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THE USE OF INPUT ENERGY FOR SEISMIC HAZARD ASSESSMENT WITH DIFFERENT DUCTILITY LEVEL

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SUMMARY

The seismic hazard assessment based on input energy may prove useful for the identification of scenario earthquakes because input energy is a convenient descriptor of strong ground motion duration and amplitude. Based on 266 strong ground motion records, an attenuation relationship was developed for absolute and relative input energy spectra with earthquake magnitude, distance, and site class for 4 ductility levels under the damping ratio of 5%, in the period range 0.1 to 3.0 second. It is found that the site has a significantly effect on both absolute and relative input energy and input energy spectra increase rapidly with the increasing of earthquake magnitude and attenuate quickly with the increasing of distance, so, larger magnitude earthquakes contribute more to seismic hazard if input energy were used. The effect of ductility is very different for the input energy spectra constructed from the attenuation relationship with the change of periods. The input energy spectra increase with the increasing of ductility factor when the period of SDOF oscillator is less than 0.5 second and decrease with the increasing of ductility factor when the period is larger than 0.5 second. The effect of ductility on the relative energy spectra in short period range is much larger than that on the absolute energy spectra. After comparison of the two kinds of energy spectra constructed from the attenuation relationship, it is found that the absolute energy is some larger than relative energy in the short period range and some less than relative energy in long period range, and they are almost equivalent at the period about 0.5 second. The input energy demand of structures in future earthquake could be evaluated according to the result of the paper.

INTRODUCTION

Estimation of an attenuation relationship for strong ground motion parameters has been an interesting research subject in the field of engineering seismology and has played a very important role in seismic hazard analysis, earthquake resistant design, seismic safety evaluation, seismic zoning, etc. The first important work is to choose a proper parameter to establish the attenuation relationship. Much work has been done about intensity, peak acceleration, response spectra and so on. Such parameters mentioned above are essentially independent of the duration of the strong ground motion. It is widely held that the duration plays some important role in producing cumulative damage to structures. The input energy spectra, established by Uang and Bertero [1], characterize the duration very well, and are considered as a convenient single-parameter descriptor of strong ground motion duration and amplitude. Based on 304

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strong ground motion records, Chapman [2] established the attenuation relationship of the elastic absolute input energy spectra, that is, he did not consider the effect of ductility. It is well known that structures are generally put into non-linear state under the action of strong ground motion. That is to say, the ductility must be taken into account. Chou and Uang [3][4] established the attenuation model for absorbed energy spectra from the view of structure damage; they considered the absorbed energy as the index of structure damage. For seismic hazard assessment and seismic safety evaluation, the input energy contributed to structures needs to be understood very well. As Uang and Bertero [1] had shown, the absolute input energy and relative input energy are very different when the period of Single-Degree-of-Freedom (SDOF) is very short or very long. As we all know, the period of a general structure is often not very long, and the comparison between the two kinds input energy need to be made necessarily in short period range. In this study, the attenuation of the two kinds input energy was investigated in detail and the effects of parameters such as site class, magnitude and ductility factor on the input energy spectra constructed from the attenuation relationship were discussed. The emphases were placed on the effect of ductility on the two kinds input energy and the comparison of the two kinds input energy in short period range.

INPUT ENERGY SPECTRA

The absolute and relative input energy can be established from the equation of motion of a damped SDOF system as equation (1) and (2) show respectively [1].

$$E_a = \int m\ddot{v}_t dv_g \tag{1}$$

$$E_r = -\int m\ddot{v}_g dv \tag{2}$$

Where m =mass, $v_t = v + v_g$ =absolute displacement of the mass, v =displacement of the mass with respect to ground and v_g =displacement of ground. The definition of absolute input energy E_a is physically meaningful in that the term $m\ddot{v}_t$ represents the inertia force applied to the structure and the E_a represents the work done by the total base shear at the foundation on the foundation displacement. The relative input energy E_r is the work done by an equivalent lateral force ($-m\ddot{v}_g$) on a fixed base system, that is, it neglects the effects of rigid body translation of the structure. Uang and Bertero [1] had shown the difference between two kinds of input energy of SDOF with different periods.

