# STRENGTH AND ENERGY DEMANDS FROM THE AUGUST 1999 KOCAELI EARTHQUAKE GROUND MOTIONS

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## ABSTRACT

Traditionally, the intensity of ground shaking and the demand on structures has been characterized using parameters such as peak ground acceleration as well as strength-based parameters such as response spectrum ordinates (e.g., spectral acceleration) that represent the maximum amplitude of shaking for structures with specified natural periods and damping ratios. It has long been recognized that to understand the demands placed on structures during earthquakes one might also employ an energy-based approach, especially when there is an interest in assessing the damage potential of ground motions. An input energy spectrum, obtained with the same level of effort as is required to construct a conventional response spectrum, is a convenient single-parameter description of both amplitude and duration of ground motion and can be a useful means by which to describe the performance of structures. Both elastic and inelastic input energy spectra can be easily constructed – the latter can provide useful information for systems that undergo inelastic deformations (or that are designed with adequate ductility capacity) and for assessing the damage potential of ground motions.

The two earthquakes that occurred in Turkey in 1999 and the damage suffered by structures in those events motivated the present study that examines recorded ground motions from those events. Input energy spectra and response spectra are computed for recorded ground motions from the Kocaeli earthquake. Several Western United States attenuation models have been established from a larger database of ground motions than are available for Turkey. Because of reported similarities between the San Andreas and the North Anatolian fault systems, strength and energy spectra estimated from Kocaeli motions are compared with these empirical attenuation models developed for the Western United States.

## Introduction

Attenuation models for ground motion have historically been developed for different regions of the world by considering strength-based demand parameters such as spectral acceleration or even peak ground acceleration. More recently, research studies have investigated the attenuation of energy-based parameters such as absorbed energy (Chou and Uang, 2000) and input energy (Chapman, 1999). Understanding seismic demands on structures using an energy approach can be important, especially when there is an interest in assessing damage potential.

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The North Anatolian fault system, a western portion of which ruptured during the Kocaeli earthquake in August 1999, has been compared with the San Andreas fault in the Western United States in several studies (see Çelebi et al (1999), for example) – these two fault systems are both right-lateral, strike-slip faults with remarkably similar lengths and long-term rates of movement. Attenuation models developed based on the extensive ground motion data from California might possibly have similarities with regions in Turkey influenced by the North Anatolian fault system. This is because of the similarity in characteristics of this fault system with the San Andreas fault in California – a fact that has been noted by many researchers (see, for example, Ambraseys (1990) or Çelebi et al (1999)). Also, according to Dewey (1976), the normal-fault earthquakes of northwestern Anatolia are seismologically similar to some normal-fault earthquakes of the western United States.

Despite regional geological differences between California and relevant areas of Turkey, the noted similarities raise interesting questions regarding the possibility of some similarity in the characteristics of ground motion attenuation for these two fault systems as well. This study addresses such questions by examining ground motion recorded at stiff soil and rock sites during the August 1999 (Kocaeli) earthquake and comparing these observations to predicted motions for the $M_w$ 7.4 event at various distances. The relative sparseness of the network of ground motion measuring stations in Turkey that exists today suggests that in this earthquake, the ground motions that were recorded were likely not the largest ones that might have actually occurred. This has already been pointed out by others (see Çelebi et al, 1999). As such, a study of the attenuation of recorded ground motion, which is undertaken here, is subject to this bias. Nevertheless, we discuss comparisons of attenuation of strength- and energy-based ground motion parameters of recorded data with regression-based models in current use for California.

Studying the energy demands of ground motion on structures has been a topic of recent interest (see Chou and Uang (2000), and Chapman (1999)). Energy-based demand parameters include input energy, absorbed energy, hysteretic energy (for inelastic behavior), etc. – these might be expected to be more robust indicators of damage potential than strength-based parameters such as spectral acceleration. We discuss here how computation of (frequency-dependent) energy spectral ordinates requires the same amount of effort as conventional response spectra. Since energy is a cumulative measure of ground shaking, however, it also captures duration effects. What is significant about several of the records obtained during the Kocaeli earthquake is the presence sometimes of two distinct strong shaking episodes in the recorded ground acceleration time traces. Such effects are especially well represented in energy-based spectra; elastic strength-based spectra, will generally not be influenced by a second, less severe shaking that occurs several seconds after the first.

The attenuation of several different ground motion parameters is discussed here. These include conventional elastic strength-based parameters such as peak ground acceleration (*pga*), spectral acceleration or velocity ($S_a$ and $S_v$) as well as elastic energy-based parameters (such as the *energy-equivalent* velocity parameters defined in the following). In addition, the attenuation of inelastic ground motion demand parameters (both strength- and energy-based) is studied using results based on recorded motions for structures exhibiting nonlinear, inelastic behavior.

