural system of the instrumented building are included in addition to the basic station data.

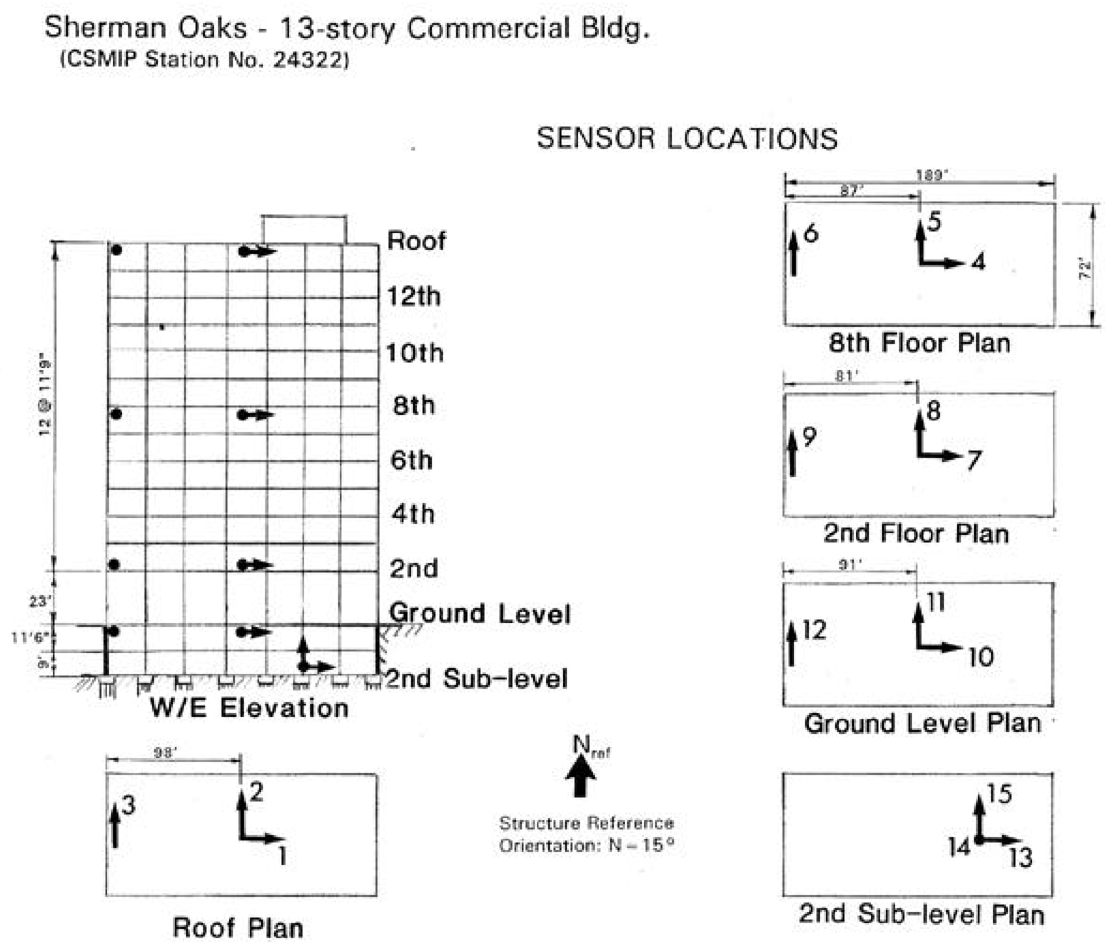
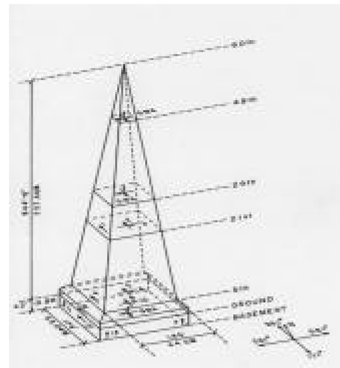


Figure 5. An image of the sensor layout for the building page shown in Figure 4. The full scale image is displayed when users click on the link to the sensor layout in the building page.

San Francisco - 60 story Office Bldg **(USGS Station No. 1239)**

Instrumented by: USGS/NSMP



(Sensor Layout - click to enlarge)

Latitude	37.795N
Longitude	122.401W
Elevation	4m
Site Geology	Alluvium, 150 ft (50m) over rock

No. of Stories above/below ground	60/3
Plan Shape	Square
Base Dimensions	174 x 174 ft (53 x 53 m)
Typical Floor Dimensions	Decreases with height
Design Date	1980
Instrumentation	1985, 22 accelerometers, on 6 levels

Vertical Load Carrying System	Concrete slabs on metal decks supported by steel beams and columns.
Lateral Force Resisting System	Steel moment frames in the upper stories; concrete shear walls in the basements.
Foundation Type	9 ft (2.7 m) concrete mat foundation.
Remarks	Landmark pyramidal building in San Francisco.

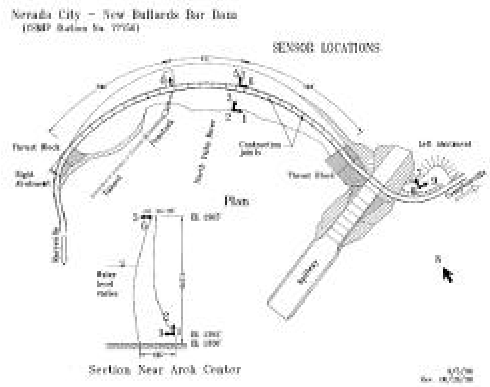
Page Last Updated: 06 Sep 2001 17:20

Press* **[Back] *button in your web browser to return to the previous page.*

Figure 6. An example Internet page for a building station instrumented by USGS/NSMP.

Nevada City - New Bullards Bar Dam **(CSMIP Station No. 77756)**

Instrumented by: CDMG/SMIP



(Sensor Layout - click to enlarge)

Latitude	39.393N
Longitude	121.141W
Elevation	604M
Site Geology	Granitic rock

Height	Dam Height 645' (19.7m)
Plan Shape	Multi-radius circular
Base Dimension	- -
Structure Dimension	Crest Length 1918' (585m)
Design Date	- -
Instrumentation	1998, 9 accelerometers, on crest, toe and abutment

Vertical Load Carrying System	Concrete arch (thickness varies from 35' on crest to 185' at foundation) dam
Lateral Force Resisting System	Concrete arch dam
Foundation Type	- -
Remarks	- -

Page Last Updated: 22 Aug 2001 16:38 Sta. List Ver. 3.9

Press **[Back] button in your web browser to return to the previous page.*

Figure 7. An example Internet page for a lifeline structure station. The format of the page is similar to the building page shown in Figure 4 except that some field designations are unique for this structure type.

IMPLICATIONS OF STRONG MOTION DATA FROM THE 2001 NISQUALLY, WASHINGTON EARTHQUAKE

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Summary

Approximately 100 strong-motion digital accelerographs recorded ground motions throughout the Pacific Northwest during the M 6.8 Nisqually earthquake, which occurred near Olympia on the subducted Juan de Fuca plate in the same general vicinity of the M7.1 1949 and M6.5 1965 events. Although many ground-motion records were obtained, only two buildings (DNR in Olympia and the Crowne Plaza Hotel in Seattle) recorded the shaking.

The peak ground acceleration (PGA) data from the Nisqually earthquake exhibited a higher rate of attenuation with distance than predicted by representative attenuation equations, an observation attributed mainly to the historical processing of older, strong motion paper and film records above a certain PGA threshold. Nevertheless, PGA values from the few records from the 1949 and 1965 earthquakes are within the band of PGA values from the Nisqually earthquake. In fact, records from common or nearby sites (within 100m) during these three earthquakes are similar when allowances are made for differences in magnitude and size of the recording stations.

The above observations, which pertain to stiff soil motions, suggest the Nisqually earthquake was a typical Puget Sound intraplate subduction event. However, this conclusion may not be valid in the softer soil deposits of the Duwamish River Valley in the industrial area of South Seattle where widespread liquefaction was observed during all three events. Strong motions were recorded at several of these soft soil sites that liquefied during the Nisqually earthquake with PGA's ranging from 0.25 to 0.30 g, the highest values generally recorded in the region from this event. The anomaly is the 1949 Seattle accelerogram, also recorded in this area (Army District site) on soft soil but with acceleration levels around a factor of 4 less than the soft soil Nisqually motions. This site, within 500m of the Duwamish River, showed no apparent signs of liquefaction during the 1949, 1965, and 2001 earthquakes, whereas, the historical evidence indicates that many of the same strong motion sites that liquefied during the Nisqually earthquake also liquefied during the 1949 and 1965 events. Although these observations suggest that the Army District site may have anomalously low site response, it is difficult to imagine that the actual ground motion at this site during the Nisqually earthquake was

significantly less (by factors of 5 to 10 in spectral acceleration within some period bands) than the motions at the other strong motion sites that did liquefy during this event. A resolution of this issue is important because the question posed by structural engineers engaged in post-Nisqually seismic retrofit of buildings in South Seattle is whether consistently strong motions have been and will continue to be observed on soft soil sites in this area during future intraplate events, which are a dominate contributor to the seismic hazard in Puget Sound. A continually operating station at the Army District site would have helped address the question.

Another interesting observation from the Nisqually earthquake was the site response in South Seattle. The soft soil and nearly soft rock records from this area indicated relative site amplification factors of 2 to 3 in response spectra across a wide oscillator period band from 0 to 5 sec. Estimates of soft soil motions from the SHAKE code were in fair to good agreement with observed motions provided both liquefaction and non-liquefaction cases were modeled. The latter case represents the soil profile prior to the onset of liquefaction, which appears to have occurred several seconds after the first S-wave arrival at one of the strong motion stations.

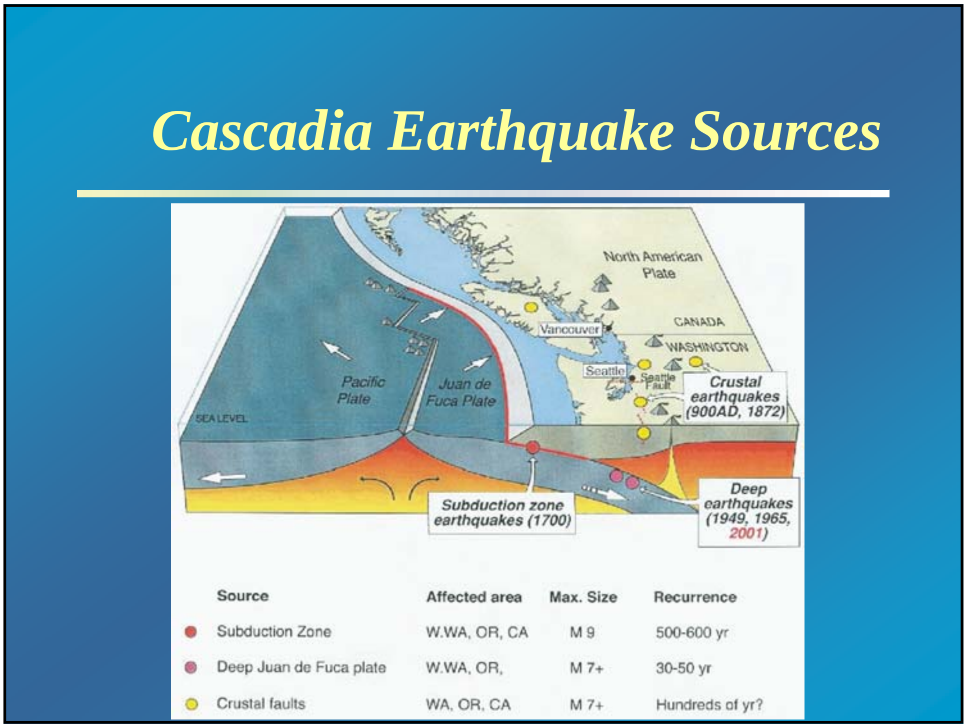
Engineering Implications

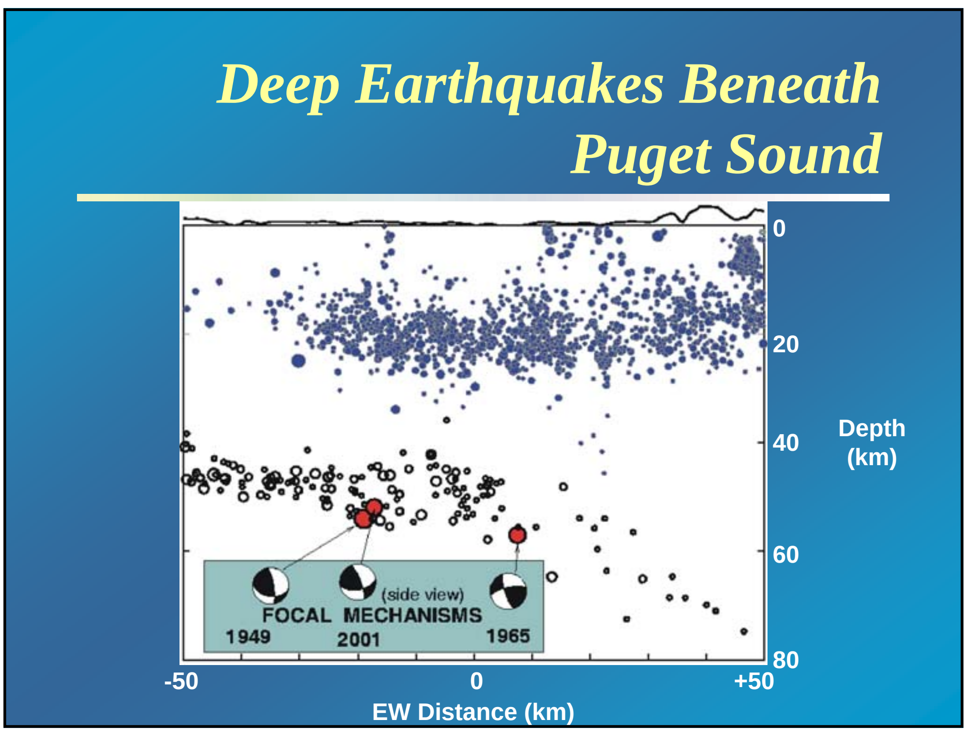
Nisqually Earthquake
Ground-Motion Data

URS

Presentation

- Background
- Comparison with 1949 and 1965
- South Seattle data


Cascadia Earthquake Sources
North American Plate
CANADA
WASHINGTON
Vancouver
Seattle
Seattle Fault
Pacific Plate
Juan de Fuca Plate
SEA LEVEL
Crustal earthquakes (900AD, 1872)
Subduction zone earthquakes (1700)
Deep earthquakes (1949, 1965, 2001)
Source
Affected area
Max. Size
Recurrence
Subduction Zone
W.WA, OR, CA
M 9
500-600 yr
Deep Juan de Fuca plate
W.WA, OR,
M 7+
30-50 yr
Crustal faults
WA, OR, CA
M 7+
Hundreds of yr?

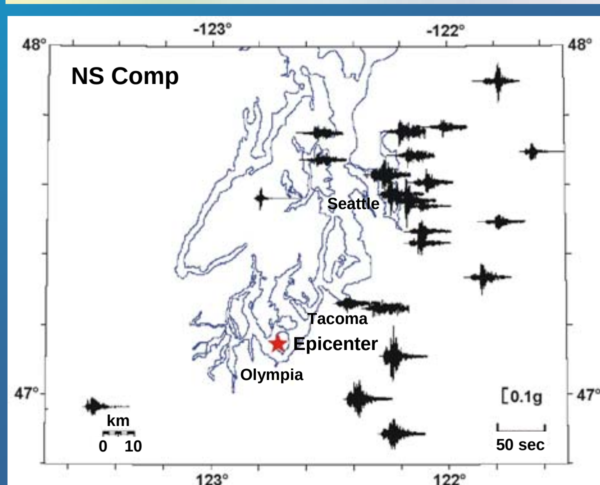

Deep Earthquakes Beneath Puget Sound
0
20
40
60
80
Depth (km)
(side view)
FOCAL MECHANISMS
1949
2001
1965
-50
0
+50
EW Distance (km)

Two Instrumented Buildings

Olympia
DNR Building
- **6 Stories**
- **11 Channels**

Seattle
Crowne Plaza Hotel
- **34 Stories**
- **12 Channels**

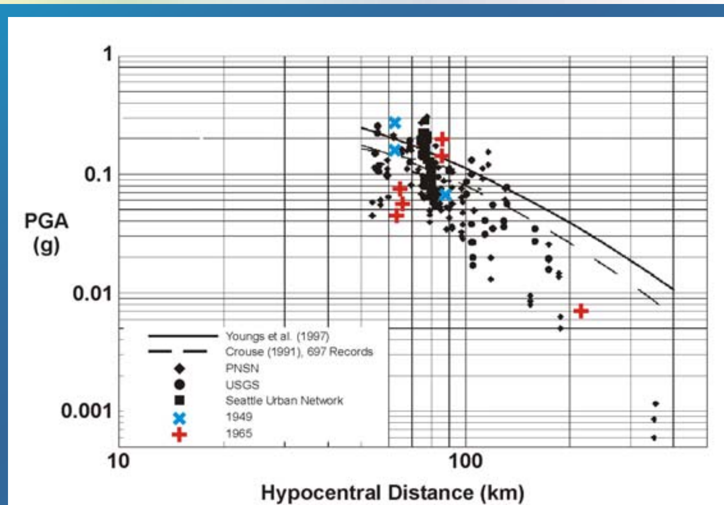
Regional Accelerograms

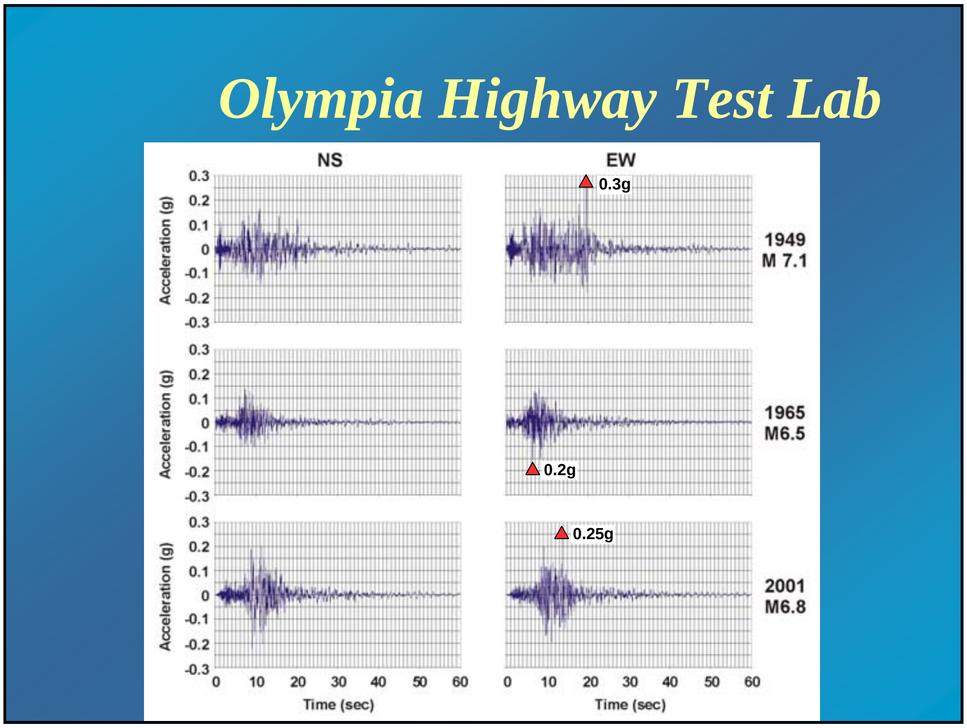


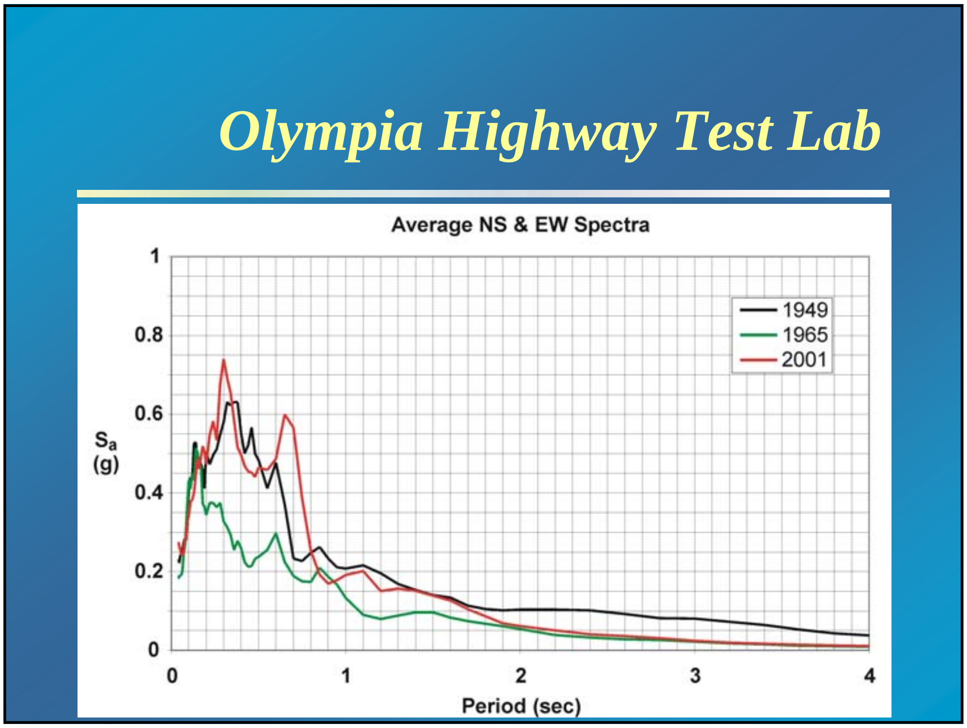
- ~100 records
- Three arrays

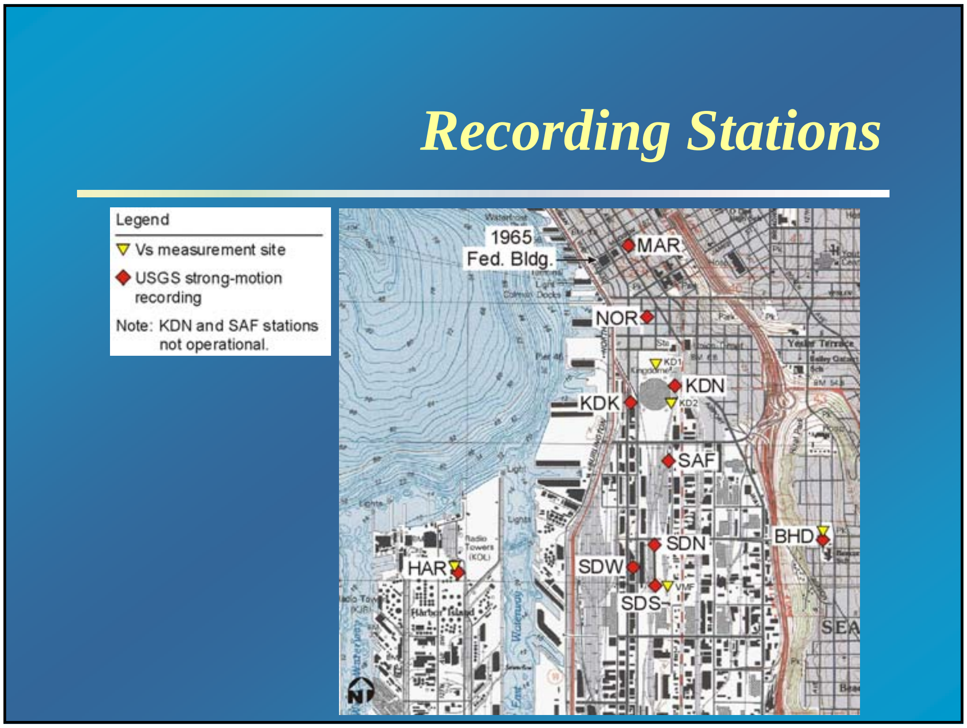
How do 2001 data compare to 1949 and 1965 data?

