Assessment of Site Amplification Effect from Input Energy Spectra of Strong Ground Motion

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SUMMARY:
To analyze and estimate the amplification effect of different soil sites, the input energy spectra of strong ground motions at different sites including bed rock, very dense soil and stiff soil are computed, and the attenuation law of input energy spectra is regressed and obtained by using two-stage nonlinear regression method. The mean input energy spectra for a given magnitude and distance for different sites are computed from the attenuation law, and the input energy spectra ratios between different soil sites and rock site are calculated and analyzed. It is found that the mean amplification factors are 1.66 and 2.43 from the very dense soil and stiff soil sites to rock site respectively in a wide range of periods. The results of the paper can be referenced by the seismic hazard analysis, seismic regionalization and related works.

Keywords: site amplification effect, strong ground motion, input energy spectra, attenuation law

1. INSTRUCTION

The strong ground motion is the basic material for seismic design in the field of earthquake engineering. It is well known that the strong ground motion characteristics are influenced greatly by the site conditions (Lu *et al*, 2008), and in general, the strong ground motion is amplified by soil sites. However, the strong ground motion is affected by many parameters such as magnitude, source to site distance, propagation medium, etc. The characteristics of these factors are usually studied by using attenuation law for strong ground motion parameters, such as peak ground acceleration, peak velocity, response spectra and so on. However, 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 (1990), characterize the duration very well, and are considered as a convenient single-parameter descriptor of strong ground motion duration and amplitude. Based on 304 strong ground motion records, Chapman (1999) established the attenuation relationship of the elastic absolute input energy spectra, that is, he did not consider the effect of ductility. As we all know, 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 (2000) established the attenuation model for absorbed energy spectra from the view of structure damage and they considered the absorbed energy as the index of structure damage, and they also analyzed the effects of site conditions on absorbed energy spectra from the attenuation law.

In order to analyze the effect of site conditions, the attenuation law of strong ground motion input energy spectra is obtained by using two-stage regression method with nonlinear Gauss-Newton estimation based on 266 strong motion records. However, according to the study of Uang and Bertero (1990), there are two kinds of input energy spectra, including absolute input energy spectra and relative input energy spectra, and they are very different when the period of Single-Degree-Of-Freedom (SDOF) system is very short or very long. As we all know, the period of a real structure is often not very long, so differences between the two kinds input energy need to be compared necessarily. In this study, the attenuation law of the two kinds input energy is investigated, and the two kinds of input energy spectra, including absolute and relative input energy spectra, are obtained for a given magnitude and distance from the attenuation law. The authors had discussed the attenuation of input energy spectra (Gong *et al*, 2005; 2009), so in the paper, the two kinds of energy spectra are compared, and the mean effects of soil site on input energy spectra are analyzed. Some remarkable conclusions are obtained at last.

2. STRONG GROUND MOTION RECORDS

A total number of 266 strong ground motion records from 15 significant earthquakes in California of America are used for the analysis (Gong *et al*, 2005), and each record includes two mutually perpendicular and a vertical corrected acceleration time histories. Herein, the geometric mean of energy spectra calculated from the two horizontal components of each record is used for the analysis. The local site condition of each record is classified based on the average shear-wave velocity (V_s) over up to 30 meters in depth from the ground surface as shown in Table 3.1. Site classes A (hard rock) and B (rock) are combined to one kind of site condition for the analysis because the shortage of strong motion records (Chou and Uang, 2000). Moreover, the very dense soil and stiff soil mean Site C and Site D respectively as shown in Table 3.1, and three kinds of sites conditions are analyzed in the paper, i.e. Site A+B, Site C and Site D.

The data distribution with the relationship between magnitude (M) and fault distance (D) is shown in Figure 2.1. It can be seen that there is some dependence between the magnitude and distance which presents a tendency that the data of large magnitude, long distance and small magnitude, short distance are more than the data with large magnitude, short distance and small magnitude, long distance. This kind of dependence could affect the regression results, and in order to avoid the effect of dependence on the coefficients, the two-stage regression method is adopted for the analysis.