The goal of the present study is to attempt to understand the degree to which attenuation models that have been developed for California can represent observed data from stations that recorded the Kocaeli earthquake motions. Due to the sparseness of the network of recording stations mentioned before, some caution needs to be exercised in interpreting similarities or differences for the two regions. Nevertheless, especially for purposes of planning or in assessing the seismic hazard at sites all over Turkey, current attenuation models in use may be usefully augmented by models developed for California until the Turkish ground motion database is enhanced. A second objective of the present study is to compare energy-based ground motion parameters and their attenuation with strength-based parameters, especially to understand differences between these two, if any, for structures of different natural periods.

## Ground Motion Data from the August 17, 1999 (Kocaeli) Earthquake

The Kocaeli earthquake that occurred on August 17, 1999 had a moment magnitude that was estimated to be 7.4 with rupture beginning at a depth of approximately 17 km. The epicenter of the Kocaeli Earthquake was Gölcük. This earthquake was the largest on record to hit a modern, industrialized area since the 1906 San Francisco earthquake and the 1923 Tokyo earthquake. The earthquake was caused by slippage along the Sapanca-İzmit segments of the North Anatolian fault that is 900 km long and has several characteristics similar to that of the San Andreas fault in California – both fault systems exhibit right-lateral strike-slip mechanisms, similar long-term rates of movement, and are of roughly similar lengths.

Records taken from 15 different stations are used in the analysis. All the records are for stiff soil and/or rock site conditions (see Table 1). The locations of these stations are shown as well. The geometric mean of the two horizontal components is used in the studies that are described here. For distance calculations, the closest distance to the rupture surface is used. This is also the distance measure used in the various attenuation models employed here.

## Description of Seismic Demands using Strength- and Energy-Based Parameters

Ground motion may be described quantitatively in different terms when one is interested in understanding its effect on structures with different natural period and damping values. Conventionally, strength-based parameters (such as spectral acceleration ($S_a$) or velocity ($S_v$) or even *pga*) have been used. Regression-based models describing the attenuation of these parameters as a function of magnitude and distance (for specified site conditions and faulting types) have been developed for various regions of the world. Not as extensively studied are energy-based ground motion parameters and models describing their attenuation.

We define various strength- and energy-based parameters here. Consider the equation of motion for a single-degree-of-freedom (SDF) system subjected to a horizontal ground motion:

$$m\ddot{u}_t + c\dot{u} + f_s = 0 \tag{1}$$

where $m$, $c$, and $f_s$ are the mass, viscous damping coefficient, and restoring force, respectively. Also, $u_t$ is the absolute (total) displacement of the mass, while $u = u_t - u_g$ is the relative displacement of the mass with respect to ground, and $u_g$ is the ground displacement.

For a specified natural period and damping, solution of Eq. 1 can yield the maximum displacement, $u_{max}$, which is also referred to as the spectral displacement, ($S_d$). In terms of the natural frequency, $\omega$, it is convenient to define two parameters, spectral velocity, ($S_v$) and spectral acceleration, ($S_a$). Thus, we have:

$$u_{\max} = S_d = \frac{S_V}{\omega} = \frac{S_a}{\omega^2} \tag{2}$$

Transformation of the equation of motion into an energy balance equation can be easily accomplished by integrating Eq. 1 with respect to $u$ from the beginning of the input ground motion (see, for example, Uang and Bertero, 1988). This leads to:

$$\frac{m(\dot{u}_t)^2}{2} + \int_0^t c\dot{u}du + \int_0^t f_s du = \int_0^t m\ddot{u}_t du_g \tag{3}$$

where the right-hand side of Eq. 3 is, by definition, the input energy, $E_i$, since $m\ddot{u}_t$ represents the inertia force experienced by the structure. Also, since this inertia force equals the sum of the damping and restoring forces, it is also equal to the total force applied at the base of the structure. Thus, $E_i$, can also be thought of as the work done by the total base shear on foundation/ground displacement. Note that the first term on the left hand side of Eq. 3 is the *kinetic energy* ($E_k$) while the second and third terms are, respectively, the *damping energy* ($E_d$) and the *absorbed energy* ($E_a$), which is the sum of recoverable *elastic strain energy* ($E_s$) and irrecoverable *hysteretic energy* ($E_h$). Thus, the energy balance equation can be rewritten as:

$$E_i = E_k + E_d + E_a\,; \qquad E_a = E_s + E_h \tag{4}$$

It is convenient to define parameters with units of velocity that relate to the input energy and the absorbed energy. Thus, we define two parameters, "input energy-equivalent velocity" ($V_i$) and "absorbed energy-equivalent velocity" ($V_a$), as follows:

$$V_i = \sqrt{\frac{2E_i}{m}} \quad ; \qquad V_a = \sqrt{\frac{2E_a}{m}} \tag{5}$$

Attenuation models for $S_a$, $S_v$, $V_i$ and $V_a$ will be presented and compared with estimates based on the Kocaeli ground motion data. Five-percent damping will be considered in all cases.