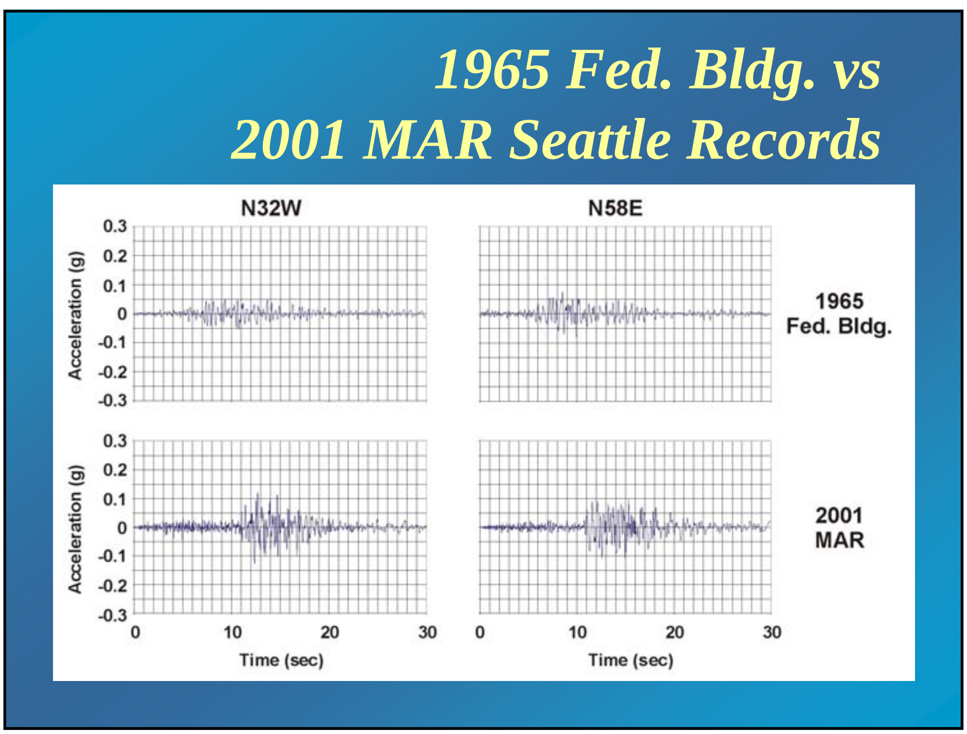
PGA vs Hypocentral Distance Soil Sites

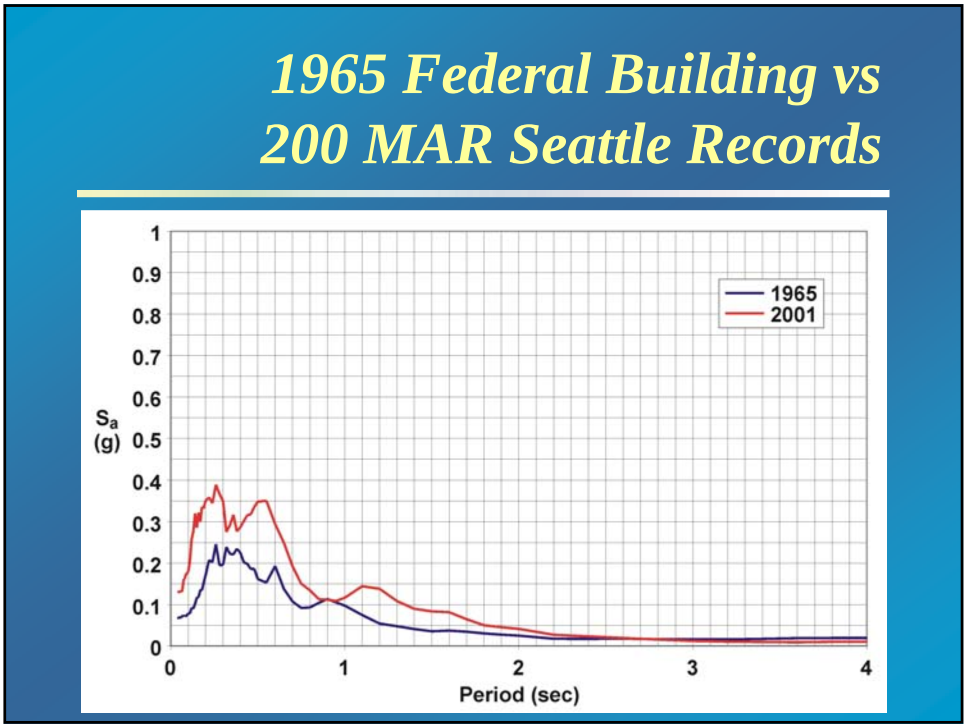


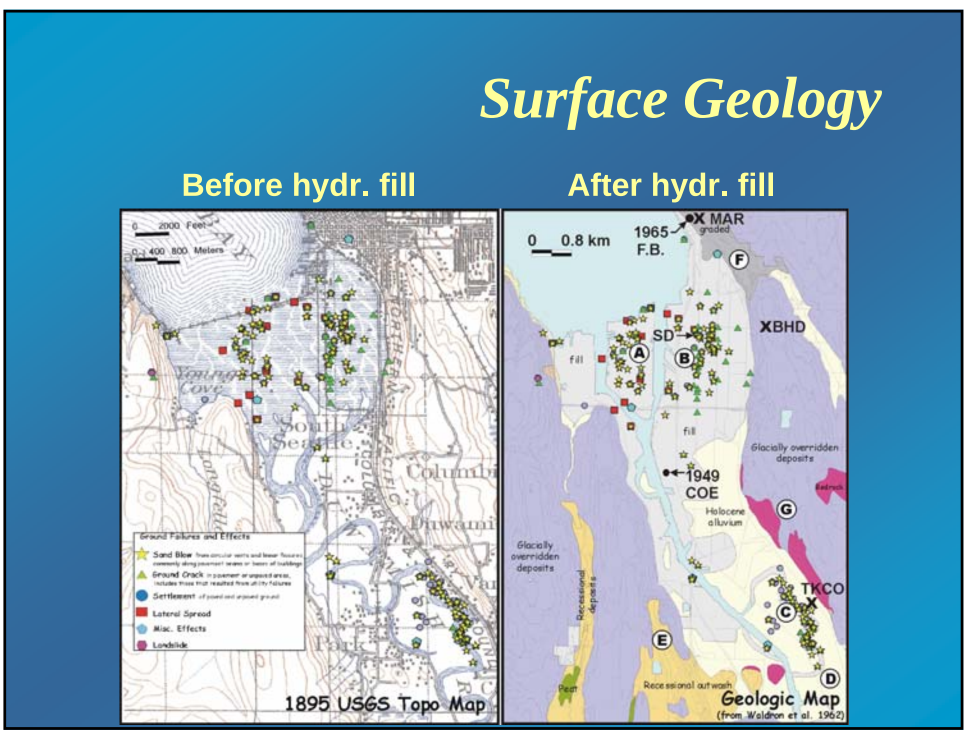

Olympia Highway Test Lab
NS
EW
Acceleration (g)
0.3g
1949
M 7.1
1965
M6.5
0.2g
0.25g
2001
M6.8
Time (sec)

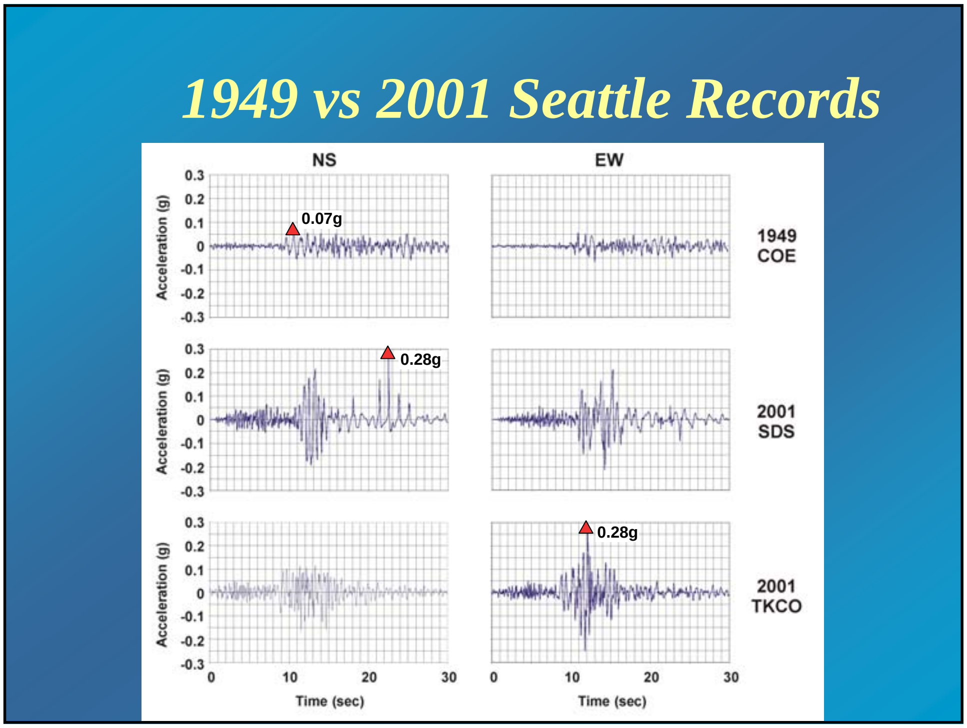

Olympia Highway Test Lab
Average NS & EW Spectra
1949
1965
2001
Sa (g)
Period (sec)

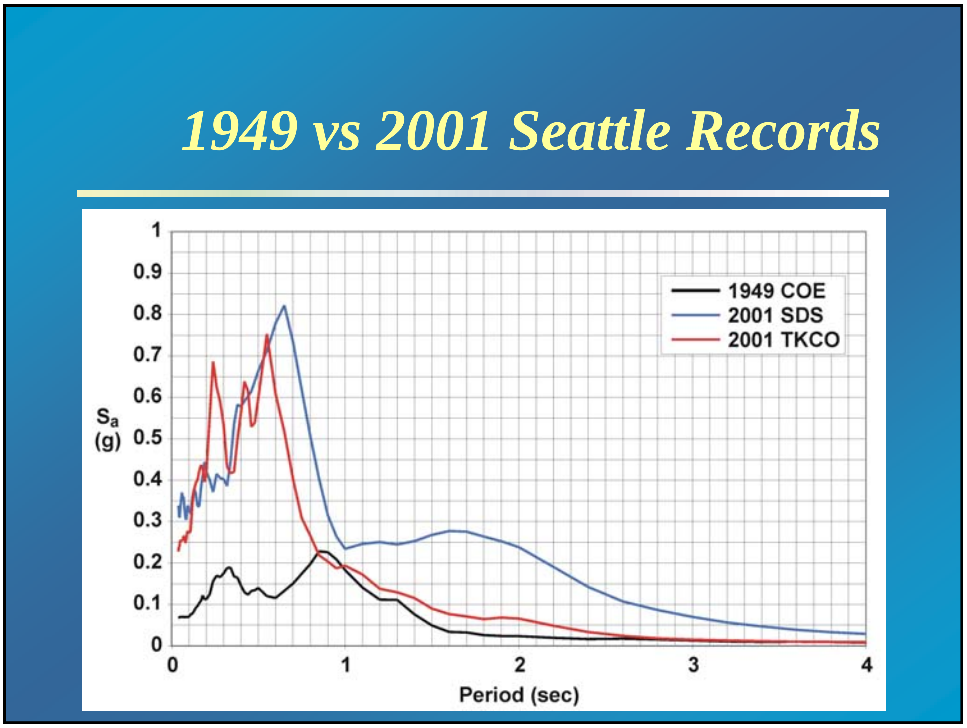

Recording Stations
Legend
Vs measurement site
USGS strong-motion recording
Note: KDN and SAF stations not operational.
1965 Fed. Bldg.
MAR
NOR
KD1
KDN
KDK
KD2
SAF
BHD
SDN
HAR
SDW
SDS
SEA


1965 Fed. Bldg. vs
2001 MAR Seattle Records
N32W
N58E
Acceleration (g)
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
1965 Fed. Bldg.
2001 MAR
0
10
20
30
Time (sec)

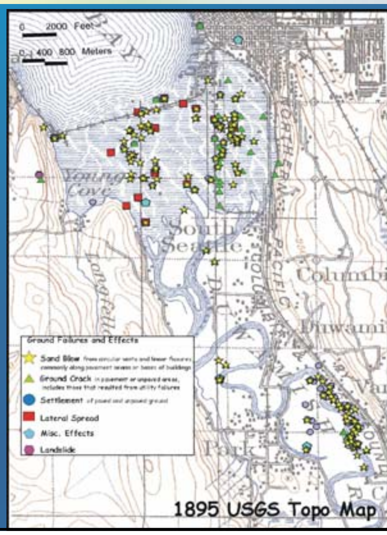

1965 Federal Building vs
200 MAR Seattle Records
Sa
(g)
Period (sec)
1965
2001
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4

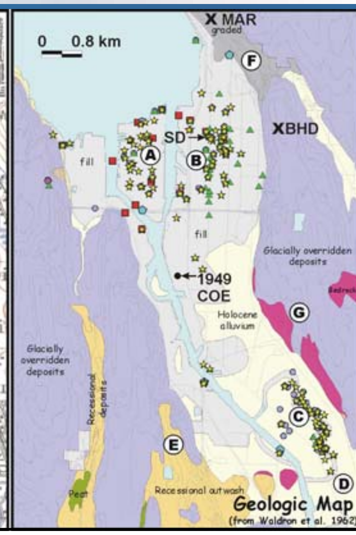

Surface Geology
Before hydr. fill
After hydr. fill
1895 USGS Topo Map
Ground Failures and Effects
Sand Blow
Ground Crack
Settlement
Lateral Spread
Misc. Effects
Landslide
0 0.8 km
1965 F.B.
X MAR
SD
XBHD
fill
1949 COE
Holocene alluvium
Glacially overridden deposits
Recessional deposits
Recessional outwash
TKCO
Geologic Map
(from Waldron et al. 1962)


1949 vs 2001 Seattle Records
NS
EW
0.07g
0.28g
0.28g
1949
COE
2001
SDS
2001
TKCO
Acceleration (g)
Time (sec)


1949 vs 2001 Seattle Records
1949 COE
2001 SDS
2001 TKCO
Sa
(g)
Period (sec)

SODO District Records





Recording Stations

Legend

- Vs measurement site
- USGS strong-motion recording

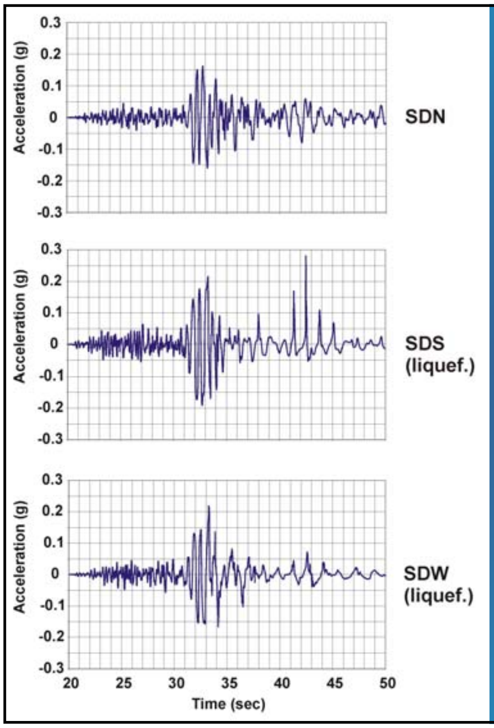
Note: KDN and SAF stations not operational.