The input energy can be converted to an equivalent velocity by the following relationship:

$$V_{ea} = \sqrt{2E_a / m} \tag{3}$$

$$V_{er} = \sqrt{2E_r / m} \tag{4}$$

In this paper, the equivalent energy velocity V_{ea} and V_{er} were used to investigate the attenuation of the strong ground motion input energy. The Comparison between V_{ea} and V_{er} spectra constructed from the attenuation model was made because they were very distinctive in very short period range.

STRONG GROUND MOTION DATABASE

A total of 266 records (Table A in appendix) from 15 significant earthquakes in California of America were used for the analysis, and each record included two mutually perpendicular corrected acceleration time histories. All the strong ground motions were recorded either at free field or ground level of a structure no more than two stories in height. The local site classification of each recording station was based on the average shear-wave velocity (V_s) over up to 30 meter in depth from the ground surface [5]. The same classification criterion was adopted by other researchers [3][4][6]. In this study, the Chou's classification scheme was used for site classification as Table 1 shows [3][4]. Site classes A and B were combined for analysis only because few data of the two site classes were available. Figure 1 shows the distribution of data in term of magnitude, distance and site classification.

Table 1: Site Classifications

NEHERP	General Description	V_s (m/s)	This Study
A	Hard rock	V_s>1500	A+B
B	Rock	1500 ≥ V_s>760	A+B
C	Very dense soil and soft rock	760 ≥ V_s>360	C
D	Stiff soil	360 ≥ V_s ≥ 180	D
E	Soil	V_s<180	/
F	Liquefiable soils, sensitive clays, collapsible cemented soils	V_s<180	/

The earthquake magnitude is a parameter describing the earthquake size. There are many kinds of definition of earthquake magnitude, such as local magnitude (M_L), surface-wave magnitude (M_S), body-wave magnitude (m_b or m_B), Japan Meteorological Agency magnitude (M_{JMA}) and moment magnitude (M_W). Each of the magnitude, except moment magnitude M_W, has an upper limiting value (saturate) as the size of earthquake increases [7]. The moment magnitude (marked as M in this paper) was adopted for the analysis in this study, and the range of magnitude was from 5.5 to 7.4 that is the most concern range for earthquake engineering.

The propagation parameters characterize the effects of wave scattering, geometrical attenuation and anelastic attenuation of ground motion as it travels from the source to site [8]. The distance measures have several definitions such as hypocentral distance, epicentral distance, distance to energetic zone, closest distance to rupture zone and closest distance to the surface projection rupture zone. For sites located several source dimensions from the earthquake, there is little difference between distance measures, but in near source region, the difference between distance measures is very significant. Also, the near source region is the most concern of engineers. The distance parameter should be chosen properly. In this study, the closest distance to the surface projection rupture zone (marked as D in this paper) was used for analysis and the ultimate distance was 118km of all the strong ground motion records.

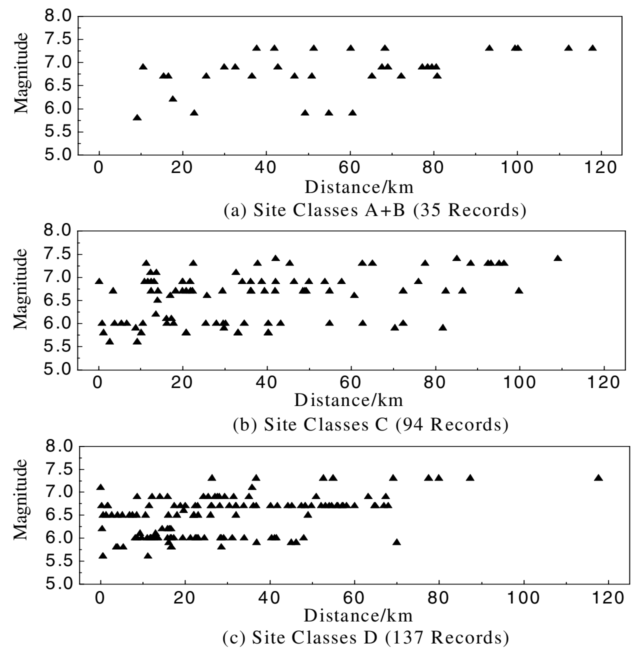


Figure1: Distribution of data in terms of magnitude, distance and site classification