## Numerical Studies

The response of elastic and inelastic structures to the ground motion records in Table 1 was studied and the results from those analyses are briefly summarized here.

**Attenuation of peak ground acceleration:** Figure 1 shows a plot of *pga* versus distance for the records analyzed. Five different attenuation models are studied. These include models by Boore et al (1997), Campbell (1997), Chapman (1999), Lawson (1996), and Sadigh et al (1997). Especially for distances less than about 30 km, the Kocaeli records generally yielded somewhat lower levels of *pga* than is predicted by most of the models. Clearly, the relatively small number of records available prevents us from making broad conclusions from this finding. For larger distances, the *pga* values appear to be comparable to levels predicted for California.

**Response and Design Spectra:** Next, we study response spectra from the fifteen motions. In Fig. 2, the mean and mean-plus/minus-one-standard-deviation values of spectral acceleration ($S_a$) are shown versus period for the motions. For comparison, design spectrum levels as specified in the Turkish code are also shown for four different zones (1-4). The motions, on average, were somewhat lower than design levels for Zone 3. Variability among the Kocaeli motions as indicated by the standard deviation of $S_a$ is seen to be fairly large especially at short periods.

**Attenuation of spectral velocity ($S_v$):** A comparison of recorded spectral velocity ($S_v$) levels with predicted levels based on attenuation models is studied next. Seven different attenuation models are studied for $S_v$. In addition to the models used for *pga*, two additional models proposed by Chou and Uang (2000), Abrahamson and Silva (1997) are considered. Figure 3 shows a plot of the 1-sec $S_v$ values versus distance for the records analyzed. Predictions based on the different attenuation models are also included. Again as was observed for *pga*, the models were all found to predict higher $S_v$ levels than were obtained using the Kocaeli data. This, however, may be due to sparseness of data in the near field. We compare the Kocaeli $S_v$ response spectra next by studying the data in four distinct distance groups: (i) two records, IZT and SKR; attenuation models with distance = 5 km; (ii) three records, ARC, GBZ, and GYN; models with distance = 25 km; (iii) eight records, ATK, BRS, CAN, DHM, IST, MCD, MSK, and ZYT; models with distance = 65 km; (iv) two records, BLK and BTS; models with distance = 150 km. As seen in the results grouped by distance in Fig. 4, significant variability in the data was observed at longer distances; at shorter distances, the sparse data set makes it difficult to make meaningful conclusions. The Western U.S. (WUS) attenuation models, however, are seen to predict similar period-dependent $S_v$ character to the Kocaeli data on average.

**Attenuation of elastic input energy-equivalent velocity ($V_i$):** Two attenuation models for $V_i$ are considered: Chapman (1999) and Lawson (1996). Figure 5 shows a plot of the 1-sec $V_i$ values versus distance for all the records analyzed in this study. Mean and mean-plus/minus-one-standard-deviation predictions based on the two attenuation models are also included. WUS models are seen to predict 1-sec $V_i$ values fairly well on average; however, we found that for shorter periods, the Kocaeli data were somewhat larger than model predictions. We compare the Kocaeli $V_i$ spectra ($V_i$ values versus natural period) next by studying the data in the same four distinct distance groups that were used while studying $S_v$. Again, we consider the same two attenuation models for $V_i$ as in Fig. 5 and include mean and mean-plus/minus-one-standard-deviation model predictions together with the $V_i$ values from the Kocaeli data in Fig. 6. As seen in the figure, model predictions closely match the Kocaeli data over all distances.

**Attenuation of inelastic absorbed energy-equivalent velocity ($V_a$)** For elasto-plastic systems, a comparison of computed absorbed energy-equivalent velocity ($V_a$) levels for the ground motion records with predicted levels based on one attenuation model is studied for two ductility levels, $\mu$ = 2 and 6. The attenuation model proposed by Chou and Uang (2000) is considered. Figure 7 shows plots of 1-sec $V_a$ versus distance for the two ductility levels for the records analyzed. Attenuation model predictions (mean and mean-plus/minus-one-standard-deviation levels) are also included. WUS models predict inelastic 1-sec $V_a$ values fairly well on average. Also, very small differences in $V_a$ values are seen between the results at the two ductility values.