SDN and SDS Stations

SDW Station

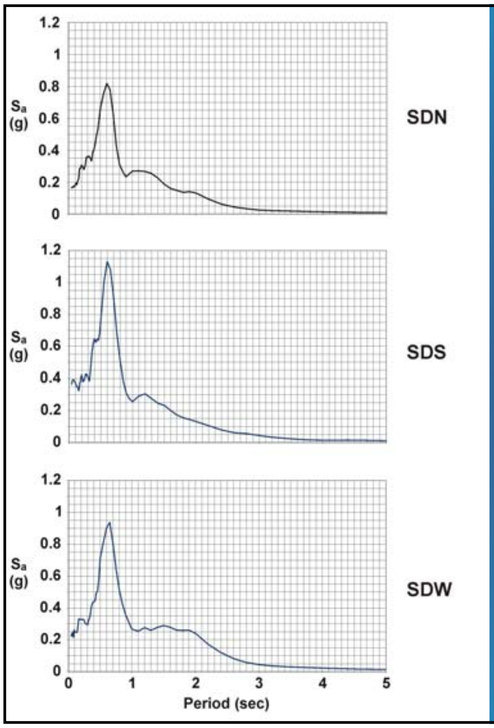
Front

Back



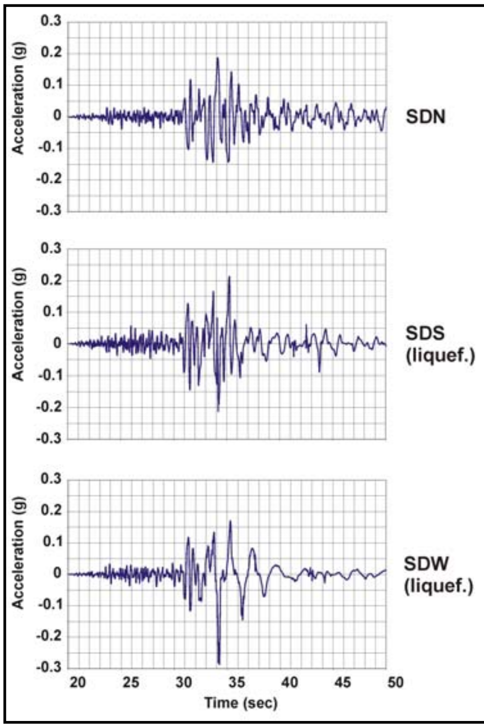
SODO District Soft Soil, NS Records

- Strong 1/2-sec period motion 31-34 sec
- Suggestion of liquifaction



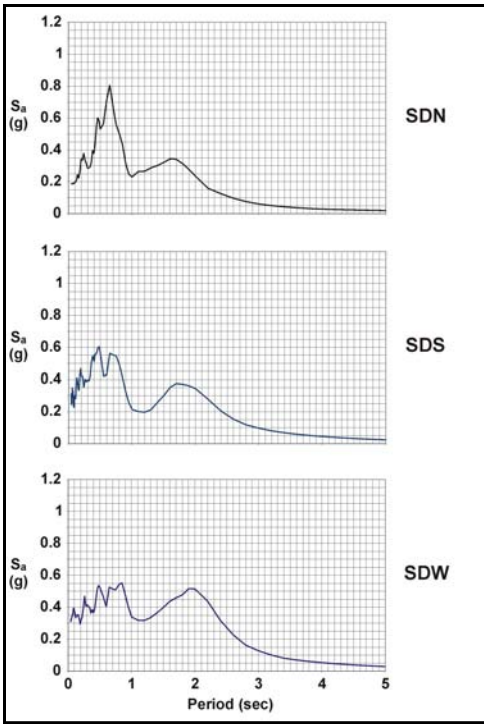
NS Response Spectra, $\xi = 5\%$

- Peak ~ 1 g @ 0.6 sec



SODO District: Soft Soil, EW Records

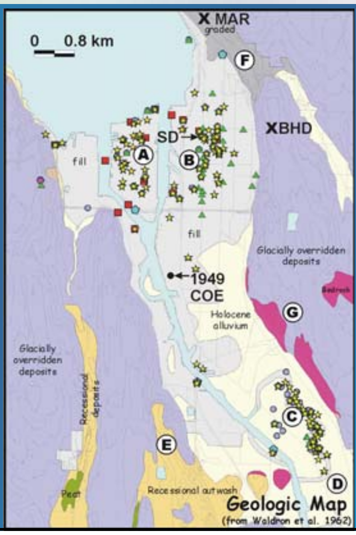
- Strong evidence of liquefaction @ ~ 34 sec @ SDW
- Apparent 2-sec motion



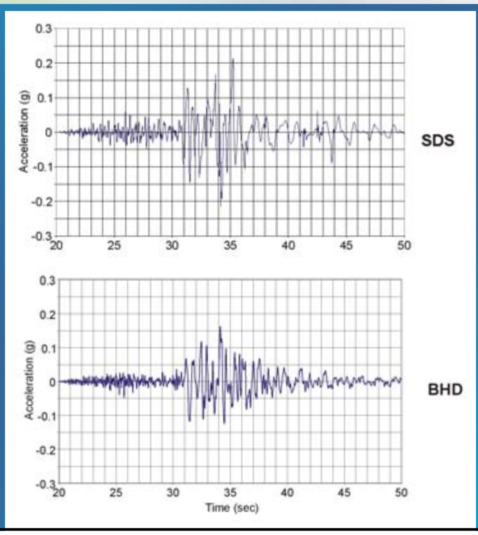
EW Response Spectra, $\xi = 5\%$

- S_a = 0.4-0.5g @ 2 sec!
- Period shift
  1.6 sec (SDN)
  2.0 sec (SDW)

Site Response



Soft vs. Stiff Soil EW Records

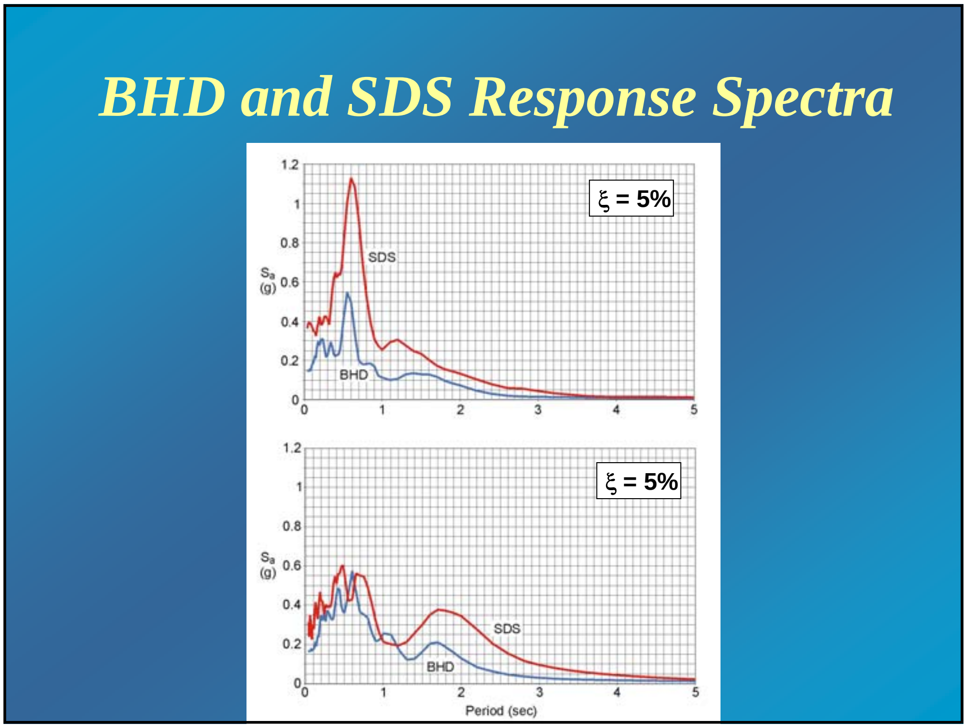


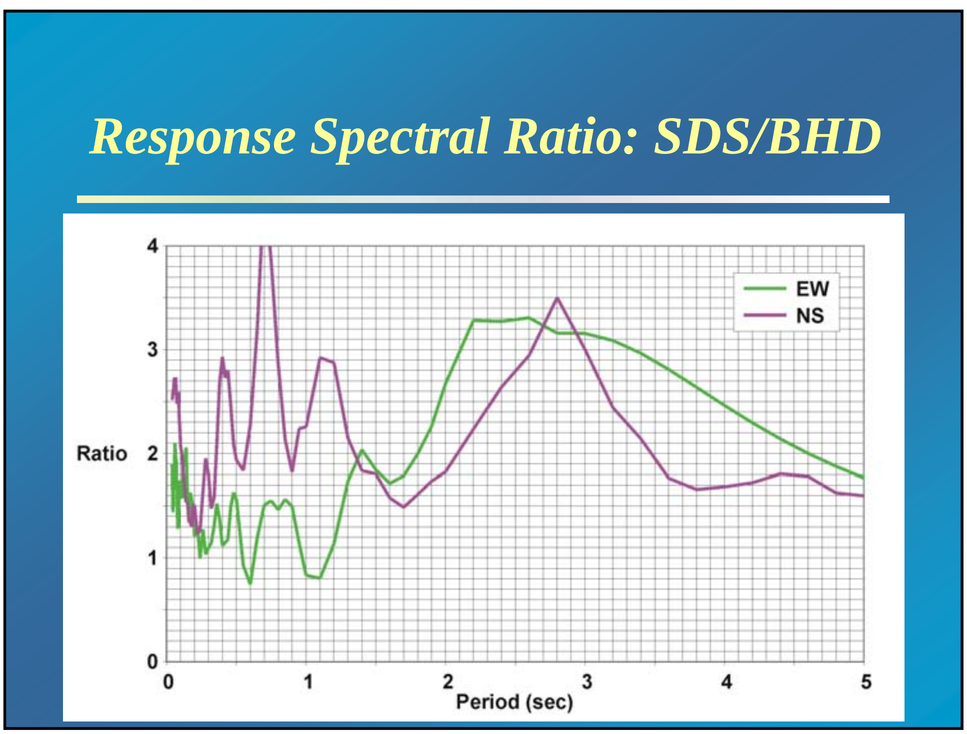
S_F Soil

$\overline{V}_S^{30m}$ = 148 m/s

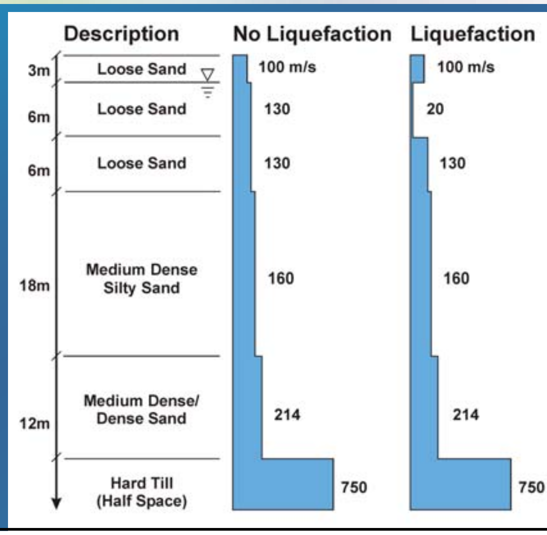
S_C Soil

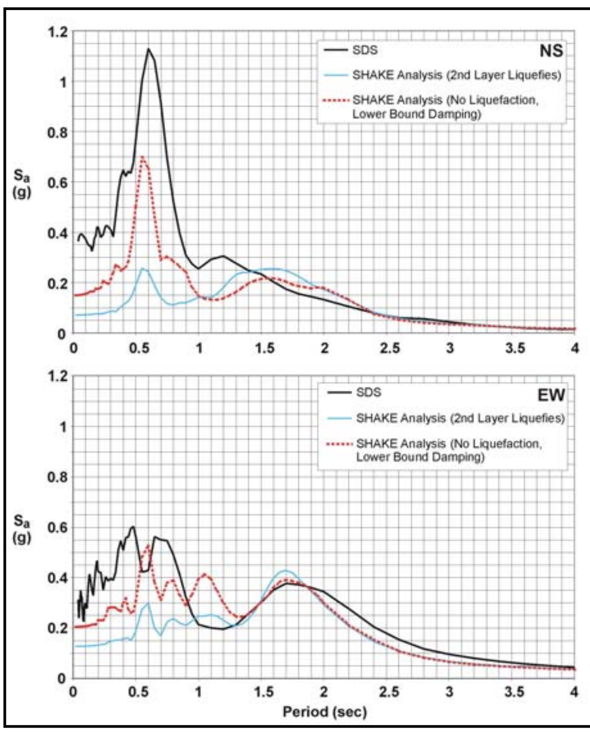
$\overline{V}_S^{30m}$ = 680 m/s


BHD and SDS Response Spectra
ξ = 5%
SDS
BHD
Sa (g)
ξ = 5%
SDS
BHD
Sa (g)
Period (sec)


Response Spectral Ratio: SDS/BHD
EW
NS
Ratio
Period (sec)

Soil and V_s Profiles - SDS





Shake Prediction vs SDS Recording

2001 Nisqually Earthquake Conclusions

- Average ground motions
- Interesting site response
  - Liquefaction
  - Nonlinear response

2001 Nisqually Earthquake Recommendations

- Reoccupy 1949 and 1965 stations
- Reoccupy and enhance SODO sites
  - Add downhole array at SDS
- Measure ambient building periods

GUIDELINES FOR UTILIZING STRONG-MOTION AND SHAKEMAP DATA IN POSTEARTHQUAKE RESPONSE: AN OVERVIEW

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ABSTRACT

The ATC-54 Report, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, under preparation by the Applied Technology Council for the California Division of Mines and Geology, provides guidance on (1) the use of near-real-time computer-generated ground-motion maps in emergency response, and (2) the use and interpretation of strong-motion data to evaluate the earthquake response of buildings, bridges, and dams in the immediate postearthquake aftermath. Guidance is also provided on the collection of data describing the characteristics and performance of structures in which, or near which, strong-motion data have been recorded.

INTRODUCTION

Background. Since the installation of the initial network of nine strong-motion instruments at ground sites and in buildings in California in 1932 (Matthiesen, 1980), the number of strong-motion recording stations and records has grown dramatically. Today there are more than 1000 instrumented sites and structures in California, including buildings, dams, bridges, and other lifeline structures. The instruments are operated by a wide variety of agencies and owners, including the California Division of Mines and Geology (CDMG), California Division of Water Resources, California Department of Transportation, U. S. Geological Survey (USGS), U.S. Bureau of Reclamation, U.S. Army Corp of Engineers, several universities and university-affiliated centers, utility companies in northern and southern California, and owners of buildings where instruments have been mandated by building code requirements. Hundreds of strong-motion time histories have been recorded at these stations, resulting primarily from large damaging earthquakes, such as the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes. Such data are available in digital form from the principal network operators (CDMG and the USGS) and other sources, including the world wide web virtual data center operated by the Consortium of Organizations for Strong-Motion Observation Systems (COSMOS).

Over the last 40 to 50 years, the technology for recording, analyzing, and representing strong-motion data has also advanced significantly. Major advances have included: the development of rapid scanning and processing techniques for converting photographic analog records to digital format; the development and deployment of digital accelerographs; the development of new computer analytical methods that use strong-motion records to verify and refine computer models of structural response and to compute estimated component forces and displacements; and, most recently, the introduction of computer-generated ground-motion maps that provide overviews of the regional distribution of ground shaking within minutes, and without human intervention, after damaging earthquakes.

Collectively the existing network of strong-motion instruments, the existing sets of strong-motion data, and the available techniques and technology for processing, analyzing, and displaying strong-motion data provide an ideal set of tools and information for postearthquake response planning and execution, as well as postearthquake evaluation of structures. In recognition of the enormous potential of these tools and information, and with the realization that practicing professionals do not have guidance readily available on how to take advantage of these current technical capabilities, CDMG awarded a Year 2000 California Strong-Motion Instrumentation Program (CSMIP) Data Interpretation Project to the Applied Technology Council (ATC) to prepare the needed guidance. Specifically, the contract required that ATC develop *Guidelines* to: (1) facilitate improved emergency response with the use of near-real-time computer-generated ground-motion maps and (2) facilitate postearthquake evaluation of structures using strong-motion data from ground sites and instrumented buildings, bridges, and dams. Under this project ATC will also provide guidance on the collection of data describing the characteristics and performance of structures in which, or near which, strong-motion data have been recorded.

Guidelines Development Process. Now under development by ATC, the *Guidelines* are being developed through a multi-step approach by a multi-disciplinary team of experienced specialists in earthquake and geotechnical engineering, risk analysis, geographic information systems (GIS), and emergency response planning. Initially, the project team identified and described the state-of-the-art in available data resources, building and lifeline inventory data, GIS hazard maps, and loss estimation tools. The next step was to define the state-of-the-practice in emergency response planning at the state, regional, and local level, as well as in postearthquake structural surveys and evaluations. Based on this information, primarily developed through literature reviews and interviews with key individuals in various agencies and organizations throughout the state, an assessment was made of the existing capabilities in emergency response planning and postearthquake evaluation of structures. This assessment served as the basis for determining the level of information and extent of guidance to be provided in the *Guidelines*. Upon completion, the *Guidelines* will be presented in draft form at a Users' Workshop organized to solicit input on the draft. The final version of the *Guidelines* will be based on input received at the Users' Workshop, as well as review comments from the CSMIP staff and the California Seismic Safety Commission's Strong-Motion Instrumentation Advisory Committee (SMIAC).

Paper Focus and Contents. This paper is one of three papers presented in the SMIP01 Seminar describing the contents of the resource document being prepared under this project, namely *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, to be published as the ATC-54 Report (ATC, in preparation). The intent of this paper is to provide an overview of the ATC-54 *Guidelines* and pertinent background information, including a description of the format, content, and preparation of computer-generated ground-motion maps, a new technology that shows promise for emergency response planning and execution. We begin with a description of the purpose and scope of the *Guidelines*, followed by a brief description of computer-generated ground-motion maps. The remainder of the paper is devoted to a description of the *Guidelines* contents and to a set of preliminary recommendations for improving the use of strong-motion data and maps in postearthquake response planning and execution and postearthquake evaluation of structures. The companion papers, "Guidelines for Utilizing ShakeMaps for Emergency Response", by S.A. King et al., and "Guidelines for Utilizing Strong-Motion Data for Evaluation of Structures", by A. G. Brady and C. Rojahn, provide more in-depth information pertaining to the use of ShakeMaps and to the use of strong-motion data for structural evaluation, respectively.

PURPOSE AND SCOPE OF THE *GUIDELINES*

The *Guidelines* are intended to increase the utilization of strong ground motion data for improving postearthquake response and postearthquake evaluation of buildings, bridges, and dams. They are also intended, as is the goal of all CSMIP data utilization projects, to improve the understanding of strong ground shaking and the response of structures so as to improve seismic design codes and practices. This document is not intended to be a loss-estimation methodology; however, as discussed in the *Guidelines*, much emphasis is placed on the use of strong-motion data within existing loss-estimation tools for estimating the regional impacts of earthquakes.

The audience for this document is diverse and includes local, regional, and state agencies with postearthquake responsibilities; design professionals; facility owners; policy makers; and researchers concerned with the various uses of strong ground-motion data. It is anticipated that most readers will not be interested in all sections of the *Guidelines*.

The *Guidelines* focus on two distinct topics. The first concerns effective means for using computer-generated ground-motion maps in postearthquake response. The intended use of this part of the document is to provide guidance on the development and implementation of applications using such maps for emergency response. Specifically, the applications focus on assessing the following:

- extent of damaged buildings and planning related safety evaluation inspections
- condition of hospitals and other emergency response structures
- impact on utility systems and transportation networks
- extent of liquefaction, landslide, and inundation
- casualties and associated need for victim extraction from damaged structures
- extent of debris from collapsed structures
- sheltering needs
- extent of possible hazardous materials release
- insurance claims
- other postearthquake disaster and recovery ramifications

With respect to these applications, the *Guidelines* are intended to help users evaluate existing practices and policies, plan for future improvements, coordinate mutual aid, allocate resources, and design and budget for mitigation and planning exercises and programs.

The second topic concerns the rapid utilization of near-real-time instrumental recordings from ground and structure stations for postearthquake response and evaluation of structures. In this regard, the *Guidelines* are intended to help with damage determination, rapid estimation of structural distortions (e.g., inter-story displacements), and mathematical model identification and verification. Information is provided on (1) how to interpret data from strong-motion instruments to evaluate structural response rapidly, and (2) the form, type, and extent of data (in the immediate earthquake aftermath) to be collected from structures in the vicinity of strong-motion recordings.

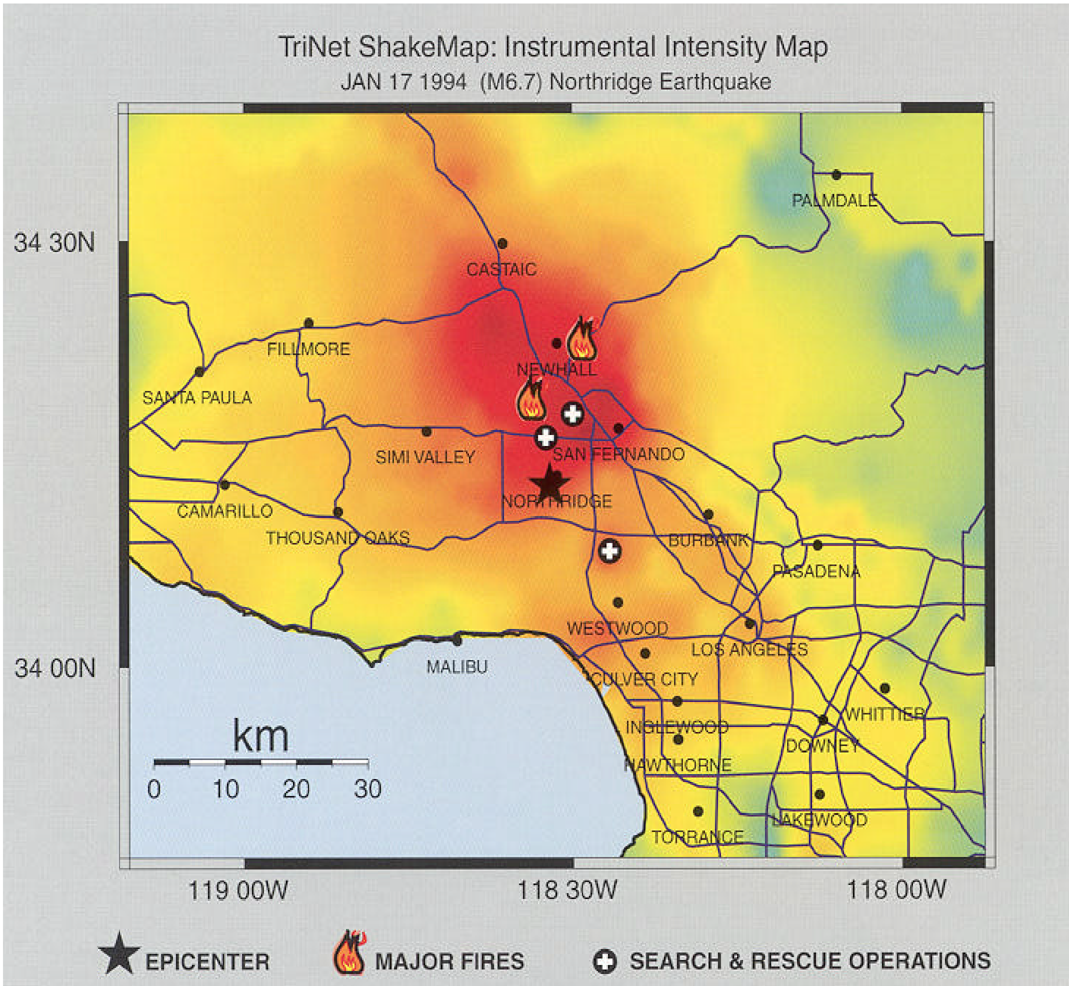
No new research, other than the determination of the state-of-the-art and state-of-the-practice, was undertaken under this project; rather the intent was to create one resource document containing broad guidance on the use of ShakeMaps and currently available resources and techniques for rapid evaluation of structures using strong-motion data.