ATTENUATION MODEL AND REGRESSION METHOD

The following regression model [6] was fitted to the input energy equivalent velocity V_{ea} and V_{er}.

$$\lg Y_i = a + b(M_i - 6) + c(M_i - 6)^2 + d\lg(D_i^{\,2} + h^2)^{1/2} + eG_{ci} + fG_{di} + \varepsilon_{ri} + \varepsilon_{ei} \tag{5}$$

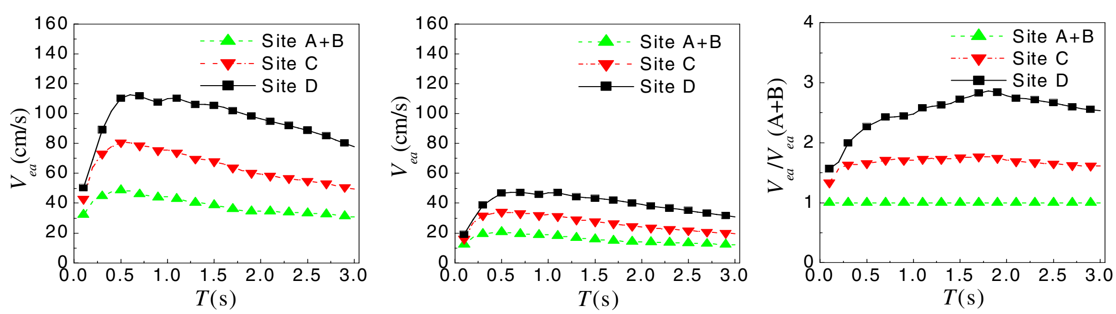
Where logarithm is based on 10, Y_i, M_i and D_i are the response variable (geometric mean of the two horizontal components), moment magnitude and distance parameter respectively of the *i-th* strong ground motion record. G_{ci} and G_{di} are the site classification factor of the *i-th* record ($G_{ci}=1$ for class C and zero otherwise; $G_{di}=1$ for class D and zero otherwise). For each period T, unknown coefficients *a, b, c, d, e, f, h,* and variance $\sigma^2_{\lg Y}$ of random errors $\boldsymbol{\varepsilon}_r$ and $\boldsymbol{\varepsilon}_e$ were determined using the two-stage regression procedure of Joyner and Boore [9][10]. Fukushima and Tanaka [11] had shown that the two-stage stratified regression analysis using dummy variables was confirmed to be a very effective method to determine the unknown coefficients of the attenuation model, and they gave a detailed prove. In this study, the two-stage regression method was employed for analysis.

REGRESSION RESULTS ANALYSIS

For each horizontal component of one record, two kinds of input energy equivalent velocity, V_{ea} and V_{er}, were calculated for 4 ductility levels (μ=1,2,4 and 6) and one damping ratio (ξ=5%), in the period (marked as T) range 0.1 to 3.0 second. The geometric mean of the two horizontal components for each kind of input energy was used in a two-stage regression method. The coefficients of the predictive equation (5) for V_{ea} and V_{er} at the different ductility factors (1,2,4 and 6) were not tabulated in this paper for limitation of the length of the paper. The effects of parameters such as site class, magnitude and ductility factor on the input energy spectra constructed from the attenuation relationship were discussed.

Effect of Site Class

The site class has a significant effect on V_{ea} and V_{er} spectra. Figure 2 and Figure 3 show the comparison of three site classes. Take V_{ea} for example, V_{ea} at site D is much higher than at site A+B and site C for a given period, magnitude and distance. The increase of V_{ea} from site A+B to site C and site D is shown in Figure 2(c). It can be observed obviously that the increase of V_{ea} is about 70% and 170% for site C and site D respectively in a wide period range except very short periods (less than 0.5 second). The effect of site class on V_{er} is very similar to that on V_{ea} as Figure 3 shows.