**Attenuation of inelastic input energy-equivalent velocity ($V_i$)** For inelastic systems (bilinear with 5-percent strain hardening), a comparison of computed input energy-equivalent velocity ($V_i$) levels for the ground motion records with predicted levels based on one attenuation model is studied next for two ductility levels, $\mu$ = 2 and 6. The attenuation model proposed by Lawson (1996) for this energy-based parameter is considered. Figure 8 shows plots of the 1-sec $V_i$ values for the two ductility values versus distance for the records analyzed in this study. Attenuation model predictions (mean and mean-plus/minus-one-standard-deviation levels) are also included. As with the inelastic $V_a$ results in Fig. 7, the WUS models predict inelastic 1-sec $V_i$ values fairly well on average. Also, very small differences in $V_i$ values are seen between results at the two ductility values for the bilinear system with 5%-hardening consistent with what was found in studying $V_a$ differences at the two ductility values for elasto-plastic systems.

## Conclusions

Studies employing strong motion data from the Kocaeli earthquake examined the possibility of using various energy-based ground motion parameters. Elastic and inelastic strength- and energy-based parameters were compared for various distances. Predictive attenuation models used confirmed that the Kocaeli data, in general, resemble ground motion recorded from events in the Western U.S fairly well.

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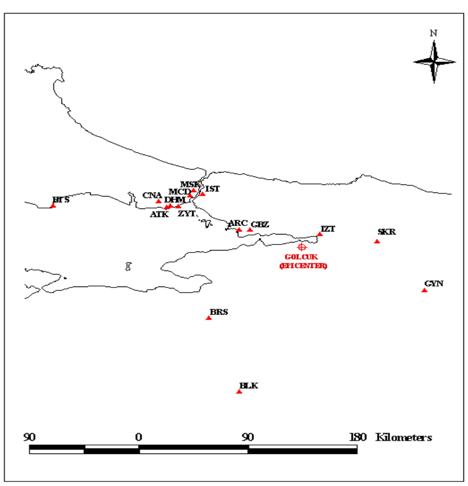
Table 1. Summary of the stations and the Kocaeli earthquake (August 17, 1999) ground motion records used in the analysis. (*For the Sakarya (SKR) station, only one horizontal component of ground acceleration was available and used in this study.)




| No. | Station | Abbr. | Operated by | Dist. (km) |
|---|---|---|---|---|
| 1 | Arçelik | ARC | KOERI | 22 |
| 2 | Ataköy | ATK | ITU | 67 |
| 3 | Balıkesir | BLK | ERD | 183 |
| 4 | Botaş | BTS | KOERI | 136 |
| 5 | Bursa Sivil Savunma | BRS | ERD | 67 |
| 6 | Çekmece | CNA | KOERI | 76 |
| 7 | Gebze | GBZ | ERD | 13 |
| 8 | Göynük | GYN | ERD | 35 |
| 9 | Havaalanı-İstanbul | DHM | KOERI | 69 |
| 10 | İstanbul | IST | ERD | 61 |
| 11 | İzmit | IZT | ERD | 5 |
| 12 | Maslak | MSK | ITU | 64 |
| 13 | Mecidiyeköy | MCD | ITU | 62 |
| 14 | Sakarya* | SKR | ERD | 4 |
| 15 | Zeytinburnu | ZYT | ITU | 63 |

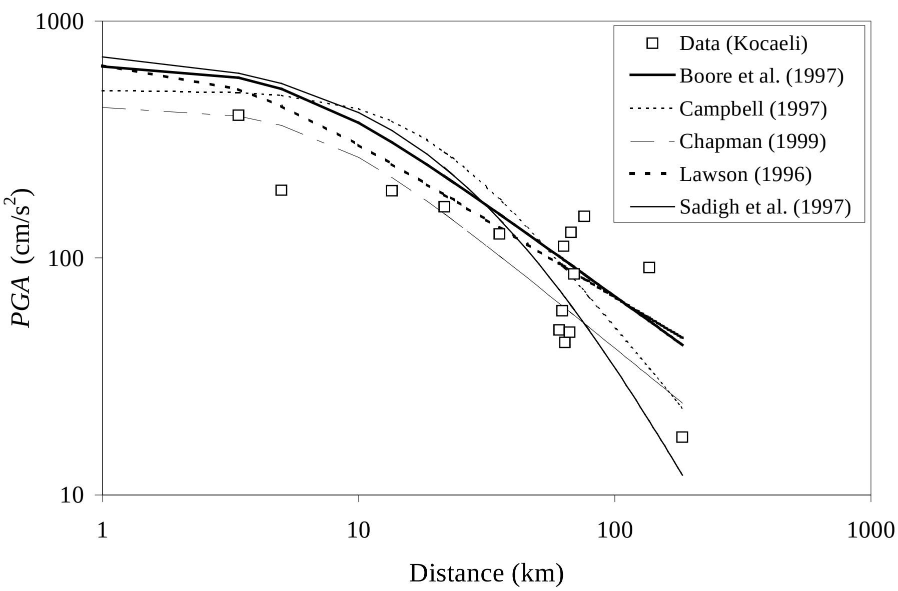



Figure 1. Peak ground acceleration (*pga*) versus distance for Kocaeli motions compared with Western U.S. attenuation model predictions