COMPUTER-GENERATED GROUND-MOTION MAPS

One of the primary focuses of the *Guidelines* is on the computer-generated ground-motion maps produced by the TriNet program. TriNet is a five-year collaborative effort among the California Institute of Technology (Caltech), the U. S. Geological Survey, and the California Division of Mines and Geology to create an effective real-time earthquake information system for southern California and eventually northern California. A complete description of the history, background, and products of TriNet is available on the web site www.trinet.org.

TriNet ShakeMaps, an example of which is shown in Figure 1, are representations of the ground shaking produced by earthquakes. They are generated automatically following moderate and large earthquakes. These are preliminary ground shaking maps, normally posted within several minutes of the earthquake origin time. They show the distribution of peak ground acceleration and velocity, spectral acceleration at three periods, and an instrumentally-derived, estimated distribution of Modified Mercalli Intensity. The Instrumental Intensity Map is based on a combined regression of recorded peak acceleration and velocity amplitudes. In order to stabilize contouring and minimize the misrepresentation of the ground-motion pattern due to data gaps, the data are augmented with predicted values in areas without recorded data. Given the epicenter and magnitude, peak motion amplitudes in sparse regions are estimated from attenuation curves. As the real-time TriNet station density increases with the passage of time, the reliance on predicted values will decrease.

In addition to producing near-real-time ground-shaking maps, the TriNet ShakeMap program also produces earthquake scenario ground-shaking maps. The earthquake scenarios describe the expected ground motions and effects of specific hypothetical large earthquakes. The maps are used in planning and coordinating emergency response by utilities, emergency responders, and other agencies. The scenario earthquakes provide a more realistic example for training exercises and loss-estimation studies, and can be generated for any hypothetical or historic earthquake.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1. TriNet ShakeMap for the 1994 Northridge, California earthquake (USGS, 2000).

The steps involve assuming that a particular fault or fault segment will (or did) rupture over a certain length, estimating the likely magnitude of the earthquake, and estimating the ground shaking at all locations in the chosen area around the fault. The ground motions are estimated using an empirical attenuation relationship, which is a predictive relationship that allows the estimation of the peak ground motions at a given distance and for an assumed magnitude.

The web address for the TriNet ShakeMaps is www.trinet.org/shake/. Users of the *Guidelines* are encouraged to visit this site often, not only for the near-real-time ground shaking maps, but also for the new or improved products that are periodically added to the web site.

ORGANIZATION OF THE *GUIDELINES*

The *Guidelines* are intended to be used by a diverse audience, many of whom will only be interested in specific sections of the document. In addition, the document is written for the most basic level of user, so more advanced users will likely be able to skim certain sections within their areas of interest.

The *Guidelines* are organized into five chapters so that users will be able to target quickly their sections of interest (Figure 2). Chapter 1 contains introductory material and pertinent background information. Chapters 2 through 4 provide procedures for using strong ground-motion maps and recordings in emergency response, for evaluating the performance of individual buildings, bridges and dams, and for collecting and documenting postearthquake investigation data, respectively. The final chapter provides a summary of the *Guidelines* and highlights recommendations for more effectively utilizing strong ground-motion maps and data.

ATC-54: *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*

Contents

1. Introduction and Background
2. Use of Computer-Generated Ground-Motion Maps in Postearthquake Response
3. Interpretation of Strong-Motion Records for Postearthquake Structural Response Evaluation
4. Documentation of Structural Attributes and Performance in the Vicinity of Ground Motion Recordings
5. Summary and Recommendations
6. Appendices

Figure 2. Guidelines Table of Contents

Chapter 1 provides a broad range of information designed to familiarize the reader with computer-generated ground motion maps, sources of strong-motion data and computer-generated ground-motion maps (including current web site addresses of principal providers). Chapter 1 also introduces current strategic planning for seismic monitoring statewide, including the goals for the next five years of the California Integrated Seismic Network[1] (CISN). The discussion notes that as efforts are undertaken over the next five years to meet these goals, as well as the goals of the proposed Advanced National Seismic System[2] (ANSS), the overview of strong-motion data resources in California provided in Chapter 1 is certain to be superceded by more current information. In general, it is noted that the efforts under the CISN and ANSS will

[1] The California Integrated Seismic Network is being proposed to provide the organizational framework to integrate the existing, separate monitoring networks in California into a single seismic monitoring system. The CISN Draft Strategic Plan for 2002-2006 includes the following goals: (1) operate a reliable and robust statewide system to record earthquake ground motions over the relevant range of frequencies and shaking levels; (2) distribute information about earthquakes rapidly after their occurrence for emergency response and public information; (3) create an easily accessible archive of California earthquake data for engineering and seismological research, including waveform data and derived products; (4) maintain CISN infrastructure as a reliable state-of-the-art data collection, processing, and information distribution system; (5) apply the latest research and technology to develop new algorithms for analyzing earthquake data and extracting more detailed information for new user products; and (6) maximize the use and benefit of real-time seismic information and other rapidly evolving tools and technologies through technology transfer to the user community.

[2] The Advanced National Seismic System Network, as currently planned, will be a nationwide network of at least 7,000 shaking measurement systems, both on the ground and in buildings (USGS, 2000).

provide additional resources and programs that will undoubtedly result in the more effective implementation of the *Guidelines.*

Chapter 2 covers procedures for using computer-generated maps for postearthquake response. The chapter begins with a section on the general framework for the use of real-time data for emergency response, including the data resources and procedures that are commonly related to the utilization of strong ground motion data for the various areas of emergency response. The subsequent sections review the particular interests and needs of the ten emergency response areas listed above. Real and hypothetical examples are included to illustrate the use of ShakeMap products in emergency response.

Procedures for using and interpreting strong-motion records to evaluate the postearthquake response of structures, including structures in or on which strong-motion instruments have been installed as well as non-instrumented structures, are described in Chapter 3. The chapter covers buildings, bridges, and dams. For each of these three structure type, the most commonly used procedures are described, including assumptions about structural properties, applicable structure types, minimum instrumentation and data required, steps to be taken, outputs, and example applications. For buildings, the *Guidelines* address:

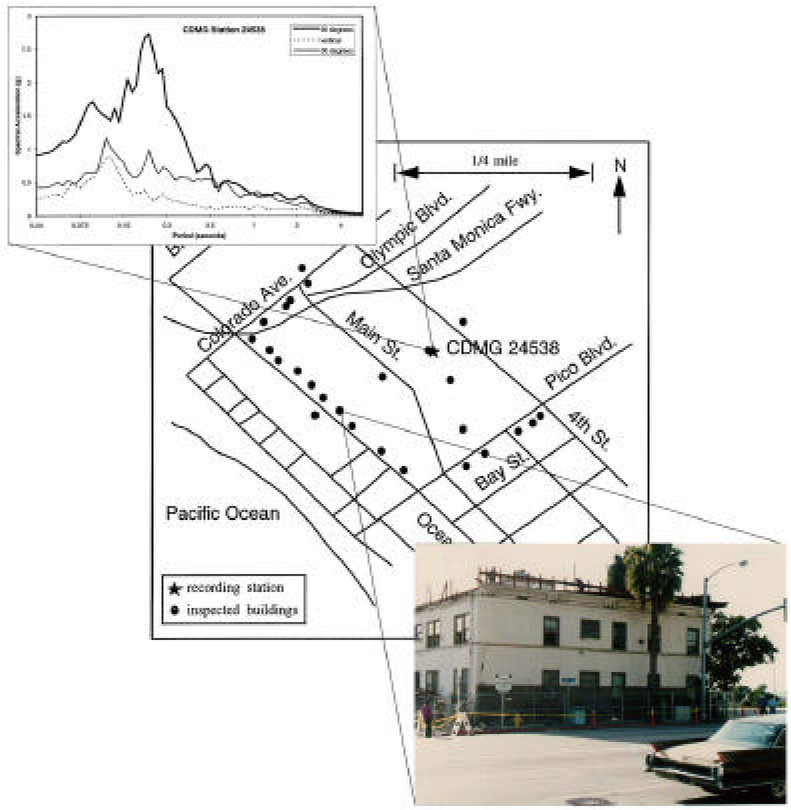
- damage indicators that are sometimes evident in strong-motion data from instrumented buildings;
- procedures for rapid visual and hand-calculator analysis of strong-motion data from instrumented buildings (using data collected both at the ground level and in the upper stories, including perhaps film records);
- rapid estimation of changes in building period during strong ground shaking, using visual inspection and Fourier analysis techniques;
- rapid estimation of inter-story drifts, including estimates based on response spectra calculated for ground motion records and estimates based on displacement time-history analysis involving differencing of displacement time histories calculated from acceleration time-histories recorded at different story levels; and
- procedures to verify and define mathematical models of building behavior.

Similar procedures are provided for bridges and dams, but not in such detail.

Chapter 4 focuses on procedures for documenting structural attributes and performance in the vicinity of ground motion recordings. Similar to Chapter 3, this chapter covers procedures for buildings, bridges, and dams and provides guidance for both instrumented and non-instrumented structures. For non-instrumented buildings, the procedures draw heavily on the approach used after the 1994 Northridge earthquake to collect data on the characteristics and performance of more than 500 buildings within 1000 feet of strong-motion recording sites (see Figure 3). For each structure type, the steps for data collection, data formatting and archiving, and data analysis and dissemination are included.

ATC-38, Development of a Database on the Performance of Structures Near Strong-Motion Recordings

This project was formulated by ATC, the USGS, and several other northern California organizations immediately after the 1994 Northridge earthquake. The purpose was to document systematically the effects of the earthquake on structures adjacent to locations of strong ground motion recordings. Shortly after the earthquake, ATC dispatched teams of licensed civil and structural engineers to the areas of strong ground shaking to survey approximately 500 buildings in the vicinity of 30 strong-motion recording sites (within approximately 1000 feet) to document the characteristics and performance of buildings and other structures.



Prior to the site investigations, ATC provided training sessions to all inspectors instructing them on how to document their findings on the ATC-developed standardized survey forms, as well as in photographs. The data collected at each building site include information on the structure size, age, and location; the structural framing system and other important structural characteristics; nonstructural characteristics; geotechnical effects; performance characteristics; casualties; and estimated time to restore the facility to pre-earthquake usability. Damage is defined in both qualitative terms relating to repairability and in quantitative terms (estimated damage repair costs as a percentage of building replacement value). The survey data were archived in a relational database management system and mapped in a geographic information system. Digitized versions of the strong ground-motion recordings, as well as response spectra, for each site in the vicinity of which buildings were inspected, were also collected and archived with the survey data. The survey data and strong-motion information are documented in the ATC-38 Report and CD-ROM, *Database on the Performance of Structures Near Strong-Motion Recordings: 1994 Northridge, California, Earthquake*, which is available from the Applied Technology Council.

Figure 3. An Overview of the ATC-38 Database on the Performance of Structures Near Strong-Motion Recordings: 1994 Northridge, California, Earthquake (ATC, 2000).

A summary of the *Guidelines* is given in Chapter 5, along with an emphasis on the key recommendations for how the strong-motion maps and data can be effectively utilized for postearthquake response and evaluation of structures. The recommendations highlighted in this chapter, as well as in other sections of the *Guidelines*, are based on input from current and potential users obtained from interviews and the Users' Workshop. Additional input was provided by the project Resource and Advisory Panel.

Three appendices are included that contain supplemental information. Appendix A describes the process that was used to develop this document, Appendix B includes a summary of the most commonly used regional earthquake loss-estimation methods, and Appendix C includes a summary of the most commonly used linear and nonlinear structural analysis software programs.

References and a Glossary listing the acronyms and notation used in the document follow the appendices.

PRELIMINARY RECOMMENDATIONS

Based on the efforts to date, the Project Team has developed the following preliminary recommendations for improving the use of strong-motion data and maps in postearthquake response planning and execution and postearthquake evaluation of structures:

1. For emergency response topics:
    - Develop or improve electronic databases containing facility information;
    - Convert information to GIS format and develop method for importing ShakeMap;
    - Automate simple damage and loss models based on specific post-event needs;
    - Consider use of maps that depict damage-potential ground-motion parameters (e.g., results from Bozorgnia's Year 2000 CSMIP Data Interpretation Project);
    - Automate the ranking of regions or facilities for response or inspection, respectively, if possible;
    - If already using loss-estimation software, improve databases for local regions;
    - Test system regularly;
    - Incorporate personal knowledge in all automated procedures to help convince personnel to start to trust computer output for first-order screening and ranking; and
    - Produce ShakeMaps at a larger scale, such as 1:15,000.
2. For evaluating data recorded in structures:
    - Develop pre-event computer models of the structure for the various types of analysis described;
    - Develop means for quickly gathering and processing data; and
    - Test system regularly.

3. For post-earthquake data collection:
   - Have procedures, personnel and funding ready before the event happens, including criteria for selecting facilities to inspect, and standardized data-collection forms;
   - Have computer database tables set up with trained personnel for data entry; and
   - Train inspectors in advance to collect the needed information using the standardized forms.
4. For strong-motion data and maps:
   - Increase density of instrumentation by:
     - Instrumenting additional buildings and other structures; and
     - Installing more free-field stations for improving ShakeMap interpolation between stations.

REFERENCES

ATC, in preparation, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, ATC-54 Report, Applied Technology Council, Redwood City, California.

ATC, 2000, *Database on the Performance of Structures Near Strong-Motion Recordings: 1994 Northridge, California, Earthquake*, ATC-38 Report, Applied Technology Council, Redwood City, California.

Matthiesen, R. B., 1980, "Building Instrumentation Programs," in *Proceedings, Workshop on Interpretation of Strong-Motion Earthquake Records in and/or Near Buildings*, UCLA Report No. 8015, University of California at Los Angeles.

USGS, 2000, *ANSS-Advanced National Seismic Sy*stem, U. S. Geological Survey Fact Sheet 075-00, Reston, Virginia.

ACKNOWLEDGMENTS

The authors gratefully acknowledge Gerald Brady, Sarah Nathe, Maurice Power, and Evan Reis, who gathered data and summarized the state-of-the-art and state-of-the-practice, and the Project Resource and Advisory Group, who provided guidance on various aspects of the project: Thalia Anagnos, Lloyd Cluff, Charles Eadie, Terry Haney, Anne Kiremidjian, Ronald Mayes, Andrew Merovich, Lawrence Reaveley, James Russell, and Chris Tokas.

GUIDELINES FOR UTILIZING SHAKEMAPS FOR EMERGENCY RESPONSE

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ABSTRACT

This paper describes portions of the document, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, currently being developed by the Applied Technology Council (ATC) for the California Division of Mines and Geology's (CDMG) Strong Motion Instrumentation Program (SMIP) 2000 Data Interpretation Project. The focus of this paper is on the use of computer-generated ground-motion maps, i.e., TriNet ShakeMaps, for emergency response applications. Two companion papers presented at the SMIP01 Seminar, by C. Rojahn et al. and by A.G. Brady and C. Rojahn, focus, respectively, on the overall description of the *Guidelines* and on the use of strong-motion data for structural evaluation. The procedures outlined in this paper are a summary of the information contained in the current draft of the document, which addresses ShakeMap applications for ten areas of emergency response. The general framework is given here, with illustration for one application – damaged buildings and safety inspections.

INTRODUCTION

The development of the document, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, is a 2000 California Strong-Motion Instrumentation Program (CSMIP) Data Interpretation Project in progress by the Applied Technology Council (ATC) under contract to the California Division of Mines and Geology (CDMG). The primary objective of the *Guidelines* is to improve the state of the practice and facilitate improved emergency response and structural evaluation with the utilization of near real-time computer-generated ground-motion maps and strong-motion instrument recordings. The intended audience of the document includes emergency managers, contingency planners, government officials, risk managers, and practicing engineers.

The *Guidelines* focus on two primary topics. The first concerns the use of computer-generated ground-motion maps, such as TriNet ShakeMaps, in post-earthquake response. The intended use of this part of the document is to provide guidance on the development and implementation of applications using ShakeMap for emergency response. The second topic concerns the rapid utilization of near real-time instrumental recordings from ground and structure stations, so that the data will be particularly useful for post-earthquake response and evaluation of structures.

This paper is one of three papers presented at the SMIP01 Seminar that describe the in-progress development and anticipated contents of the document, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, to be published as the ATC-54 Report (ATC, in preparation). The focus of this paper is on the first of the two primary topics of the *Guidelines* discussed above – the use of computer-generated ground-motion maps, such as TriNet ShakeMaps, in post-earthquake response. The companion paper, "Guidelines for Utilizing Strong-Motion Data and ShakeMap Data in Post-Earthquake Response", by C. Rojahn, C.D. Comartin, and S.A. King provides an overview of the *Guidelines*, including the purpose, scope, development process, and contents. The second primary topic of the *Guidelines* – the use of strong-motion data for structural evaluation, is covered in the companion paper, "Guidelines for Utilization of Strong-Motion Data for Evaluation of Structures", by A.G. Brady and C. Rojahn.

This paper begins with a description of computer-generated ground-motion maps, in particular the TriNet ShakeMaps. The procedures for using ShakeMaps in post-earthquake response are discussed next, including how the procedures were developed, general principles and guidelines, essential information and basic steps, and limitation on the use of ShakeMaps. The *Guidelines* address ShakeMap applications for approximately ten areas of emergency response. Due to space limitations in this paper, the application description is limited to only one area – damaged buildings and safety inspections.

The material contained in this paper forms a portion of the *Guidelines* document, which is currently under development. The information has not yet been reviewed by intended users of the *Guidelines*, the CSMIP staff, the California Seismic Safety Commission's Strong Motion Instrumentation Advisory Committee (SMIAC), the ATC-54 Project Resource and Advisory Panel, or others, and as such should be considered preliminary and subject to revision.

COMPUTER-GENERATED GROUND-MOTION MAPS

In that portion of the *Guidelines* pertaining to computer-generated ground-motion maps, the focus is on ShakeMaps, produced by the TriNet program. TriNet is a five-year collaborative effort among the California Institute of Technology (Caltech), the United States Geological Survey (USGS), and the California Division of Mines and Geology (CDMG) to create an effective real-time earthquake information system for southern California and eventually northern California. A complete description of the history, background, and products of TriNet is available on the web site **www.trinet.org**. Most of the information described in this section is based on material contained in the ShakeMap section of the TriNet web site.

TriNet ShakeMaps are a representation of the ground shaking produced by an earthquake, an example of which is shown in Figure 1. They are generated automatically following moderate and large earthquakes. These are preliminary ground shaking maps, normally posted within several minutes of the earthquake origin time. They show the distribution of peak ground acceleration and velocity, spectral acceleration at three periods, and an instrumentally-derived, estimated Modified Mercalli Intensity. The Instrumental Intensity map is based on a combined regression of recorded peak acceleration and velocity amplitudes. In order to stabilize contouring and minimize the misrepresentation of the ground motion pattern due to data gaps, the data are augmented with predicted values in areas without recorded data. Given the epicenter and magnitude, peak motion amplitudes in sparse regions are estimated from attenuation curves. As the real-time TriNet station density increases, the reliance on predicted values will decrease.

In addition to producing near real-time ground shaking maps, the TriNet ShakeMap program also produces earthquake scenario ground shaking maps. The earthquake scenarios describe the expected ground motions and effects of specific hypothetical large earthquakes. The maps are used in planning and coordinating emergency response by utilities, emergency responders, and other agencies. The scenario earthquakes provide a more realistic example for training exercises and loss estimation studies, and can be generated for any hypothetical or historic earthquake. The steps involve assuming a particular fault or fault segment will (or did) rupture over a certain length, estimating the likely magnitude of the earthquake, and estimating the ground shaking at all locations in the chosen area around the fault. The ground motions are estimated using an empirical attenuation relationship, which is a predictive relationship that allows the estimation of the peak ground motions at a given distance and for an assumed magnitude.