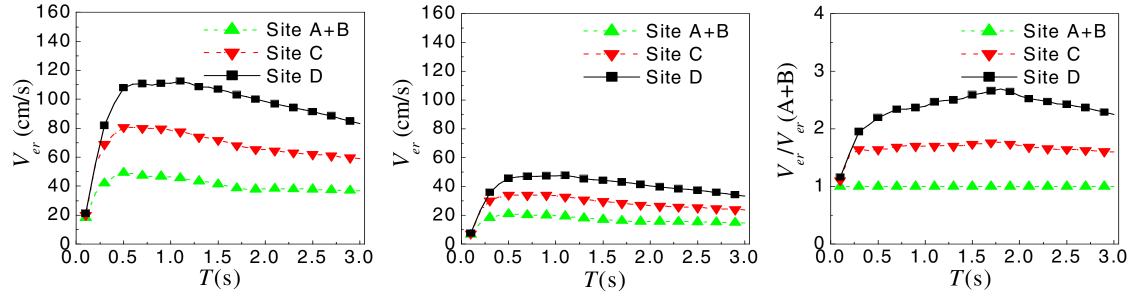
(a) D = 10km (b) D = 40km (c) D = 10km

Figure 2: Effect of site class on V_{ea} spectra (M=7.0, μ =2)

Effect of Ductility

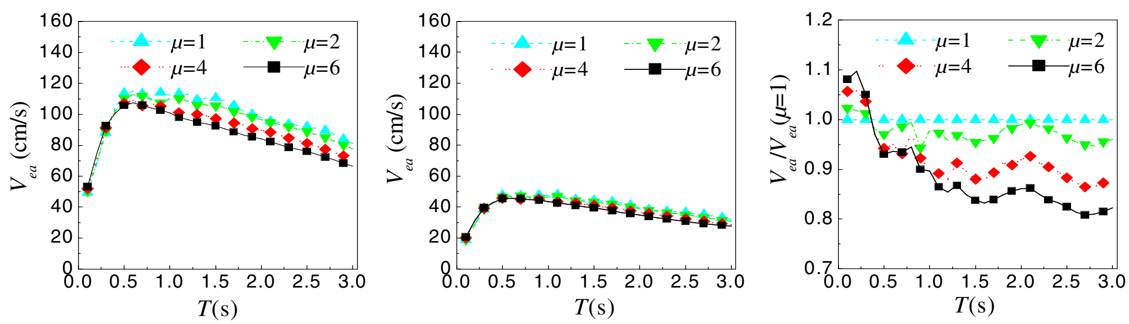
The effect of ductility on V_{ea} and V_{er} spectra for a given magnitude of 7.0 and site D are shown in Figure 4 and Figure 5. It is obviously that the effect of ductility is very different with the change of period. V_{ea} and V_{er} increase with the increasing of ductility factor in short period range (less than 0.5 second). On the contrary, in the long period range (larger than 0.5 second), they decrease with the increasing of ductility factor. Detailed information are shown in Figure 4(c) and Figure 5(c) which show the result of

$V_{ea}/V_{ea}(\mu=1)$ and $V_{er}/V_{er}(\mu=1)$. It can be observed that the maximum increase ($\mu=6$) of V_{ea} and V_{er} are 10% and 60% respectively at the period of 0.1 second. The maximum decrease ($\mu=6$) of V_{ea} and V_{er} are both about 20% at the period about 2.7 second. It can be concluded that the effect of ductility on V_{er} is much larger than that on V_{ea} in short period range and the ductility almost has the same effect on V_{ea} and V_{er} in long period range (larger than 0.5 second) as Figure 4(c) and Figure 5(c) show.