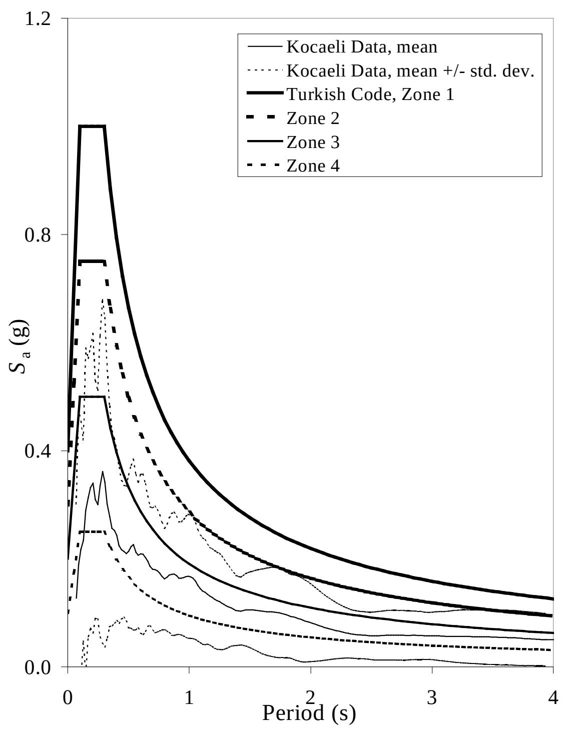



Figure 2. Mean response spectra ($S_a$) and mean-plus/minus-one standard spectra of the Kocaeli motions compared with the Turkish design spectra.

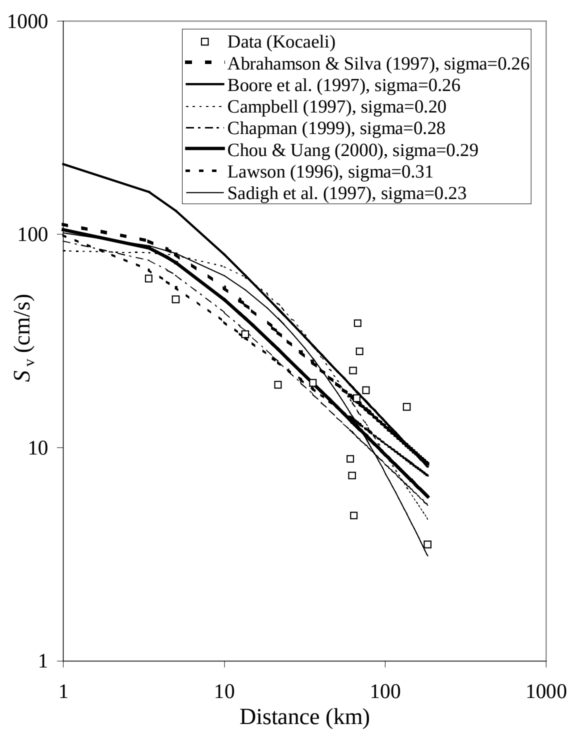



Figure 3. 1-second $S_v$ versus distance for Kocaeli motions compared with Western U.S. attenuation model predictions.