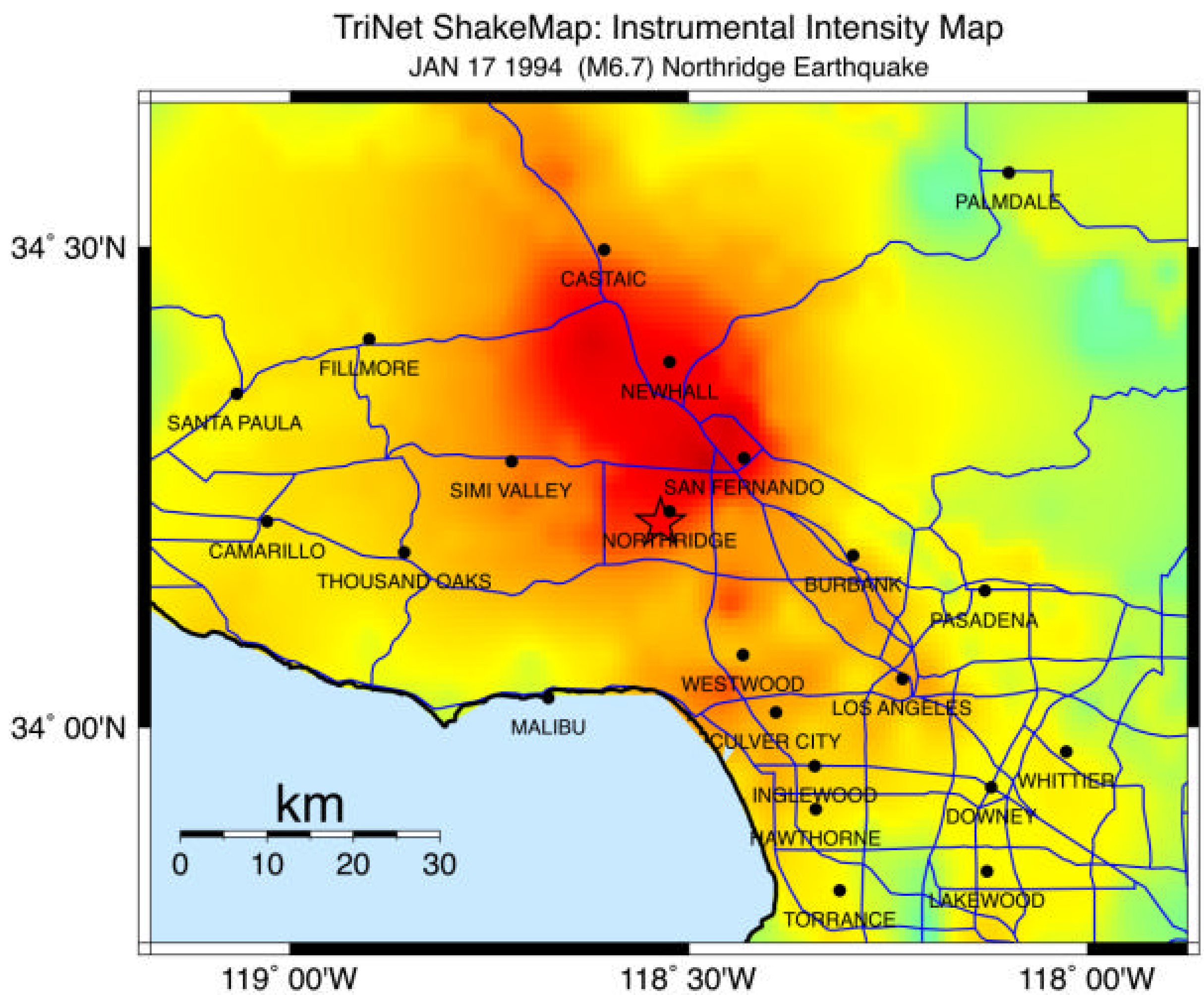
The web address for the TriNet ShakeMaps is **www.trinet.org/shake/**. Users of the *Guidelines* are encouraged to visit this site often, not only for the near real time ground shaking maps, but also for the new or improved products that are periodically added to the web site.

PROCEDURE FOR USING COMPUTER-GENERATED GROUND-MOTION MAPS IN POST-EARTHQUAKE RESPONSE

As discussed above, the *Guidelines* address the development and implementation of applications using ShakeMap for post-earthquake response, Specifically, the applications focus on the following emergency response topics:

- extent of damaged buildings and planning related safety evaluation inspections
- condition of hospitals and other emergency response structures
- impact on utility systems and transportation networks
- extent of liquefaction, landslide, and inundation
- casualties and associated need for victim extraction from damaged structures
- extent of debris from collapsed structures
- sheltering needs
- extent of possible hazardous materials release
- preliminary economic loss estimates
- management of insurance claims

With respect to these applications, the *Guidelines* are intended to help users evaluate existing practices and policies, plan for future improvements, coordinate mutual aid, allocate resources, and design and budget for mitigation and planning exercises and programs.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	*<.17*	*.17-1.4*	*1.4-3.9*	*3.9-9.2*	*9.2-18*	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	*16-31*	*31-60*	*60-116*	*>116*
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 1 *TriNet ShakeMap for the 1994 Northridge, California earthquake (image provided by David Wald, U.S. Geological Survey).*

Background

The *Guidelines* were developed through a multi-step approach, which is described in more detail in Appendix A of the document and in the companion paper by C. Rojahn, C.D. Comartin, and S.A. King presented at this seminar. The guidance provided on how to develop capabilities for using computer-generated ground-motion maps in post-earthquake response is the result of many months of effort by the project team members. They first identified and described the state-of-the-art in available data resources, building and lifeline inventory data, geographic information system (GIS) hazard maps, and loss estimation tools. Next, for each of the ten emergency response topics listed above, they defined the state-of-the practice at the state, regional, and local levels. Based on this information, primarily gathered through interviews with key individuals, an assessment was made of the existing capabilities in emergency response planning, i.e., how the identified available data resources are currently being used and how they might be utilized more effectively.

In the *Guidelines*, the procedures for using computer-generated ground-motion maps in post-earthquake response are described for each of the ten emergency response topics. This information is prefaced by a section that outlines the general framework for use of near real-time data, covering material that is common to the ten areas of emergency response. The general framework includes the essential information and basic steps, as well as the limitations to the ShakeMap applications, and is summarized below.

General Principles and Guidelines

There are several basic concepts related to the use of strong ground motion maps and data for post-earthquake response. The focus here is on emergency response – the decisions that are made immediately after an earthquake has occurred. Time and effective communication are critical, as the needs for quick and reliable decisions and information dissemination are typically the most important issues facing emergency managers. Given an earthquake occurrence, questions such as the following need to be immediately addressed:

- What has happened and where?
- How bad is it?
- How can I allocate my resources most effectively?

As discussed briefly in this paper and more thoroughly in the *Guidelines*, the use of near real-time ground-motion maps can provide information that helps answer these questions.

Essential Information

Near real-time ground-motion maps (i.e., TriNet ShakeMaps) provide excellent information on the distribution of shaking in the region affected by the earthquake. Post-earthquake response decisions can be made based only on the ground shaking information, however; these decisions require various levels of inference and are not making the most effective use of the ground shaking data. Combining the ground shaking information with other types of data for the region will allow for more reliable and meaningful emergency response decisions.

The basic information that is essential for making quick and reliable post-earthquake response decisions includes:

- Ground Shaking Data – information about the distribution of ground shaking in the region
- Facility Inventory Data – information about structures in the region
- Demographic Data – information about people who live or work in the region
- Vulnerability Data – information about how structures and people are typically affected by various levels of ground shaking

The most efficient procedure for storing, combining, and displaying these various types of data is through the use of a geographic information system (GIS). A GIS is similar to a regular database management system, except that in addition to dealing with tables of data, it has the added capability of storing and processing data on maps. Information on individual maps can be overlaid (or combined to form new maps) to show relationships and help with decision making, especially those that involve locations in a region.

A GIS with complete databases for a region is the ideal, but not often the reality, of those involved with post-earthquake response. The time and financial resources involved with setting up the system with required maps and data can be quite substantial, even for a small region. The procedures described in the *Guidelines* assume the most basic level of user in terms of experience and know-how, but not in terms of access to computer and data resources, as well as GIS or relational database management software. The purpose of the *Guidelines* is to outline the procedures for the most effective use of strong-motion data and maps, which in almost all cases involves combining the strong-motion maps and data with other types of data for the region.

Basic Steps

The basic steps for effectively using computer-generated ground-motion maps in post-earthquake response are outlined in this section. They are general, as the more specific information is described in the sections of the *Guidelines* that deal with the individual emergency response topics. Ideally, some of these steps would be done before an earthquake occurs, or the entire process could be done as a training/planning exercise. The steps include:

1. Download the relevant ShakeMaps that illustrate the distribution of ground shaking parameters in the region.

2. Assemble the relevant inventory data, such as building portfolio information, Census data, street maps, and utility system maps, that can be overlaid or combined with the ShakeMaps to identify areas or facilities subjected to high levels of shaking.

3. Estimate damage or loss to regions or facilities based on the combination of ground shaking levels and inventory information. Some users will rely on a specific loss estimation methodology or software for this step. The three most commonly used ones,

HAZUS (NIBS, 1999), ATC-13 (ATC, 1985), and EPEDAT (Eguchi, et al, 1997), are described in Appendix B of the *Guidelines*.

4. Combine or overlay additional inventory data, such as emergency vehicle locations, shelters, and hospitals, as needed to provide information for decision making.

Limitations

There are several general limitations that should be kept in mind when using the computer-generated ground-motion maps for post-earthquake response. The most important issues include the following; more specific ones are discussed in the sections of the *Guidelines* that deal with the individual emergency response topics:

- ShakeMaps are generated automatically after moderate and large earthquakes and are not initially checked by humans. They are based on recorded data and augmented with predicted values in areas without a sufficient number of recording instruments. It is possible that the distribution of shaking will be biased towards a high anomalous recording, such as the Tarzana record in the 1994 Northridge earthquake.

- Following an earthquake, users need to be able to rapidly update data and mapped information based on reports from the field and revised ShakeMaps.

- Inventory data needs to be kept up to date in terms of accuracy and completeness, especially with respect to locations and facility information.

APPLICATION TO DAMAGED BUILDINGS AND SAFETY INSPECTIONS

For each of the ten areas of emergency response listed previously, the *Guidelines* describe the procedures for effectively utilizing ShakeMaps for post-earthquake response by discussing the typical users and needs, the potential data resources, and the potential models or data analysis procedures. Examples, real or hypothetical, are included to illustrate the concepts. The remainder of this paper summarizes the information contained in the *Guidelines* for one of the ten areas of emergency response – damaged buildings and safety inspections.

Typical users and needs

Near real-time ground-motion data will be most useful in aiding engineers or officials in local jurisdictions with prioritizing building inspections within the first day or two following an event. In this application, the focus is on the use of ShakeMaps for help with making quick and reliable decisions, typically for a large group of buildings or for all buildings within a specific region. More advanced structural modeling for individual buildings using recorded instrumental data is covered in other sections of the *Guidelines*.

Following a moderate to large earthquake, a building owner or manager is under pressure from the occupants to have a trained professional inspect the building and determine whether or not it is safe to occupy. Owners and managers of multiple buildings, as well as the consulting engineers they hire for building investigation services, typically need some sort of priority ranking to effectively deal with occupancy decisions within a reasonable amount of time. Computer-generated ground-motion maps, such as ShakeMap, can be used to quickly determine the level of ground shaking experienced at each building and, when combined with structural and occupancy information, help illustrate which buildings should be inspected first.

An owner or manger of a single building is not likely to be interested in the ground shaking at the site, as this person will probably either call an engineer immediately after the event based on its magnitude and location or later after receiving reports of damage from the building occupants. Similarly, an owner or manager of several buildings clustered in a small region would assume that the ground motion is constant throughout the region, and would likely rely on an inspection priority scheme that relates only to building type and/or occupancy.

Local emergency response managers and building officials would use near real-time ground-motion maps to help prioritize the inspection of public and essential services buildings, as well as allocate staff or consultants for responding to citizen requests for assistance with building safety issues. In addition, this information could be used to notify residents or businesses about the potential loss of city services in specific areas, assign police and fire response to neighborhoods most likely to be damaged, establish the most critical locations to set up emergency shelters, and several other uses as described in the sections of the *Guidelines* focusing on these other applications.

Potential data resources

In order to effectively use computer-generated ground-shaking maps for prioritizing building inspections and determining regions of most severe damage, building information needs to be stored electronically and geographically referenced. Most building owners or managers have electronic databases of their facilities; however, few have this information in a geographic information system (GIS). As described previously, one of the basic analysis steps involves being able to overlay a map of facilities on the map of ground shaking distribution in the region. Converting existing electronic or paper building inventory databases to GIS format is not as difficult or time consuming as it would seem, given the user-friendly and reasonably-priced GIS software that is now available. In addition, the ability to store and manipulate building inventory data in a GIS has many benefits beyond responding to an earthquake.

Overlaying a map of buildings on a map of ground shaking distribution in the region will identify which buildings were subjected to the various levels of ground shaking. To make the most effective use of the GIS data and capabilities, the building data should include structural information, attributes that are often not part of typical building inventories. The exact structural information to be collected and stored depends on the resources available for database development (some information may require a structural engineer), as well as how the data are going to be used in the future, for post-earthquake response and other building management decisions. A relatively complete record in a building inventory database would include the following information:

- Location: address, ZIP code, Census tract, longitude and latitude
- Size: square footage, height, number of stories
- Construction data: year built, lateral load system, gravity load system,
- Occupancy data: use type, daytime occupancy, nighttime occupancy
- Other: existing condition, retrofits, irregularities, importance factor

The information listed above is sufficient in most cases to make first order estimates of earthquake damage and loss to buildings when combined with a map of ground shaking distribution. More detailed information on building attributes, such as that collected during rapid visual screening using ATC-21 procedures (ATC, 1988), results from detailed building evaluations using FEMA 310 (ASCE, 1998) or push-over analysis investigations to develop capacity curves, would provide an improved capability for estimating building vulnerability. Most building owners and managers are not likely to make the investment required to hire structural engineers to develop these data, as the cost versus the perceived benefit in automatically generating more detailed damage estimates for post-earthquake inspection is not readily apparent. They do, however, see the benefit in having engineers write reports on the structural quality of select critical buildings, and for the engineers to be available after an earthquake to use these reports in their damage assessment.

For regional use of computer-generated ground-shaking maps, building information is typically stored by summary statistics for the area. For example, Census tract or ZIP code maps can have the number or square footage of each building type as an attribute in the GIS database. The information is typically not very detailed because it is aggregated by geographic region and any building-specific information will be lost in the aggregation. Additionally, the use of the data for first-order prioritization of damaged areas, does not warrant more detailed building-specific information. Regional databases of building inventory can be found in existing loss estimation software or can be developed using techniques described in the loss estimation methodology reports. Information on loss estimation methods and software is described in Appendix B of the *Guidelines*.

Potential models or data analysis procedures

Building owners and managers typically rank life safety as the top priority and business operation as the next most important for prioritizing post-earthquake building inspections. In order to use near real-time ground motion information they must develop at least four important pieces of information before the earthquake occurs. These are similar to the four basic steps outlined previously, and include:

- A database of their facilities with information on occupancy and the importance to overall business operations.
- A list of engineers who are contracted to provide post-earthquake inspections. In lieu of this, companies will rely on building officials from the local jurisdiction to make inspections.
- A software program (typically a GIS) that can be used to access and store the near real-time ground motion maps and combine them with the facility database.

- Models that: (1) relate the level of ground shaking to damage and loss of function for each building (such as those found in the loss estimation methods described in Appendix B of the *Guidelines*), and (2) assign an inspection priority to each building (this is user-dependent). The level of sophistication of the models depends on the financial resources of the building owner or manager, the in-house technical capabilities, the level of detail in the facility databases, and the desired results. These models can include:
    1. Simple visual inspection of map overlays to make qualitative decisions
    2. Programs within the software that will do the analyses automatically
    3. Programs external to the software, run as a post-processor on the output of the map overlays

The information described above also applies to regional use by local emergency response managers and building officials. The main differences are in the facility databases as discussed above. In this case, the building information is stored in an aggregated format. Local officials are likely to be estimating building damage in conjunction with other effects of the earthquake, such as casualties, need for shelter, and preliminary economic loss – many of which are conditional on building damage. Although several of them still rely on manual methods as discussed in the *Guidelines*, the most efficient methods for making first-order estimates of emergency response needs in a region require the investment to develop accurate regional databases of facility information, and to acquire and learn an automated GIS-based loss estimation methodology.

Example

In the following example, a city and two building owners within the city cooperate to develop a post-earthquake response and recovery program. For this example, a city in southern California and two hypothetical companies (ABC, a high-technology company, and XYZ, a chain of grocery stores) are used. After an earthquake, the city's primary responsibility is to inspect its residential housing stock and the facilities it owns. A secondary but important goal is to make sure that businesses are adequately inspected. The purpose of both of these goals is two-fold: first, to insure that dangerous buildings are declared unsafe (red-tagged), and second, to allow safe buildings to be reoccupied.

ABC company has ten facilities in the area, located at four campuses. The campuses are primarily: manufacturing, research and development (R&D), office, and warehousing. A basic seismic study of the buildings has been done by the company's structural engineering consultant, and the estimated performance of each in a given Modified Mercalli Intensity (MMI) event is as shown in Table 1. The company has decided that a more detailed assessment of shaking intensity is not warranted for an initial response. They have prioritized the value of their buildings in the order shown in Table 1, and have decided that if the intensity at any facility exceeds the life safety threshold, that facility is inspected first. If more than one facility exceeds the life safety threshold, they are inspected in order of the number of occupants. Buildings in areas not exceeding the life safety threshold are inspected in the order shown in Table 1.

An earthquake strikes southern California with an intensity distribution as shown in Figure 2. (Note that this map is one of the ShakeMap Earthquake Planning Scenarios taken from the

ShakeMap web site **www.trinet.org/shake/**.) Based on this intensity map and the location of the four campuses as shown, a simple GIS-based algorithm is developed to prioritize the inspections as: E, F, G, A, C, B, D, H, I, J. ABC uses this information to send its inspecting engineers to the building sites to make an ATC-20 (ATC, 1995) detailed evaluation, suitable for posting the buildings as red-tagged (unsafe), yellow-tagged (restricted use), or green-tagged (inspected).

Table 1 Estimated Seismic Performance of Buildings in Example

		Performance Threshold at MMI:	
Campus	**Building**	**Functionality**	**Life Safety**
Manufacturing	A	VI	VIII
	B	VII	IX
R&D	C	V	VII
	D	VI	VIII
Office	E	VII	IX
	F	VII	IX
	G	V	VII
Warehousing	H	VII	IX
	I	VII	IX
	J	VI	VIII

A week following the initial posting, ABC's engineers determine that buildings C, D and F are susceptible to structural damage that was not evident from an initial walkthrough of the building. ABC's engineers use pushover curves (estimates of the capacity of each building) developed prior to the earthquake with the response spectra obtained from ground motions recorded at nearby free field instruments. They are then able to determine if and where damage may be concentrated and respond accordingly.

XYZ company is unable to contract with structural engineers because of the lack of financial resources. The company has ten structures spread throughout the area and will rely on city inspectors to evaluate the facilities. The company develops a cooperative relationship with the city as follows: XYZ supplies the city with a list of its buildings, photographs, a brief description of the number of stories, year of construction, and material type, and any structural drawings it may have, reduced to 11x17 format.

The city creates a GIS map of the residential and public facilities with an intensity-based inspection prioritization similar to ABC company's. It then runs several scenario earthquakes through a model that creates estimated intensity contours. Based on these scenarios, the city determines its immediate inspection needs for the housing and public building stock. It estimates how long these inspections will take, and places XYZ company on a waiting list for inspection after the initial inspections are completed. The city then gives XYZ company an estimate of how long it will take to have its buildings inspected after each scenario. Because the city has basic information on the buildings, provided by XYZ, it is theoretically able to make inspections of XYZ's buildings more quickly and accurately. The city also determines for each scenario, which of XYZ's buildings are likely to fall outside the contours of shaking intensity that would cause moderate to severe damage.

An earthquake occurs and the near real-time map of ground shaking intensity generated from free field instrumentation is incorporated into the city's GIS software as shown in Figure 3. The city notifies XYZ company that it will take approximately 96 hours for inspectors to get to XYZ's buildings, but it also tells them that four of their ten buildings are not within the high intensity ground shaking zone, and unless hazardous damage is clearly evident the buildings can be occupied.

The use of recorded ground motion in the above example is threefold. First, on a near real time basis, the general distribution of intensity is used to make a rapid prioritization of inspection needs, both for the city and for ABC company. Near real time information would not typically be used in this case to make a determination or estimation of specific building damage. Second, more detailed ground motion information that would not have to be assembled in real time would be used in the days following the event, to help engineers analyze building damage. Third, companies are able to get estimates quickly after an event of when their buildings will be inspected, and whether or not certain buildings outside the zones of high shaking can be reoccupied immediately.