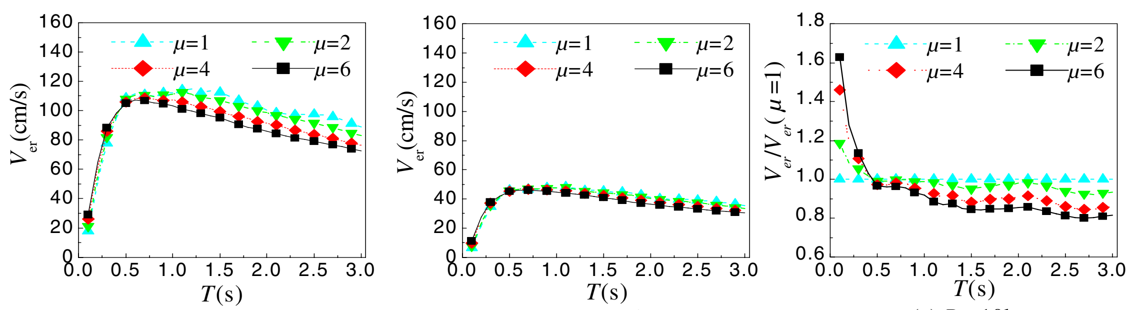
(a) D =10km (b) D =40km (c) D =10km

Figure 3: Effect of site class on V_{er} spectra (M=7.0, μ =2)



(a) D = 10km (b) D = 40km (c) D = 10km

Figure 4: Effect of ductility on V_{ea} spectra (M=7.0, Site Class D)

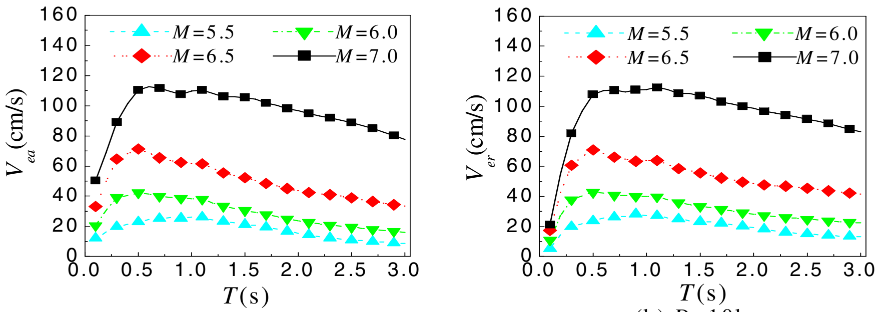


(a) D =10km (a) D =40km (c) D =10km

Figure 5: Effect of ductility on V_{er} spectra (M =7.0, Site Class D)

Effect of Earthquake Magnitude

The earthquake magnitude has a significant effect on V_{ea} and V_{er} spectra as Figure 6(a) and Figure 6(b) show. It can be observed that V_{ea} or V_{er} spectra increase with the increase of magnitude rapidly. The increase of V_{ea} or V_{er} from magnitude 6.5 to 7.0 is much larger than that from magnitude of 6.0 to 6.5, and the increase from 6.0 to 6.5 is much larger than that from 5.5 to 6.0. The peak values of V_{ea} or V_{er} are at about 0.5 second when the magnitude is equal to or larger than 6.0, but the peak values for magnitude 5.5 appear at the period of 1.0 second around as the dashed line for magnitude 5.5 show in Figure 6(a) and Figure 6(b). Effects of magnitude on V_{ea} and V_{er} spectra are almost similar for all the site classes.



(a) D =10km (b) D=10km

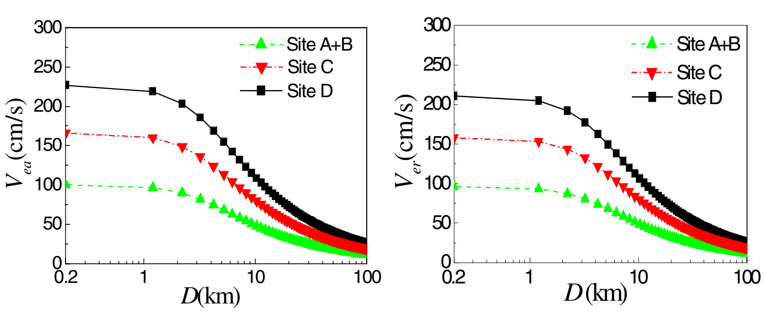
Figure 6: Effect of magnitude on V_{ea} (a) and V_{er} (b) spectra
(μ =2, Site Class D)

Effect of Distance

Figure 7(a) and Figure 7(b) show the result of V_{ea} and V_{er} for ductility factor of 2 at different source-to-site distance with a magnitude of 7.0 and at a given period of 0.5 second. It can be observed that both V_{ea} and V_{er} are almost constant within the distance of 1 kilometer, and then decrease at a rapid rate with the increasing of distance. The effect of site class can also be observed and the attenuation rate for site D is larger than site A+B and C. V_{ea} (V_{er}) for the three site classes are almost equal at the distance of 100 kilometer.