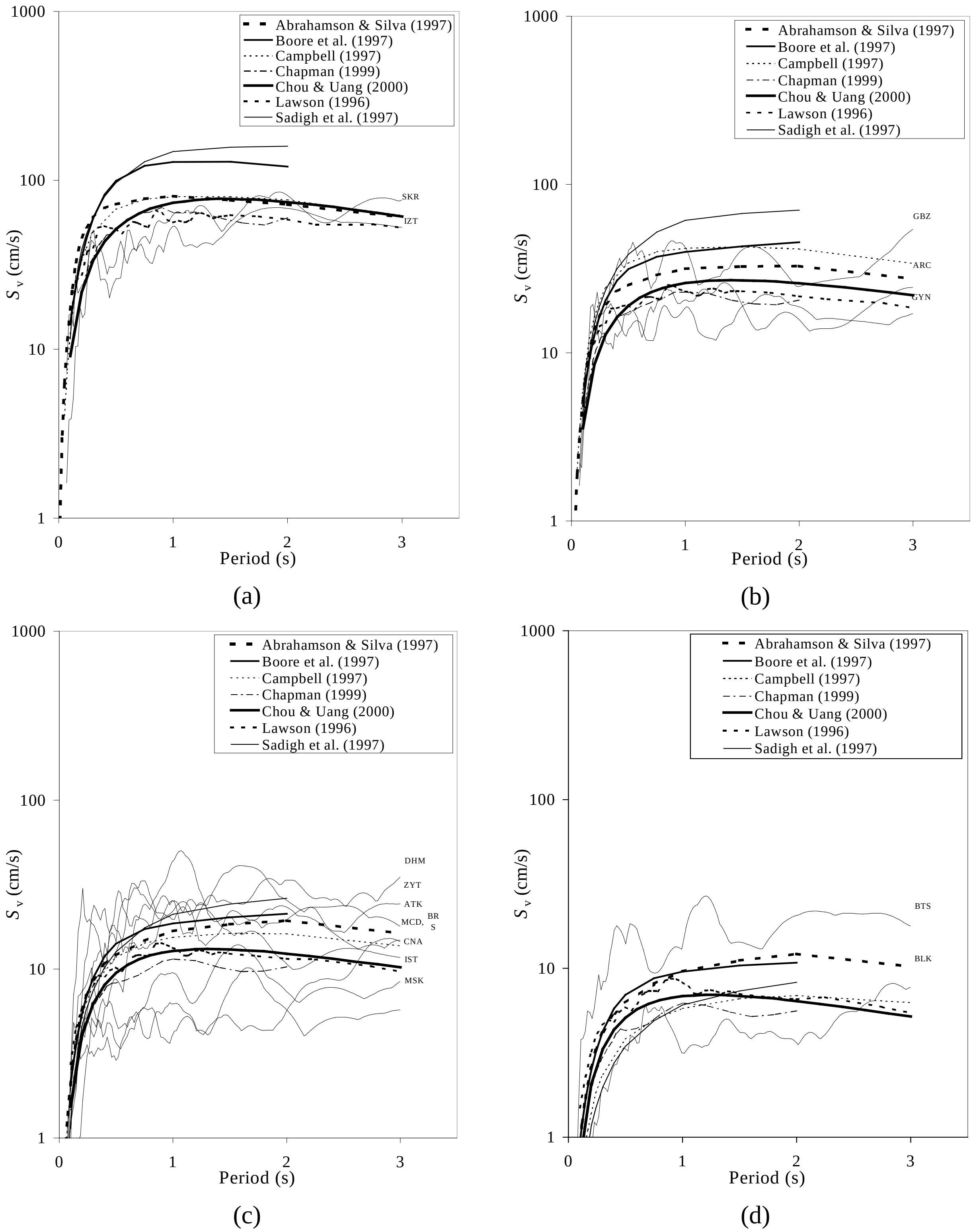



Figure 4. Spectral velocity, $S_v$, for the Kocaeli motions compared with Western U.S. attenuation model predictions grouped by distance sets: (a) 5 km, (b) 25 km, (c) 65 km, (d) 150 km.

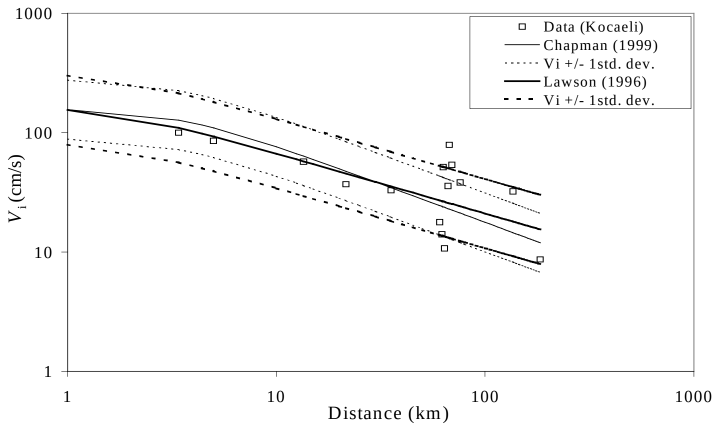



Figure 5. 1-second $V_i$ versus distance for Kocaeli motions compared with Western U.S. attenuation model predictions.