SUMMARY

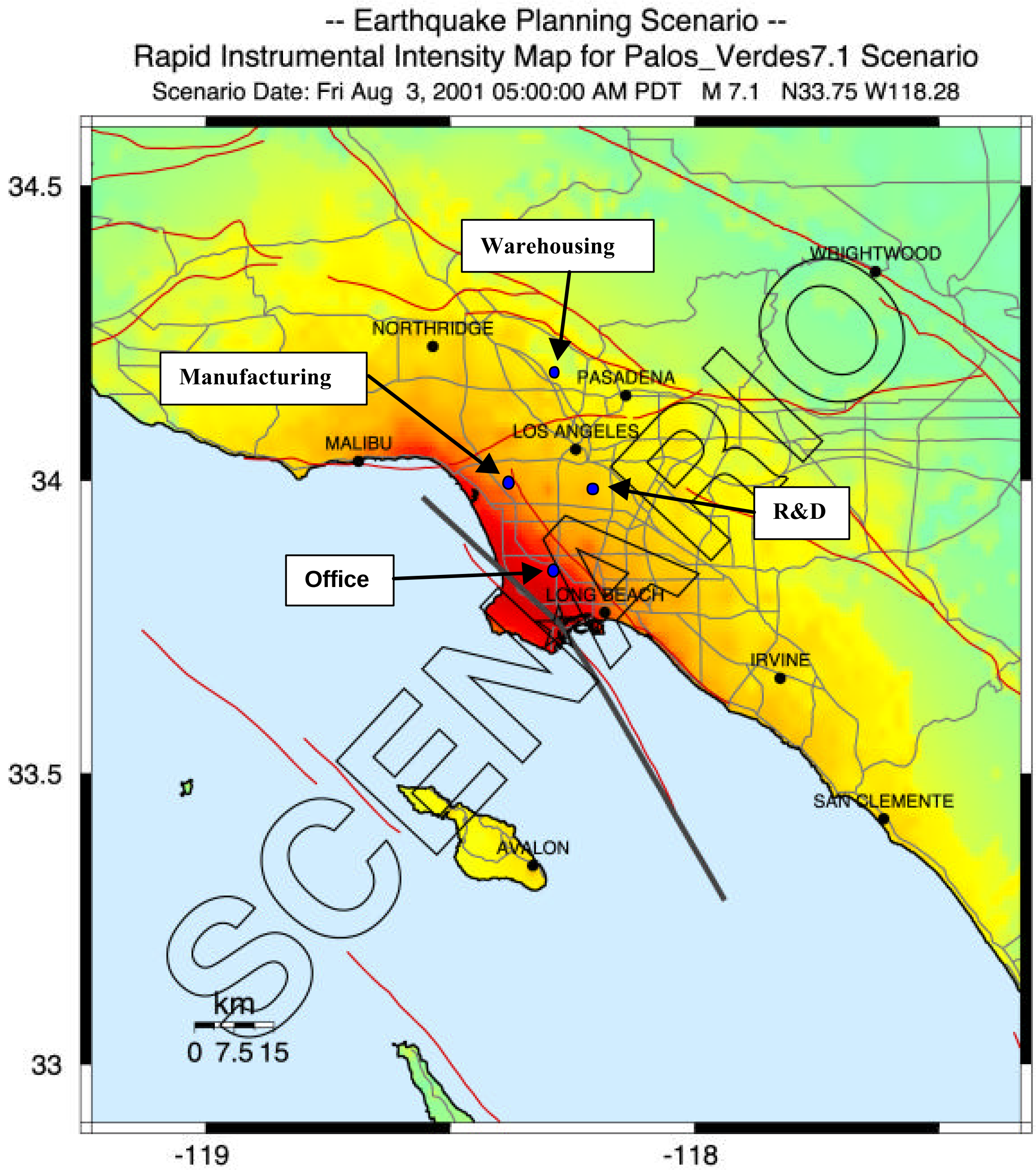
This paper describes one of the key topics of the document, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, currently being developed by ATC for CDMG as one of the 2000 CSMIP Data Interpretation Projects. It concerns the development and implementation of applications using computer-generated ground-motion maps, such as TriNet ShakeMaps, for post-earthquake response. The *Guidelines* address ShakeMap applications for approximately ten areas of emergency response. In this paper, the focus is on the general framework, including essential information, basic steps, and limitations. Due to space limitations, the application description is limited to only one of the ten emergency response topics – damaged buildings and safety inspections.

It should be emphasized again that the material in this paper forms a portion of the draft *Guidelines* document, and should be considered preliminary until the final document is released.

REFERENCES

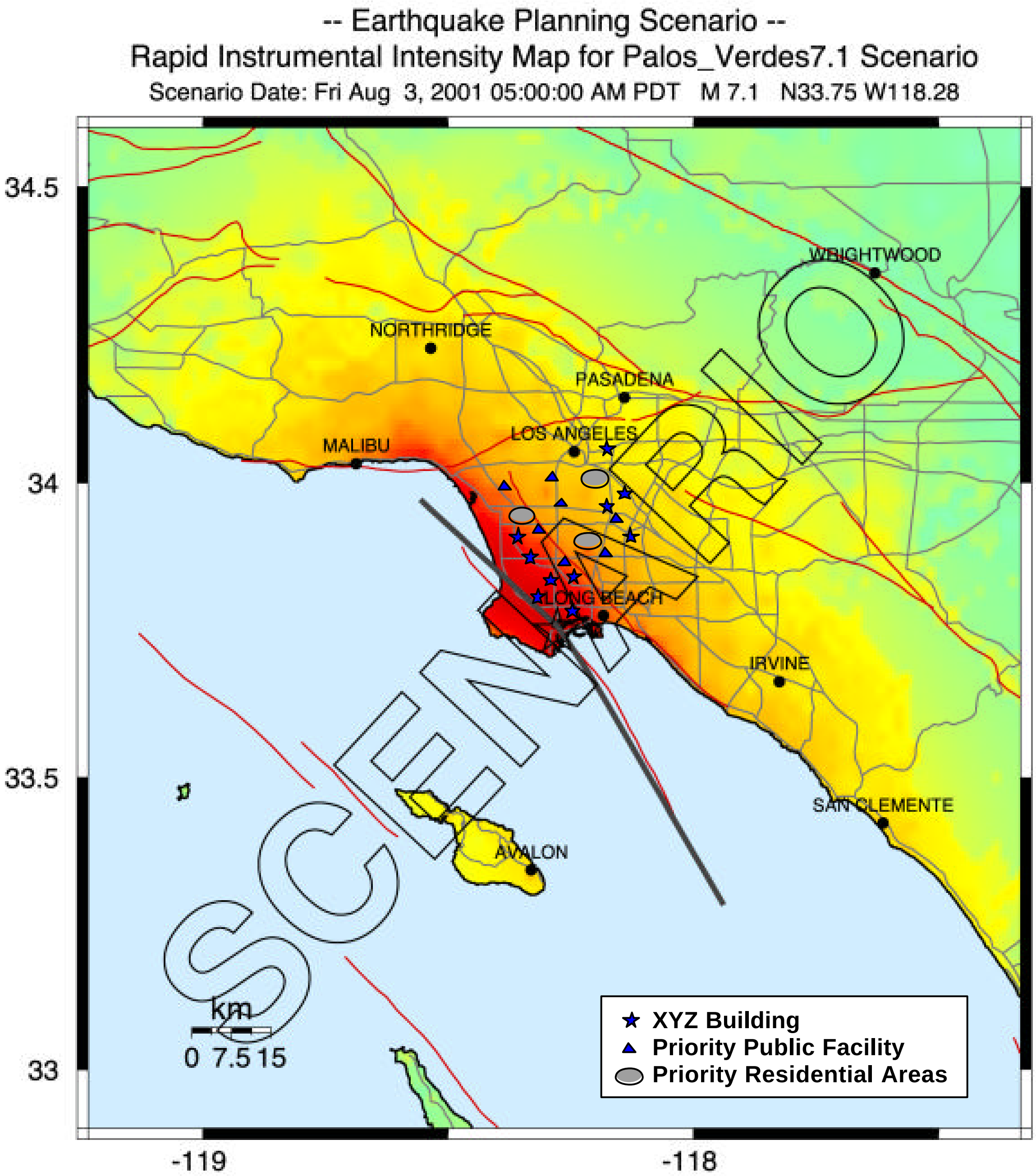
ASCE, 1998, *Handbook for the Seismic Evaluation of Buildings – A Prestandard*, prepared by the American Society of Civil Engineers for the Federal Emergency management Agency as FEMA Report 310, Washington, DC

ATC, in preparation, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, ATC-54 Report, Applied Technology Council, Redwood City, California.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 2 *Distribution of ground shaking intensity with location of example ABC Company buildings.*



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
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INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Figure 3 *Distribution of ground shaking intensity with location of example XYZ Company buildings.*

ATC, 1995, *Addendum to the ATC-20 Postearthquake Building Safety Evaluation Procedure*, ATC-20-2 Report, Applied Technology Council, Redwood City, California.

ATC, 1988, *Rapid Visual Screening of Buildings for Potential Seismic Hazards: A Handbook*, prepared by the Applied Technology Council (ATC-21 Report); published by the Federal Emergency Management Agency as FEMA Report 154, Washington, DC (note: an updated version of the document is now being prepared by ATC with funding from FEMA).

ATC, 1985, *Earthquake Damage Evaluation Data for California*, ATC-13 Report, Applied Technology Council, Redwood City, California.

Eguchi, R.T., Goltz, J.D., Seligson, H.A., Flores, P.J., Blais, N.C. Heaton, T.H., and Bortugno, E., 1997, "Real-Time Loss Estimation as an Emergency Response Decision Support System: The Early Post-Earthquake Damage Assessment Tool (EPEDAT)," *Earthquake Spectra*, Vol. 13, No. 4, pp 815-832.

NIBS, 1999, *HAZUS Earthquake Loss Estimation Methodology User's Manual*, National Institute of Building Sciences, Washington, DC.

ACKNOWLEDGEMENTS

Several people have contributed to the development of the material contained in the *Guidelines* pertaining to the use of ShakeMap for emergency response, a subset of which is contained in this paper. In particular, we wish to acknowledge the input of David Wald of the U.S. Geological Survey, James Goltz of the California Institute of Technology, several members of the California Seismic Safety Commission's Strong Motion Instrumentation Advisory Committee, the ATC-54 Project Advisory Panel, and the numerous individuals in the user community who were interviewed by members of the project team.

GUIDELINES FOR UTILIZING STRONG-MOTION DATA FOR POSTEARTHQUAKE EVALUATION OF STRUCTURES

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Redwood City, California

ABSTRACT

This paper describes portions of the document, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, currently being developed by the Applied Technology Council for the California Division of Mines and Geology's Strong Motion Instrumentation Program 2000 Data Interpretation Project. The focus of the paper is on guidance for using strong-motion data to evaluate the performance of structures in the immediate earthquake aftermath. Topics addressed include strong-motion data sources and processing, damage indicators that can often be observed in recorded data, and methods for rapid interpretation of strong-motion data to evaluate structural performance.

INTRODUCTION

Instrumentation in current strong-motion networks in California has reached different stages along the steady technological upgrade from photographic paper recording to digital recording, with the accompanying improvement in the availability of data from a delay of several months or more to a delay of only seconds after a seismic event. Instruments now in place record either analog film records or digital data, with the trend toward exclusive use of instruments that record digital data. In California the number of free-field sites, buildings, and other structures containing strong-motion instruments has expanded to more than 1000 since the original installation of nine strong-motion instruments in California in 1932. Today, the large number of instrumented sites and the rapid availability of digital data, including analog data converted to digital format, provide the real potential for using strong-motion data to evaluate the performance of buildings and other structures in the immediate earthquake aftermath. The use of strong-motion data for this purpose is, in fact, the original justification for code-required instrumentation that began to be mandated after about 1965 for most buildings over six stories in height in certain California cities like Los Angeles, which adopted the appendix to Chapter 23 of the *Uniform Building Code*.

Methods and techniques for evaluating the performance of buildings and other structures using strong-motion data have been available for several decades, but widespread use of this technology has been hampered for several reasons: (1) until recently, the relatively slow availability of data in digital format, and (2) the lack of concise descriptions of such methods in a resource readily available to structures' owners and their engineers. To help remedy this situation, the California Division of Mines and Geology (CDMG) awarded a Year 2000 California Strong-Motion Instrumentation Program (CSMIP) Data Interpretation Project to the Applied Technology Council (ATC) to prepare guidelines on this subject. The guidelines now under development by ATC address not only postearthquake structural evaluation, but also the use of computer-generated ground-motion maps in postearthquake response and the collection of data on the performance and characteristics of structures located in the vicinity of strong-motion recordings sites, or in which strong-motion instruments have been installed. The results of the ATC effort will be published in the ATC-54 report, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation* (ATC, *in preparation*).

In this paper we focus on those portions of the ATC-54 report pertaining to guidance for using strong-motion data for postearthquake evaluation of structures. We begin with background information that in part summarizes the results from our literature review to determine the extent to which strong-motion data have been used to date to evaluate structures. The background information also identifies and briefly discusses (1) the general limitations of strong-motion data for the purpose of evaluating structures; (2) the principal operators of existing strong-motion networks; (3) available resources for strong-motion data; and (4) data processing issues. The intent is to provide users of those portions of the ATC-54 *Guidelines* pertaining to structural evaluation, namely, facility owners and their engineers, with information that will enable them to understand the limitations of strong-motion data, as well as the means by which such data can be acquired and processed. The principal focus of this paper is the description of methods for rapid interpretation of strong-motion data in order to evaluate structural performance. A discussion of these methods is preceded by a discussion on damage indicators that can often be detected by visual inspection of strong-motion data. Due to space limitations we focus on methods for buildings, the type of structure for which such methods are best developed. The companion paper by Rojahn et al. (2001), "Guidelines for Utilizing Strong-Motion Data and ShakeMaps in Postearthquake Response, An Overview", describes the contents of the ATC-54 Report, *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, how the report was developed, and some of the preliminary recommendations for improving the technology and processes for using strong-motion data and computer-generated ground-motion maps for emergency response and postearthquake structural evaluation. The companion paper by King et al. (2001), "Guidelines for Utilizing ShakeMaps for Emergency Response", provides more in-depth information pertaining to the use of ShakeMaps.

BACKGROUND

<u>Prior Efforts Using Strong-Motion Data for Structural Evaluation</u>. The great majority of relevant papers in the literature describe research that used data that was available anywhere from several minutes after an earthquake event to several months afterwards, even though the research itself was completed, and reported on, up to several years later. In large part, the technical literature indicates that strong-motion data have been used in system identification studies, some of which have been quite sophisticated, and in the identification of potential global structural damage under various levels of shaking intensity. There have also been many instances where strong-motion data have been used as input in computer analysis programs to calculate structural component forces, moments, displacements, and rotations.

Interestingly enough, we could find no examples in the technical published literature of the analysis of a recording that led to an assessment of damage, that, alone, resulted in a decision or action that saved lives or property threatened by such damage. We are aware, however, as a result of interviews with various researchers and program managers, that there have been instances where strong-motion recordings have alerted building or structural personnel that steps should be taken to improve structural performance, or that a safety check should be run because ground accelerations were higher than code values. These have not been reported in the technical literature due to the sensitive nature of the situation. They include: (1) the transfer of occupants from commercial buildings so that the buildings could be demolished and rebuilt, (2) the temporary shutting down of a power-generating plant for inspection due to ground accelerations higher than design levels, and (3) retrofitting a government office building with damping devices after records confirmed that modal oscillations continued for longer durations than expected.

<u>Limitations and Uses of Strong-Motion Data for Structural Evaluation</u>. The global dynamic seismic response of complex structures (including bridges, dams, lifeline structures, and complex buildings) is not yet well understood. Interpretation of strong-motion recordings of this seismic response for details of damage is not possible. For these complex structures, such records are used for research on system identification, in order to improve the current structural model. Structural models include the mass and stiffness of all components if it is a linear model and includes in addition, yield points and ultimate strengths if it is a nonlinear model. This preparatory computer modeling of instrumented structures is a prerequisite if a detailed time-history analysis of linear or nonlinear structural response is contemplated, with a view to searching for the existence and extent of damage, directly from the records.

Most structures have separate structural components whose nonlinear behavior is difficult to model and is difficult to determine from a system identification analysis. A rapid time-history analysis that takes advantage of all the structural records, but has only an imperfect model to work with, cannot accurately show the location of local component degradation nor the location of serious damage.

Global degradation is a different matter. Without knowledge of structural detail, a rapid time-history analysis of the records alone, for example the calculation of all the floor displacements from the recorded accelerations, leads to the total drift at roof level, relative to the ground, which is a recognized global damage parameter. A time-history analysis using the ground-level input accelerations and the best available nonlinear structural model, together with a best-fit matching of the structural recordings with computed structural recordings, leads to reliable interstory drift time-histories throughout the height of the structure, which is a reliable damage indicator. At the same time, it is well-documented that the first-mode period of a building lengthens as the building and its individual components become nonlinear. Presuming that the period lengthening is caused solely by a drop in stiffness, the mass of the building remaining the same, and that the stiffness varies inversely as the square of the period,

$$\text{that is, } w = \sqrt{(k/m)},\ \ T = 2\pi \sqrt{(m/k)},$$

a period lengthening of 25% in a frame building, say, is due to the stiffness dropping to 64% of its original linear value. Damage to the partitions and other nonstructural components occurs first in contributing to this loss; damage to the seismic-resistant elements occurs next. Fourier analysis of strong-motion records using recognized moving-window procedures are successful in determining when period lengthening and damage probably occur.

In the years following the damaging 1989 Loma Prieta, 1994 Northridge and 1995 Kobe earthquakes, structural instrumentation projects have concentrated more specifically on the search for damage assessment capability. A thoroughly instrumented building has more potential for the determination of the general location of damage, but not precise locations. The appearance of a bursts of high-frequency acceleration in adjacent structural records is an indicator of possible local damage, but could also be the recording of elevated contents or nonstructural components falling to the floor.

Existing Strong-Motion Networks. The major strong-motion networks operating in California include structural instrumentation of various complexity. The three larger networks are: (1) the California Strong-Motion Instrumentation Program, Division of Mines and Geology, Department of Conservation, operating throughout California and headquartered in Sacramento (Shakal et al., 1989); (2) the National Cooperative Strong-Motion Instrumentation Network, U.S. Geological Survey, (USGS), headquartered in Menlo Park, California, and operating throughout the nation, and (3) the Southern California Instrumentation Network, headquartered at the University of Southern California (USC), and operating throughout the Los Angeles region. Smaller networks, which also include structural instrumentation, include the Army Corps of Engineers, the U.S. Bureau of Reclamation (Viksne et al., 1993), the Metropolitan Water District of Southern California, and the Los Angeles Department of Water and Power.

The instrumentation networks of CSMIP and the USGS contain ground-motion stations, instrumented buildings and other instrumented structures. The number of channels at a ground-motion station is generally three. The number of channels in a specific structure depends on the time it was first instrumented and the vibrational questions for which answers are sought, ranging from perhaps six to several dozen or more. The average is approximately sixteen. The instrument coverage in Los Angeles, in San Francisco, in California, on the Pacific coast, and across the nation ranges widely, but the percentage of the three different station types providing useful records from an urban earthquake can be judged from the numbers from the 1994 Northridge earthquake, namely, 250 ground-motion stations, 400 buildings, and 50 other structures.

Almost all instruments now record digitally at a sample rate between 50 and 200 samples per second on each channel. Often, the sensor has a wide frequency range, and the data are shared with researchers from the strong-motion seismology field. If data communication is possible between the recorder and the network central headquarters, and is not damaged nor interrupted by the earthquake, then data can be transmitted to the central headquarters for processing and dissemination to people needing to make rapid decisions. For those recorders without communication to central headquarters, a technician recovers the digital data during the days following the earthquake.

Data Sources and Processing. The technical literature and world wide web contain numerous resources describing existing strong-motion data and data processing techniques. In some instances the resources contain information on a wide variety of strong-motion recording sites and data, including both free-field sites and instrumented structures; others refer primarily to data sets from specific types of structures. Two of the most popular current resources are the

COSMOS Virtual Data Center (db.cosmos-eq.org), which is operated by the Consortium of Organizations for Strong-Motion Observation Systems, and the Pacific Earthquake Engineering Research Center (PEER) Strong-Motion database (peer.berkeley.edu/smcat). The COSMOS site provides links to nearly all of the major strong-motion data providers and is a well-designed web site for quickly identifying available strong-motion data, as well as listings of current stations.

The literature also contains numerous examples of studies and descriptions of strong-motion data sets from instrumented buildings, bridges, and dams. Citations for data from buildings, for example, include Shakal et al. (1989), Reichle et al. (1990), Huang et al. (1991), Graizer et al. (1998), Porcella and Switzer (1989), Archuleta et al. (1999), the proceedings of the annual CSMIP seminars: Huang et al. (1992, 1993, 1994, 1995), and descriptions of data from specific events, such as described by Darragh et al., (1995) and Shakal and Huang (1995) for the 1994 Northridge earthquake. The instrumentation and records from a 2540-foot-long interchange bridge excited by the 1992 Landers and 1992 Big Bear earthquakes have been described by Huang and Shakal (1995). Similarly, significant earthquake strong-motion accelerograms recorded on or near dams, and current developments in instrumentation, including near-real-time strong-motion recording, are discussed in Shakal and Huang (1996).

With improvement in the instrumentation, and the increase in magnitude of the earthquakes producing the records, there is less need for elegant processing to push the envelope of useful data beyond that envisioned by the instrument manufacturer. Because of the recording instruments and processing techniques now used by the principal providers of data (CDMG, USC, and USGS), the users of the data can be confident that: (1) there will be no stray digital points in the data; (2) the high-frequency limit will be defined by the instrument response characteristics at high frequencies (for which corrections are made) and the sampling rate; (3) the long-period limit will be defined by the signal-to-noise ratio at long periods and the duration of both the strong shaking and the total record (the larger the amplitudes over a long duration, the longer will be the selected cut-off period); and (4) pre-event memory capability will ensure that earthquake acceleration, calculated velocity, and calculated displacement can all commence with zero amplitude.

DAMAGE INDICATORS EVIDENT IN STRONG-MOTION STRUCTURAL RECORDS

If any of the following characteristics are evident in strong-motion records at specific locations, they may be indicative of damage. The damage, at the same time, may be readily seen during a visual inspection. The appearance of these characteristics in the record is a warning that the structure needs to be evaluated for the existence of damage. There may be no damage apparent on visual inspection, and an evaluation by a structural engineer with experience in seismic evaluation may be necessary.