Comparison of V_{ea} and V_{er} Spectra

Uang and Bertero [1] had shown that the absolute input energy and relative input energy are very different at the very short or very long period range. The Comparison of V_{ea} and V_{er} Spectra constructed from the attenuation model was made in this study as Figure 8 shows. It can be observed that V_{ea} are almost equal to V_{er} at periods in the neighborhood of 0.5 second for all the site classes. V_{ea} is much larger than V_{er} in very short period range and some less than V_{er} in long period range. This difference should attract the attention of engineers.



(a) (b)

Figure 7: Effect of distance on V_{ea} (a) and V_{er} (b) spectra (μ =2, M=7.0, T=0.5 second)

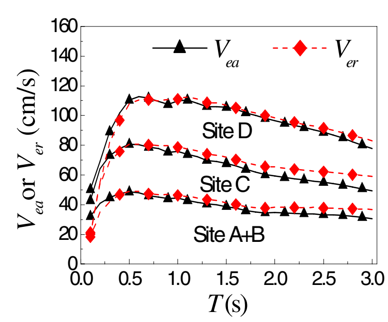


Figure 8: Comparison of V_{ea} and V_{er} spectra (M =7.0, D=10.0km,μ =2)

CONCLUSIONS

For energy-based seismic hazard analysis, earthquake resistant design, seismic safety evaluation, seismic zoning, etc., the seismic input energy demand, including absolute energy and relative energy, was established from an attenuation model in this study. The attenuation relationship was developed for two kinds of both elastic and inelastic input energy spectra with earthquake magnitude, source-to-site distance, and site class. The input energy demand of an SDOF system at given site class and distance can be predicted by the result of the paper. Main conclusions for two kinds of input energy spectra constructed from the attenuation relationship are summarized as follows.

1. The site class has a significant effect on V_{ea} and V_{er} spectra, so the site class must be considered sufficiently if V_{ea} or V_{er} were used to be the index of seismic hazard assessment.
2. The effect of ductility on V_{ea} and V_{er} are very different with the change of period. V_{ea} and V_{er} increase with the increasing of ductility factor in short period range (less than 0.5 second), but decrease in long period range (larger than 0.5 second). The effect of ductility on V_{er} is much larger than that on V_{ea} in short period range.
3. Larger magnitude and smaller distance contribute more to seismic hazard if V_{ea} or V_{er} were used. V_{ea} or V_{er} is almost constant within the distance of 1 kilometer, and then decrease at a rapid rate with the increasing of distance.
4. V_{ea} is almost equal to V_{er} at periods in the neighborhood of 0.5 second for all the site classes, much larger than V_{er} in very short period range and some less than V_{er} in long period range.
5. The peak values of V_{ea} and V_{er} appear at about the period 0.5 second for all the site classes.

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APPENDIX

Table A: Earthquake data

Earthquake	Date	Magnitude	No. of records	Site A+B	Site C	Site D
Kern County	7/21/1952	7.4	3	/	3	/
Parkfield	6/28/1966	6.1	4	/	2	2
San Fernando	2/9/1971	6.6	4	/	3	1
Coyote Lake	8/6/1979	5.8	4	1	1	2
Imperial Valley	10/15/1979	6.5	20	/	1	19
Livermore Valley	1/24/1980	5.8	5	/	3	2
Livermore Valley	1/27/1980	5.8	6	/	4	2
Westmoreland	4/26/1981	5.6	5	/	2	3
Morgan Hill	4/24/1984	6.2	7	1	1	5
Palm Springs	7/8/1986	5.9	13	4	4	5
Whittier	10/1/1987	6.0	47	/	17	30
Loma Prieta	10/18/1989	6.9	42	10	17	15
Petrolia	4/25/1992	7.1	5	/	3	2
Landers	6/28/1992	7.3	31	10	12	9
Northridge	1/17/1994	6.7	70	9	21	40