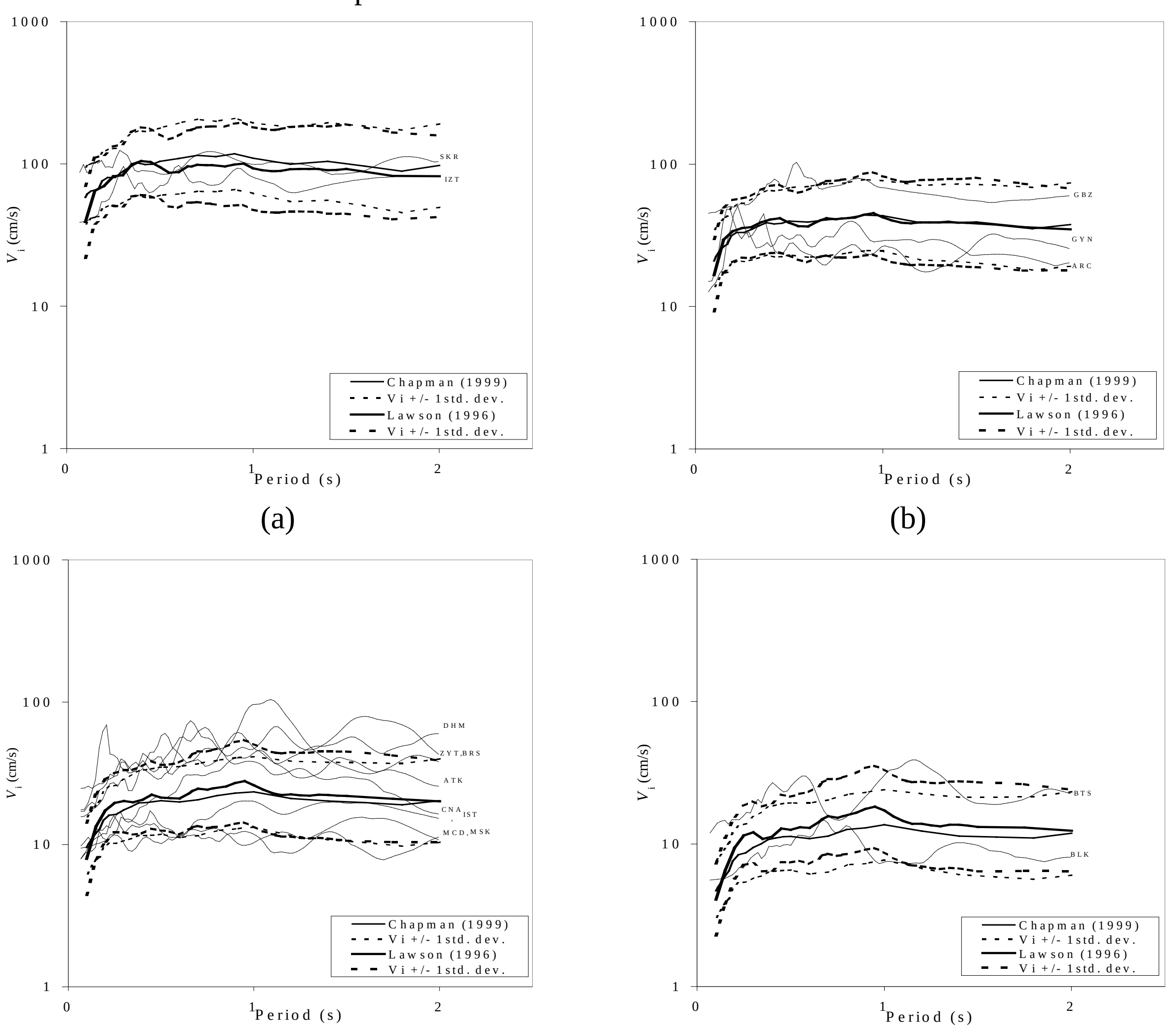
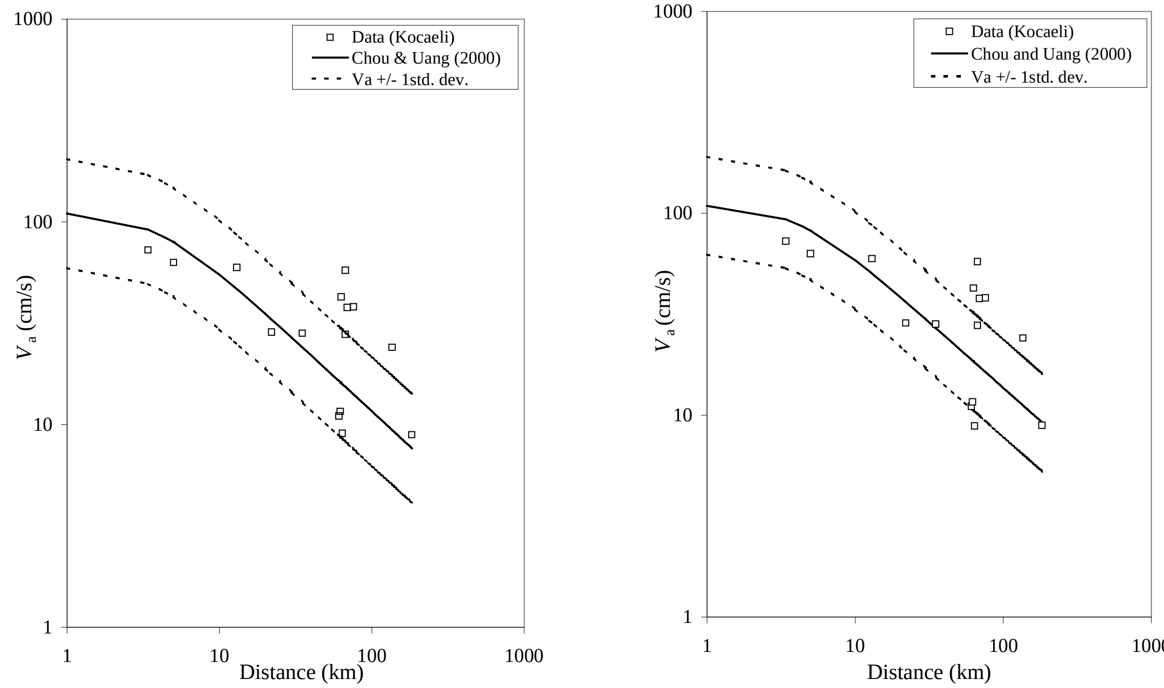
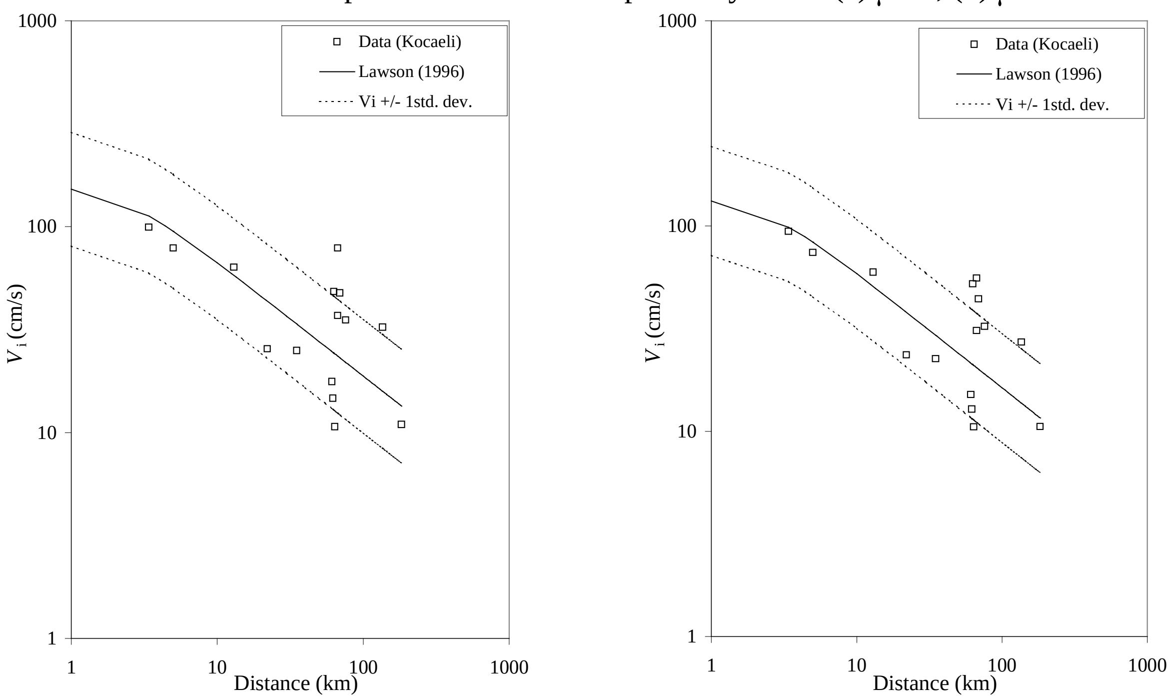



Figure 6. Elastic input-energy equivalent velocity, $V_i$, for the Kocaeli motions compared with Western U.S. attenuation model predictions grouped by distance sets: (a) 5 km, (b) 25 km, (c) 65 km, (d) 150 km.




(a) (b)

Figure 7. 1-second $V_a$ versus distance for Kocaeli motions compared with Western U.S. attenuation model predictions for elasto-plastic systems: (a) $\mu$= 2, (b) $\mu$= 6.




(a) (b)

Figure 8. 1-second $V_i$ versus distance for Kocaeli motions compared with Western U.S. attenuation model predictions for bilinear, 5% strain hardening systems: (a) $\mu$= 2, (b) $\mu$= 6.