<u>Ground Acceleration Exceeding Code Values or Design Values</u>. Design code values of acceleration are considered in the design process, and in the design engineer's mind, as constant acceleration values that the foundation experiences. On the application of this acceleration in the design process, the distribution of forces along the vertical axis of the building is normally defined by an equation provided in the code, and the building is designed as if these distributed forces (a constant acceleration times mass) were acting at the various floor and roof levels. This

constant acceleration and these forces can be more readily visualized and handled in design than short-lived peak accelerations of the same value measured in the free-field or basement level or ground level in the building. A high-frequency peak horizontal acceleration at a free-field location need not be transmitted into the foundation, whose inertia resists such motion and does not follow it. On the other hand, if both the free-field and the foundation are based on hard rock, then the recorded peak acceleration is transmitted to the foundation, and the stiffness, mass and strength of the structure's seismic-resisting elements must resist it. At high frequencies, the velocities and displacements have low amplitudes, and the structure resists with ease (e.g., a sinusoidal acceleration amplitude of 0.5 g at 10 Hz produces a displacement amplitude of 0.05 inches). Depending on the stiffness of the soil, and on the amplitude and frequency of the peak recorded acceleration, there may be damage.

Based on the above we conclude the following: If a free-field record has a sufficiently high peak acceleration (above the design-specified value), and has a sufficiently low frequency and is on hard rock, there may be damage. If a foundation record has a sufficiently high peak acceleration (above the design-specified value), and has sufficiently low frequency, there may be damage.

<u>Lengthening of the Modal Periods</u>. As described above, the first-mode period of a building lengthens during the response to earthquake excitation as the individual components making up the seismic elements of the building become nonlinear.

Naeim (1996) summarizes his work on the response of 20 CDMG-instrumented buildings during the 1994 Northridge earthquake. This summary includes buildings whose periods lengthened during the response. In a later work on the same 20 buildings, Naeim (1998) observes that the second and third modes of vibration contribute significantly to the overall response in the cases of two buildings of 13 and 20 stories. It has been known since the 1971 San Fernando earthquake that a lengthening period is associated with damage at some level. The increase in period can be visually read in a record of sufficient clarity containing a single mode response, or can be studied analytically with Fourier moving-window analyses. For a structure shown later to have no structural damage, the lengthening of the period is small, and the period returns to its original value before the end of the record. Structural damage, on the other hand, lengthens the period to greater levels, and the period does not return to its original value. Rezai et al. (1998) analyzed the important San Fernando and Northridge records from a 16-channel recording system installed in a 7-story building. During the San Fernando earthquake, structural damage was minor. During Northridge, the period lengthened by 66% in one direction, and by 100% in the other. These percentages correspond to drops in stiffness to 0.36 and 0.25, respectively, of original values. Major structural damage occurred, and it is clear, from the lengthened period on the record, when this damage commenced.

Based on the above we conclude that period lengthening indicates a decrease in stiffness. Separation of partitions from structural framing and structural walls, separation of structural infill from structural framing, and structural damage to seismic-resisting elements may contribute to this decrease in stiffness. Whether or not this is visible, an evaluation by a structural engineer is warranted.

High-Frequency Bursts of Acceleration. Damage occurring in a structure introduces impulsive forces created by the initial damage to steel and its connections, concrete and its reinforcing, masonry and its reinforcing and mortar, or wood and its connectors, followed by more impulsive forces created as damaged areas continue to impact on themselves as the response to the earthquake proceeds. The resulting compression and shear waves travel throughout the structure almost instantly. Those with audible frequencies are not recorded on the typical strong-motion recorder (these frequencies are too high) but waves with frequencies within the range of instrumental response, that is, up to 50 Hz or 100 Hz, are sensed by such recorders. The presence of a specific frequency in this range can be identified on an analog film record, but identification from a digital record depends on its sampling rate.

The conclusion here is that damage is indicated if a high-frequency burst of acceleration is identified on the record from several closely-spaced transducers, the high-frequency bursts continue to occur as time progresses, and it is evident that at the same time, modal periods lengthen and stay that way until the end of the record. It is necessary to distinguish this damage indicator from the record of heavy elevated contents falling to the floor in the vicinity of a transducer. This high-frequency burst will not be seen on distant recordings, and will not be accompanied by lengthening periods.

PROCEDURES FOR USING STRONG-MOTION DATA TO EVALUATE STRUCTURAL RESPONSE

Chapter 3 of the ATC-54 *Guidelines* provides step-by-step procedures to evaluate the response of structures (buildings, bridges, and dams) using recorded strong-motion data. For each type of structure, a variety of approaches are described, including assumptions about structural properties, applicable structure sub-types, minimum instrumentation and data required, steps to be taken, outputs, and example applications. It is assumed that the user is unfamiliar with strong ground-motion recordings. Also, a summary of available structural analysis programs and their capabilities for assisting in the interpretation of strong motion data is provided in Appendix D of the *Guidelines*.

One of the procedures for rapid evaluation of strong-motion data from instrumented buildings is described below. The reader is referred to the ATC-54 *Guidelines* for information on additional procedures, including:

- rapid estimation of changes in building period during strong ground shaking, using visual inspection and Fourier analysis techniques;
- rapid estimation of inter-story drifts, including estimates based on response spectra calculated from ground-motion records and estimates based on displacement time-history analysis involving differencing of displacement time histories calculated from acceleration time-histories recorded at different story levels; and
- procedures to define and verify mathematical computer models of building behavior.

Hand Modal Analysis of Data from Instrumented Buildings. The hand modal analysis technique was developed by the Structural Engineers Association of Southern California Seismology Subcommittee on Seismic Instrumentation and Testing (SEAOSC, 1971), as documented there by R. B. Matthiesen. It was used on instrumented buildings in which strong-motion data were recorded during the 1971 San Fernando, California, earthquake, and case studies of eight buildings analyzed using this method are documented in Gates (1973). The procedure is described in detail in the ATC-54 *Guidelines* and is summarized here, along with an example application. The procedure consists of the five following steps:

1. Estimate the maximum recorded building acceleration and compare it to the acceleration seismic loading criteria used in design. If the peak acceleration on all horizontal recorded accelerograms is less than the design value, no further action is necessary.
2. Estimate the building periods and modal acceleration components. This is carried out by visual inspection of the records from different levels in the building (often near mid-height and at the roof level) in comparison with mode shapes for the first three or four modes of response (see Figure 1).
3. Estimate the maximum acceleration response at each floor level by sketching the corresponding mode shapes of response as overlays on an elevation view of the building.
4. Evaluate the building forces, shears, and overturning moments, using the story accelerations determined in Step 3 and estimated story weights. "If the peak acceleration response is produced by the combination of several modes, each contributing a significant component to the total response, then the final force, shear, and overturning moment response should be based on the superposition of the modal components" (Gates, 1973).
5. If the modal response components cannot be recognized easily, a more rigorous dynamic analysis is required.

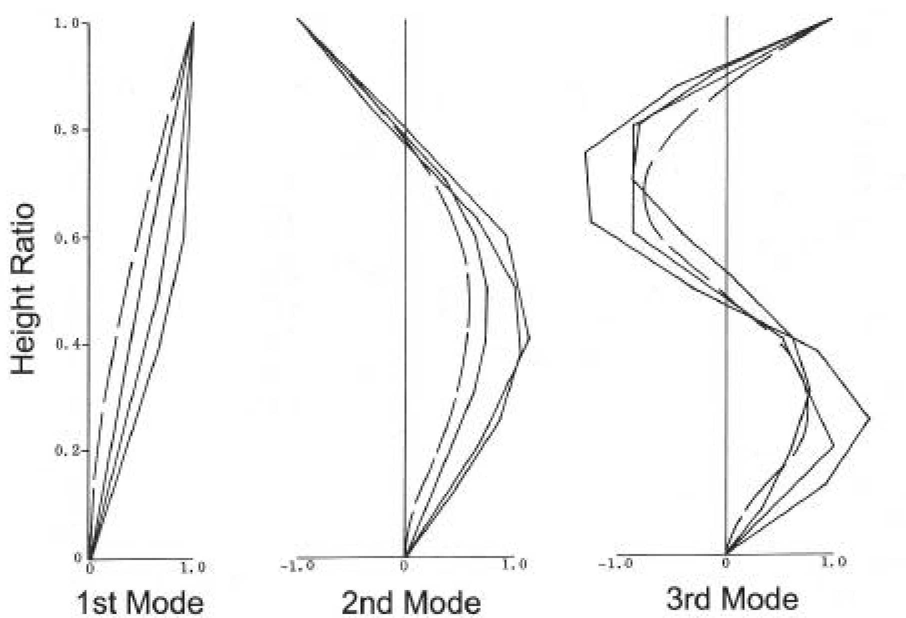

Figure 1. Experimental and analytical mode shapes for buildings (from Gates, 1973).

We use the example provided in Gates (1973) that analyzes 1971 San Fernando earthquake strong-motion recorded in the K-B Valley Center, a 16-story moment-resisting steel-frame office tower. The recording instruments were located at the basement level, 9th floor, and roof level. Strong-motion accelerograms recorded at the basement level, 9th floor and roof level for the reference east-west direction are provided in Figure 2, which also shows superimposed drawings of estimated contributions of the first and second modes (see records for 9th floor and roof). Based on visual observation and hand calculations, the fundamental periods for the first and second modes are estimated as 3.0 and 1.1 seconds, respectively.

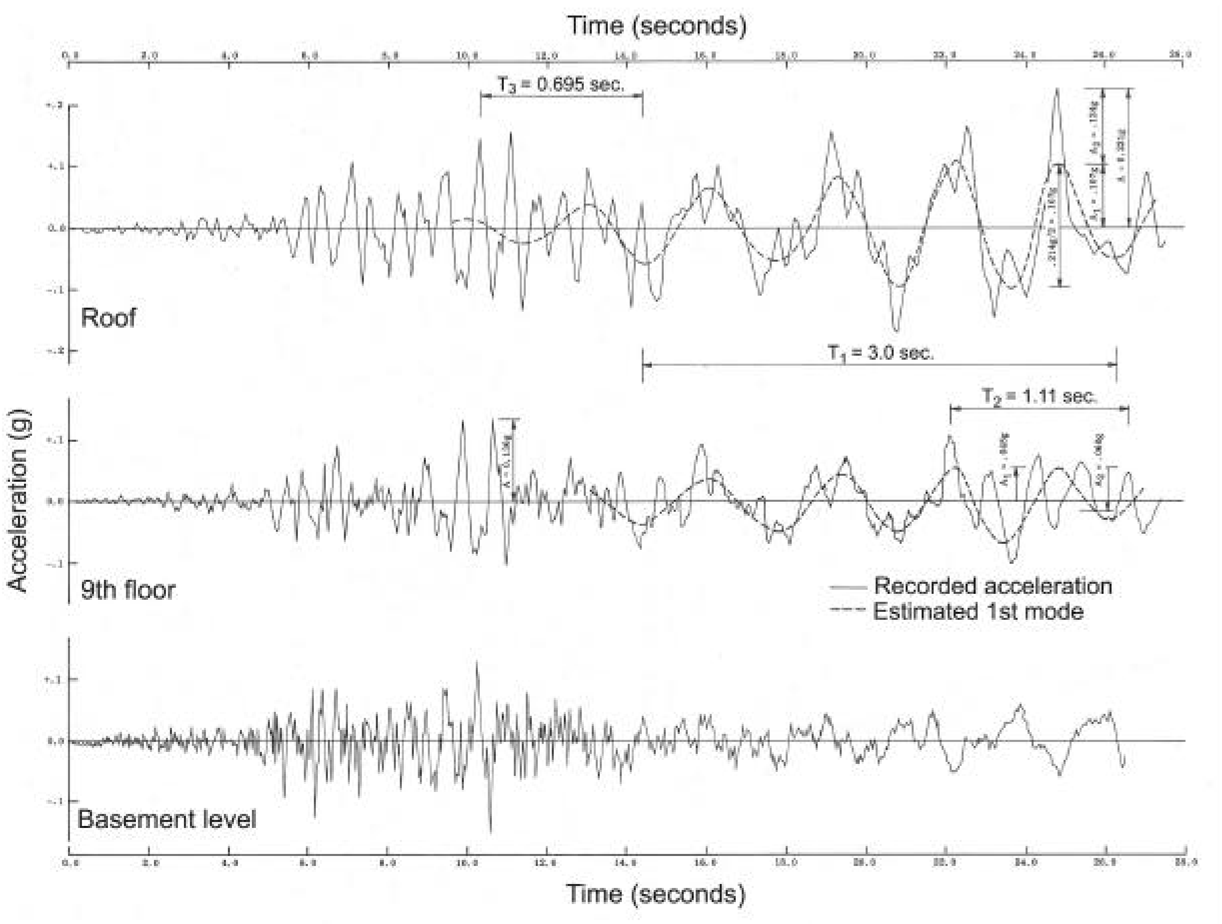

Figure 2. KB Valley Center, east-west acceleration response (from Gates, 1973).

By superimposing estimated mode shapes for the first and second modes of response (see Figure 1) on an elevation view of the building (a partial scale drawing), it is possible to estimate modal accelerations at each floor level. From this information and estimated story weights, both story shears and overturning moments are estimated. Plots showing story shears and overturning moments, in comparison to 1970 *Uniform Building Code* (ICBO, 1970) specified values and values calculated using time-history analysis, are shown in Figures 3 and 4. While the force levels during earthquake motion were roughly 2 to 2.5 times the seismic code levels, the building "performed in a very satisfactory manner … and there were no signs of structural distress in any of the [structural] members" (Gates, 1973).

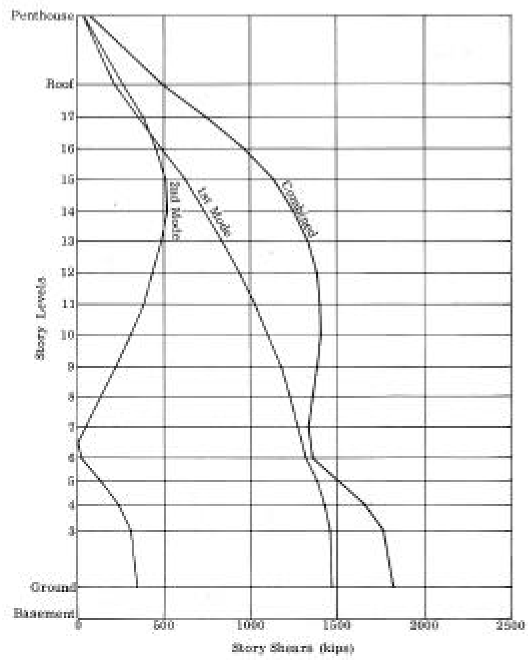

Figure 3a - MAXIMUM MODAL SHEARS

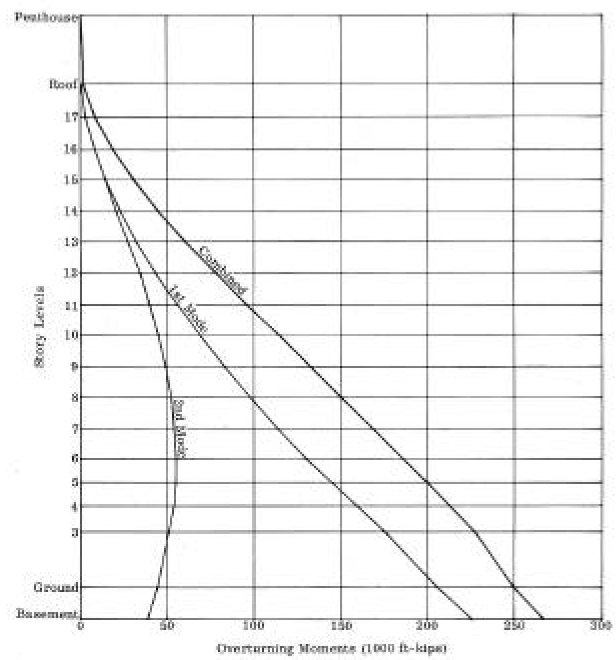

Figure 3b - MAXIMUM MODAL OVERTURNING MOMENTS

Figure 3. KB Valley Center, approximate modal responses—east-west direction (from Gates, 1973).

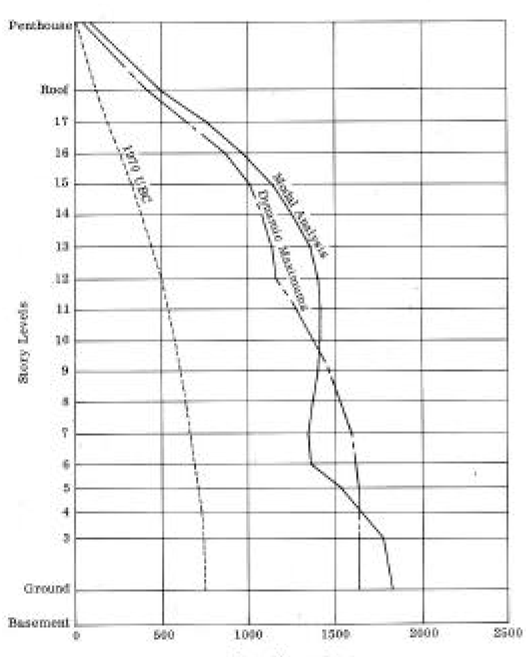

Figure 4a - MAXIMUM SHEARS

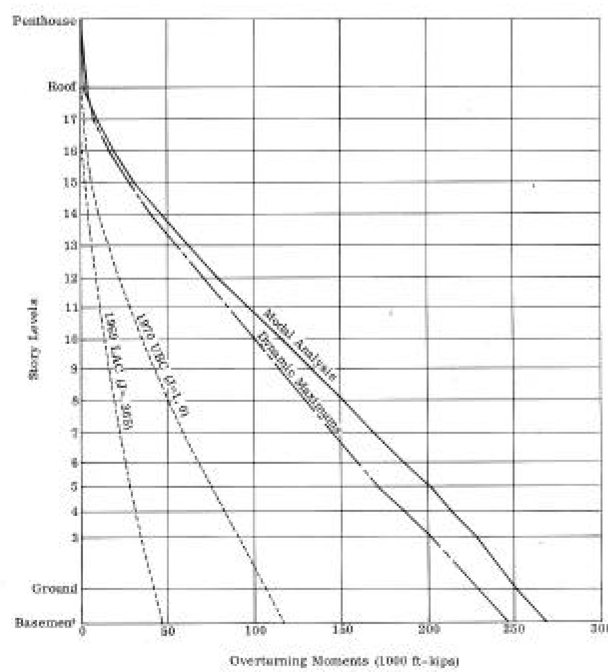

Figure 4b - MAXIMUM OVERTURNING MOMENTS

Figure 4. KB Valley Center, comparison of approximate modal response with code seismic values and dynamic time-history response—east-west direction (from Gates, 1973).

CONCLUDING REMARKS

The number of strong-motion records from instrumented structures obtained over the last several decades is impressive. From the 1994 Northridge earthquake alone, records were obtained from 400 buildings and 50 other structures. Although some recordings from the last 70 years do not have amplitudes much greater than the triggering amplitude, many records are significant for the purposes of this paper, namely, the indication of damage and the evaluation of the instrumented structures, using techniques ranging from a visual inspection of the record to a full nonlinear dynamic analysis of the building response. The number of instrumented buildings actually analyzed is surprisingly low, and although the techniques used at the time of analysis (in some cases, thirty or more years ago) were at the top technical level, it is surprising how few advances have been made in rapid evaluation techniques over the last several decades. The reasons for this are probably related to a lack of research funds, building owners' complacency, engineers' lack of available time for developmental work, and the wait for a bigger earthquake.

REFERENCES

ATC (in preparation), *Guidelines for Using Strong-Motion Data for Postearthquake Response and Postearthquake Structural Evaluation*, Applied Technology Council, Redwood City, California.

Archuleta, R., et al., 1999, "A virtual strong-motion data center for data dissemination through the Internet", *SMIP99 Seminar on Utilization of Strong-Motion Data: San Francisco, California, September 15, 1999: Proceedings*, California Division of Mines and Geology, Sacramento, pages 145-154.

Darragh, R.B., Shakal, A.F. and Huang, M.J., 1995, "Strong ground motion data from the 1994 Northridge, California, earthquake", *Special Publication 116, The Northridge, California, Earthquake of 17 January 1994*, California Div. of Mines and Geology, Sacramento, pages 55-63.

Gates, W. E., 1973, "Modal Analyses of Instrumented Buildings," in L. M. Murphy (Scientific Coordinator), *San Fernando, California, Earthquake of February 9, 1971*, Vol. 1, Part B, NOAA, Department of Commerce, Washington, DC, pages 609-624.

Graizer, V. M., et al., 1998, "Strong motion data from ground-response sites and structures recorded during the 1994 Northridge earthquake", *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, California Universities for Research in Earthquake Engineering, Richmond, California, Vol. II, pages II-331 to II-338.

Huang, M. et al., 1991, *CSMIP strong-motion records from the Sierra Madre, California earthquake of 28 June 1991*, Report OSMS 91-03, California Office of Strong Motion Studies, Sacramento, 108 pages.

Huang, M. J., ed.., 1992, *SMIP92 Seminar on seismological and engineering implications of recent strong-motion data, Proceedings*, California Division of Mines and Geology, Sacramento, 1992, 1 vol.

Huang, M. J. ed., 1993, *SMIP93 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, California Division of Mines and Geology, Sacramento, 114 pages.

Huang, M. J. ed., 1994, *SMIP94 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, California Division of Mines and Geology, Sacramento, 120 pages.

Huang, M. J. ed., 1995, *SMIP95 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, California Division of Mines and Geology, Sacramento, 105 pages.

Huang, M.J. and Shakal, A.F., 1995, CSMIP strong-motion instrumentation and records from the I10/215 interchange bridge near San Bernardino, *Earthquake Spectra*, 11, 2, pages 193-215.

ICBO, 1970, *Uniform Building Code*, 1970 edition, International Conference of Building Officials, Whittier, California.

King, S.A., Comartin, C.D., Reis, Evan, Nathe, S.K., and Power, M.S., 2001, Guidelines for utilizing ShakeMaps for emergency response, *Proceedings, SMIP01 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Los Angeles, California, September 12, 2001, California Division of Mines and Geology, Sacramento.

Naeim, Farzad, 1996, "Performance of 20 extensively-instrumented buildings during the 1994 Northridge earthquake", *Proceedings, SMIP96 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Sacramento, California, May 14, 1996, California Division of Mines and Geology, Sacramento, pages 19-36.

Naeim, Farzad, 1998, "Seismic performance of extensively-instrumented buildings during the January 17, 1994 Northridge earthquake: an interactive information system", *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, California Universities for Research in Earthquake Engineering (CUREe), Richmond, California, Vol. III-A, pages III-405 -- III-412.

Porcella, R.L. and Switzer, J.C., 1989, *Catalogue of U.S. Geological Survey strong-motion records, 1987*, Circular 1044, U.S. Geological Survey, 44 pages.

Reichle, M.S. et al., 1990, "Overview of SMIP strong motion records from the Loma Prieta earthquake of 17 October 1989", abstract, *EOS Transactions*, American Geophysical Union, 71, 8, pages 291-294.

Rezai, Mahmoud; Rahmatian, Peyman; and Ventura, C.E., 1998, "Seismic data analysis of a seven-storey building using frequency response function and wavelet transform", *Proceedings of the NEHRP Conference and Workshop on Research on the Northridge, California Earthquake of January 17, 1994*, California Universities for Research in Earthquake Engineering (CUREe), Richmond, California, Vol. III-B, pages III-421 -- III-428.

Rojahn, Christopher, Comartin, C.D., and King, S.A., 2001, "Guidelines for utilizing strong-motion and ShakeMap data in postearthquake response: an overview", *SMIP01 Seminar on Seismological and Engineering Implications of Recent Strong-Motion Data*, Los Angeles, Sep 12, 2001, California Division of Mines and Geology, Sacramento.

SEAOSC, 1971, *Basic Interpretation of Strong-Motion Accelerograms in Buildings*, Structural Engineers Association of Southern California Seismology Subcommittee on Seismic Instrumentation and Testing Preliminary Report, Los Angeles, California.

Shakal, A.F. et al., 1989, *CSMIP strong-motion records from the Santa Cruz Mountains (Loma Prieta), California, earthquake of 17 October 1989*, Report OSMS 89-06, California Office of Strong Motion Studies, 196 pages.

Shakal, A.F. and Huang, M.J., 1995, Northridge earthquake of January 17, 1994: reconnaissance report, Volume 1 -- recorded ground and structure motions, *Earthquake Spectra*, 11, Suppl. C, pages 13-96, EERI Publication 95-03.

Shakal, A.F. and Huang, M.J., 1996, Strong motion instrumentation and recent data recorded at dams, *Earthquake Engineering for Dams: 1996 Western Regional Technical Seminar, Proceedings*, Assn. of State Dam Safety Officials, Sacramento, California, pages 111-126.

Shakal, A.F., Huang, M.-J. and Ventura, C.E., 1989, "State-of-the-art report: the California strong motion instrumentation program – objectives, status and recent data", *Proceedings, Ninth World Conference on Earthquake Engineering*, Japan Assn. for Earthquake Disaster Prevention, Tokyo, Vol. VIII, Paper SB-R2, pages 105-116.

Viksne, A., Wood, C. and Copeland, D., 1993, Technical note: Bureau of Reclamation Strong Motion Instrumentation Program, *Earthquake Spectra*, 9, 4, pages 885-887.

CONSORTIUM OF ORGANIZATIONS FOR STRONG MOTION OBSERVATION SYSTEMS

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ABSTRACT

Development of COSMOS is continuing with a number of activities and initiatives. A workshop on "Instrumental Systems for Diagnostics of Seismic Response of Bridges and Dams" was successfully held and "Recommended Guidelines" were published. The COSMOS Strong Motion Programs Board completed the guideline "Guidelines for Advanced National Seismic System Strong Motion Station Installation" with funding provided by the U. S. Geological Survey. Development of the COSMOS Strong Motion Virtual Data Center (VDC) is continuing on four fronts: improvement of the user interface to make data more accessible for users; the COSMOS strong motion data format has been approved as a standard; data being held directly in the VDC continue to be expanded; and work is being initiated to develop a mirror sites. Two workshops are in planning: "Archiving and Web Dissemination of Geotechnical Data" is scheduled to be held on October 4 and 5, 2001; and, "Strong Motion Instrumentation of Buildings" is scheduled to be held on November 14 and 15, 2001. In an effort to expand strong motion recording in earthquake prone areas of the world that have few or no current strong motion stations, COSMOS and the World Seismic Safety Initiative (WSSI) have entered into an agreement to facilitate deployment of surplus instruments.

INTRODUCTION

COSMOS was formed in 1999 with the overarching purposes of providing mechanisms for ongoing coordination of strong motion programs in the United States and a forum for the Programs to receive coordinated, systematic user input and feedback on data acquisition and dissemination. Supporting these overarching purposes are other important purposes: 1) to further innovative ideas and policies to improve strong motion measurements and their application in practice, 2) to develop infrastructure for coordinated electronic dissemination of strong motion data, 3) to develop consensus standards for data processing and formatting, 4) to promote expansion of strong motion measurements in urbanized areas with high earthquake risk, and 5) to expand support for strong motion measurements. To foster these purposes COSMOS is pursuing a broad program of activities and is supporting the development and implementation of the Advanced National Seismic System (ANSS), which was authorized by the Congress in 1999 (USGS, 1999). Already, important advances have been made in developing guidelines for strong motion instrument installation, strong motion instrumentation of bridges and dams, standardization of data dissemination formats, and web-based dissemination of strong motion data through the COSMOS VDC. Ongoing efforts support development of guidelines for strong motion instrumentation of buildings, particularly those located in urbanized areas that have high earthquake risk and the expansion of the COSMOS strong motion data base by incorporating recordings from important earthquakes such as the Chi-Chi Taiwan and Kocaeli Turkey earthquakes. Planned activities will significantly advance web dissemination of strong motion data with the objective of making the COSMOS VDC an effective practical resource for earthquake practitioners.

The structure of COSMOS provides for participation of strong motion program members as well as users of strong motion data at several levels. The Consortium is governed by a Board of Directors constituted of representatives of Strong Motion Program members and strong motion data users. The Strong Motion Programs Board develops and implements the Consortium's technical program. A Senior Advisory Council provides broad high level advice with respect opportunities and activities for advancing strong motion programs to serve the Nation's need for strong motion data to protect public safety in earthquakes. Members may actively participate at any of these levels as well as at the Annual Meeting of the Consortium.

GUIDELINES

COSMOS has recently completed two important guidelines: "Instrumental Systems for Diagnostics of Seismic Response of Bridges and Dams: Recommended Guidelines" (Bolt, et al., 2001), and "Guidelines for Advanced National Seismic System Strong Motion Station Installation" (COSMOS, 2001).

Major dams and bridges are elements of the Nation's infrastructure system that are critically important for economic as well as for public safety reasons. Because of their importance, it has been recognized for many years that strong motion recordings on and around these structures are critically important. Consequently, the importance of placing strong motion instrumentation in such structures is recognized. Owners and operators require recordings of the structures' responses to strong ground shaking to determine actions to be taken during and immediately following an earthquake, to assess the extent of damage, and to determine whether in the long term retrofit or replacement is required. Increasingly, important and critical dams or bridges are required to be instrumented in consideration of public safety.

In order to fully review current practice and define the scope of instrumentation needed to capture the response of major dams and bridges, COSMOS held an invited workshop on October 26 – 27, 2000. Invitations were extended to forty-four persons who were known to have active professional interest in instrumentation of large critical structures. Short discussion papers addressed the wide range of relevant topics. The papers together with recorded comments and discussion following each paper formed the basis for recommended guidelines. The product of the workshop is an archival quality proceedings (Bolt, et al., 2001)

With funding support by the U. S. Geological Survey, COSMOS has completed "Guidelines for Advanced National Seismic System Strong Motion Station Installation" (COSMOS, 2001). The purpose of earthquake strong motion measurements within the Advanced National Seismic System (ANSS) is to quantitatively document large-amplitude earthquake ground shaking for use in various alerting, assessment, and research applications. The Guideline, which was drafted by Robert Nigbor and prepared with oversight of the COSMOS Strong Motion Programs Board (SMPB), provides specific guidance for the installation of ANSS strong motion stations to be considered as urban reference stations. The goal of urban reference stations is to accurately record the combined effects of earthquake source, propagation path, and site effects within the range of amplitudes (.001 - 2g) and frequencies (0 – 50 Hz) needed for the various public safety, engineering, and scientific applications. In urban areas, the broader goal is to measure ground motions that are representative of the ground shaking experienced by the built environment - buildings, other structures, infrastructure. The most useful urban strong motion reference stations are those installed at ground surface locations in the free field with minimum contamination of ground motions by soil-structure interaction effects. Useful reference stations may be installed within small buildings, however. Both types of installations can provide valuable information for many public safety, engineering, and scientific applications.

The Guideline provides detailed information regarding strong motion reference station siting, construction, site characterization, and documentation. The ANSS management within the USGS has reviewed and accepted the document and it is now being used by ANSS Region Managers to implement installation of urban reference strong motion stations. Although it is directed primarily to guide installation of ANSS urban reference stations, the document is broadly useful to other strong motion measurement programs.

The Guideline currently is undergoing final approval review by the COSMOS SMPB and is expected to be available on the COSMOS web (www.cosmos-eq.org) within a few weeks. Following approval the Guideline will be published as an archival quality report.

DEVELOPMENT OF THE COSMOS STRONG MOTION VIRTUAL DATA CENTER

Evolution of the COSMOS Virtual Data Center (VDC) is continuing with current developments in four activities: development of VDC server to improve access to data by users, development of a mirror site at the USGS National Strong Motion Program (NSMP) (www.nsmp.wr.usgs.gov), incorporation of important data directly into the VDC (see M. Squibb, COSMOS Newsletter No. 5), and release of the COSMOS data format standard.

The VDC user interface continues to be improved as part of the normal evolution of the database and with feedback from users. Users have been able to download earthquake parameters as an ASCII file for some time. Recently completed modifications and improved instructions on the VDC home page (www.db.cosmos-eq.org) facilitate downloading these parameters as TAB-delimited data in a spreadsheet program. Improvements in the user interface that facilitate data access is a continuing primary goal. The ultimate goal is to provide a resource that practitioners can incorporate into their every-day practices. In order to keep current with developing technology the VDC server has been upgraded to Windows2000.

Work is currently being initiated to develop a mirror site at the USGS in Menlo Park, CA and it is expected that work will be initiated later this year to develop a mirror site at the California Division of Mines and Geology (CDMG) in Sacramento, CA. When completed these mirror sites will improve performance and ensure uninterrupted user access. To provide additional assurance of uninterrupted user access, an uninterrupted power source has been installed.

Important data, especially data that are not held in either the CDMG or USGS NSMP databases, which are virtual sites of the VDC, continue to be added directly to the VDC server as such data become available. A growing number of strong motion observation programs are generously cooperating in this effort.

Strong motion recordings of the Nisqually, Washington earthquake of 28 February 2001 were added to the VDC server immediately following the earthquake (see Stepp, et al., COSMOS Newsletter No. 4, and H. Benz, COSMOS Newsletter No. 5). The M6.8 Nisqually earthquake recordings are particularly important for earthquake engineers and strong motion seismologists in the Pacific Northwest because it appears to have been a repeat of damaging earthquakes that occurred at essentially the same location in 1949 and 1965. A few strong motion recordings were obtained from both of these earthquakes. With the very active deployment of strong motion stations in recent years however, the Nisqually earthquake was recorded at 73 strong motion station sites resulting in 277 strong motion recordings. Recordings were obtained on a range of site geology and in a significant number of structures. Fifty-four channels of motion were recorded at eight instrumented dams, four U. S. Army Corp of Engineers (COE) dams, and two U. S. Bureau of Reclamation (BOR) dams as well as dams owned by Tacoma Public Utilities and Seattle Light and Power. Six channels of strong motion were recorded in waterways structures. Twenty-six channels were recorded in instrumented high-rise buildings and 21 channels were recorded in lifeline facilities. With the productive cooperation of the Pacific Northwest Seismic Network (PNSN) (www.geophys.washington.edu/SEIS/PNSN/SMO/), the NSMP (www.nsmp.wr.usgs.gov), the COE (www.geoscience.wes.army.mil), and the BOR, a significant subset of these data were incorporated into the VDC server shortly following the earthquake and the recordings were available to practitioners in the region for more informed consultation with clients.

Recently, the VDC has added uncorrected free-field strong motion recordings of the 20 September 1999 Chi-Chi, Taiwan main earthquake. With the corporation and support of the California Strong Motion Instrumentation Program (CSMIP), the participation of the Central National University of Taiwan, and the Taiwan Central Weather Bureau, processing of over 400 recordings of the Chi-Chi earthquake main shock and three major aftershocks is being carried out at CSMIP following to CSMIP standards. Full processing will be carried out to velocity, displacement and response spectra (see B. A. Bolt, COSMOS Newsletter No. 5). The processed data will be shortly available on the VDC or directly on the CSMIP server as part of the VDC, in the COSMOS standard data format (see A. F. Shakal, COSMOS Newsletter No. 5). The format can be viewed on the COSMOS web site (www.cosmos-eq.org/cosmos_format_01.pdf).

Though the generous assistance of Mustafa Erdik and the Kandilli Observatory and Earthquake Research Institute (KOERI) and Erdal Safak of the USGS, uncorrected recordings of the August 2000 Kocaeli, Turkey earthquake and 15 aftershocks are being added currently to the VDC. We anticipate adding additional recordings of the Kocaeli earthquake and aftershocks obtained by other strong motion networks in Turkey as they become available. The KOERI strong motion recordings have been converted to the COSMOS standard data format.

The VDC continues to receive strong motion recordings from observation networks in both the United States and other countries. Recently, through the generous cooperation of the Centro de Investigaciones Geotecnicas and the Universidad Centroamericana, Structural Mechanics Department uncorrected strong motion recordings of the 13 January 2001, 13 February 2001, and 17 February 2001 El Salvador earthquakes have been added to the VDC. Strong motion recordings of 10 recent earthquakes generously provided by the Kik-Net in Japan, have been added in 2001 together with recordings of 10 February 2001 Big Bear Lake, California, the 10 June, 2001 Satsop, Washington, and the 29 November 2000 Central Alaska earthquakes.

SCHEDULED WORKSHOPS

COSMOS has scheduled two invited workshops: Archiving and Web Dissemination of Geotechnical Data, and Strong Motion Instrumentation of Buildings (see J. C. Stepp and J. Swift, COSMOS Newsletter No. 5 and A. F. Shakal, J. C. Stepp, and R. L. Nigbor, COSMOS Newsletter No. 5). The first of these, supported by the PEER Center Lifelines Program, is scheduled to be held on 4-5 October, 2001; the second, supported by National Science Foundation, COSMOS, and ANSS funding, is scheduled to be held on 14-15 November, 2001.

The first of these workshops was motivated by the recognized need to make the various different types of valuable geotechnical data available in the most cost efficient way to a broad user community. Geotechnical investigations are routinely required for design and to obtain approval to construct all critical structures and significant buildings as well as for a wide range of specific research purposes. Large quantities of data are consequently generated, much of them of interest and significant value to the broad geotechnical engineering and construction community as well as for university research. While the data are generally collected following current professional practices, consistent standards and quality practices are not generally implemented. The data that have been collected over the years typically reside in the archives of local, state, and federal agencies and private sector organizations. Organizations such as Caltrans and the transportation agencies of other states, the Federal Highway Administration, the California Division of Mines and Geology, the geological surveys of other states, the U. S. Geological Survey, Army Corp of Engineers, Bureau of Reclamation, and other federal agencies, private sector companies such as Pacific Gas and Electric, and national research-focused activities such as the National Geotechnical Experimental Sites, university-government-private sector cooperative projects such as GEOINFO-ROSRINE, and the PEER Center Lifelines Program collect important data sets. A number of efforts aimed at developing databases for archiving and web dissemination of geotechnical data are now in progress. These important efforts together with the data collection absorb large resources and there are significant barriers to broadly accessing the data because common data format standards are lacking and optimally compatible data archiving and dissemination methods are not in place.

The objective of the workshop is to develop consensus recommendations for classifying, archiving, and web dissemination of the various types of geotechnical data. The final product is intended to be a road map of developmental and infrastructure needs. A workshop agenda, which can be viewed on the COSMOS web site (http://www.cosmos-eq.org), has been structured to facilitate better understanding of the common features and issues that have been identified by the various ongoing database development efforts and to address long-term infrastructure and funding requirements. The important principal deliverable of the workshop will be consensus recommendations that describe a clear path forward for implementing archiving and web dissemination of geotechnical data to meet user needs. Workshop presentations and consensus recommendations will be published in an archival quality proceedings.

The second of these workshop is an activity of the COSMOS SMPB. The workshop is motivated by the need to obtain broad input of earthquake engineering professionals for the purpose of defining strategic needs that can be used to guide the development of guidelines for strong motion instrumentation of buildings. With the authorization of the ANSS (see H. Benz, COSMOS Newsletter, No. 2, April, 2000; R. Page, COSMOS Newsletter No. 5) it is anticipated that at least 6,000 strong motion instruments will be placed in buildings during the next five years. The placement of the instruments in order to maximize the usefulness of the anticipated recordings for the purpose of advancing public safety in earthquakes is critically important.

The main objectives of the workshop are to document current practice for strong motion instrumentation of buildings, to identify the types of building that should be instrumented, and to define the types of response measurements needed to meet expanding uses of strong motion data in earthquake engineering research and practice, emergency response practice, and building health evaluation. Other important objectives are to document developing instrumentation technologies, communication technologies, and monitoring system. The workshop is being organized around four principal topics: current building instrumentation programs and guidelines, future needs for strong motion measurements in buildings, instrumentation technologies, and strategies for selecting buildings for strong motion instrumentation. The last of these topics will address national and regional priorities, priorities for selection of buildings, and mechanisms to encourage expansion of private participation in a coordinated national building instrumentation effort.

Discussion papers within these topics are being invited and will be distributed to workshop participants in advance. The discussion papers together with consensus recommendations of the workshop will be published in an archival quality proceedings. It is intended that the proceedings will serve as a technical information base for separate development of guidelines for strong motion instrumentation of buildings.

Organizations supporting this workshop include the National Science Foundation supported U. S. Committee for Advancement of Strong Motion Programs, the U. S. Geological Survey Advanced National Seismic System, COSMOS, and PEER.

SAFER CITIES INITIATIVE

COSMOS and the World Seismic Safety Initiative (WSSI) have concluded an agreement to jointly promote and facilitate deployment of surplus strong motion instruments in earthquake prone regions of the world that currently have few or no strong motion stations. Strong motion instrumentation is normally replaced by monitoring programs as instrument technology improves and the replaced instruments become surplus. The instrumentation that is replaced often in is good working order, but no longer meets the requirements of the monitoring program. In recognition that these instruments can be beneficially deployed in many areas of the world, COSMOS and WSSI have developed a project, entitled "*SAFER Cities (Strong-Motion Accelerographs For Earthquake Loss Reduction in Cities)"*. The project is intended to accomplish the redistribution of surplus instruments.

Surplus instruments provided by monitoring programs in the United States will be primarily those of the four COSMOS Core Strong Motion Program members: the ACOE, the BOR, the CSMIP, and the NSMP as well as other Strong Motion Program members. Additional instruments may be provided by monitoring programs in other parts of the world that are affiliated with or support the WSSI. Recipients of the instruments must be non-profit organizations and agencies that would otherwise have little or no means of recording the next damaging earthquake in urbanized areas of the world that have high earthquake risk exposure. Objectives of the initiative, responsibilities of the various agencies and organizations, and procedures for redistribution of unused instrumentation can be viewed on the COSMOS web page (www.cosmos-eq.org).

CONCLUDING REMARKS

COSMOS is dedicated to improving public safety in earthquakes by facilitating advancements in strong motion monitoring and the broad use of strong motion data. The

Consortium functions on the premise that public safety can be best achieved through coordinated, broad participation of strong motion monitoring programs and public and private users of strong motion data. To this end an important objective is to generate a spirit of participation through the COSMOS membership, which is open to all professionals who are interested in earthquake safety.

REFERENCES

Bolt, B. A., G. Fenves, W. D. Iwan, and A. F. Shakal, editors, 2001. Instrumental Systems for Diagnostics of Seismic Response of Bridges and Dams: Recommended Guidelines, COSMOS Publication No. CP-2001/01, Proceedings of a Workshop held at Pacific Earthquake Engineering Research Center, October 26 – 27, 2000.

COSMOS, 2001. Guidelines for Advanced National Seismic System Strong Motion Station Installation, in prepublication review.

USGS (1999). An Assessment of Seismic Monitoring in the United States: Requirement for an Advanced National Seismic System, U. S. Geological Survey Circular 1188, U. S. Geological Survey, Denver, Colorado.