Table 3.1. Site Classifications (Chou and Uang, 2000)

NEHERP	General Description	V_s(m/s^2)	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	/

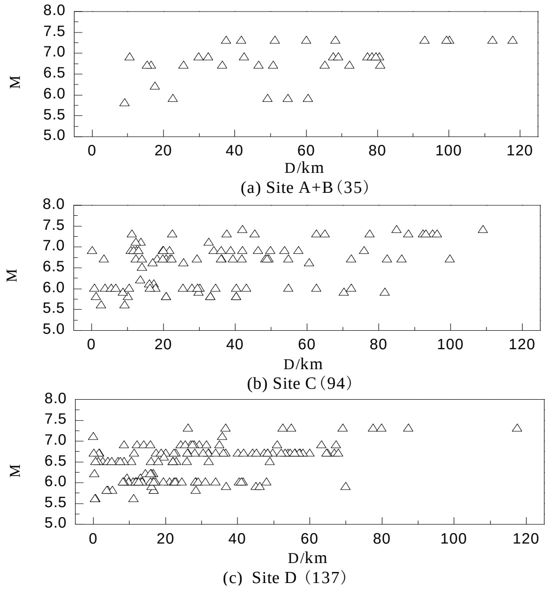


Figure 2.1. Distribution of the strong ground motion records

3. INPUT ENERGY SPECTRA

Two kinds of input energy spectra, absolute and relative energy spectra, are adopted in the paper. For a viscous damped Single-Degree-Of-Freedom (SDOF) system subjected to a horizontal strong ground motion, the differential equation of motion can be expressed as the following Eqn. 3.1.

$$m\ddot{v}_t + c\dot{v} + f_s = 0 \qquad (3.1)$$

Where m is the mass of SDOF system, v_t ($v_t = v + v_g$, v_g is the displacement of ground) is the absolute displacement of the system, v is the relative displacement of the system respect to the base, c is the viscous damping coefficient, and f_s is the restoring force. Substituting $v_t = v + v_g$ into Eqn. 3.1, it can be rewritten as the following Eqn. 3.2.

$$m\ddot{v} + c\dot{v} + f_s = -m\ddot{v}_g \qquad (3.2)$$

Therefore, the structural system under the excitation of ground motion can be equivalent to the system with fixed base and subjected to an effective horizontal dynamic force with magnitude of $-m\ddot{v}_g$. Although both systems give the same relative displacement, two kinds different energy response definitions, absolute and relative input energy, can be derived from Eqn. 3.1 and Eqn. 3.2 respectively (Uang and Bertero, 1990). The equations of absolute and relative input energy can be expressed as the following Eqn. 3.3 and Eqn. 3.4.

Absolute input energy:

$$E_a = \int m\ddot{v}_t \mathrm{d}v_g \qquad (3.3)$$

Relative input energy:

$$E_r = -\int m\ddot{v}_g \mathrm{d}v \qquad (3.4)$$

The absolute input energy definition as Eqn. 3.3 shows is physically meaningful in that the term $m\ddot{v}_t$ represents the inertia force acted on the system. The force, which is equal to restoring force plus damping force, is the same as the total force acted on the system foundation. Therefore, the E_a represents the work done by the total base shear at the foundation on the foundation displacement v_g. The relative input energy definition as Eqn. 3.4 shows physically represents the work done by the equivalent force $-m\ddot{v}_g$ on relative displacement of the equivalent fixed-base system.

The input energy equivalent velocity which is defined by Uang and Bertero (1990) is adopted for the analysis in order to eliminate the effect of mass and analyze conveniently because the definition including the unit are consistent with velocity. The input energy is converted to an equivalent velocity by the following Eqn. 3.5 and Eqn. 3.6.

$$V_a = \sqrt{2E_a/m} \qquad (3.5)$$

$$V_r = \sqrt{2E_r/m} \qquad (3.6)$$

In this way, the absolute and relative input energy spectra can be obtained by calculating the response of Single-Degree-Of-Freedom (SDOF) systems with different periods. The author had analyzed the attenuation law of the constant-ductility input energy spectra with different ductility level (Gong *et al*, 2005). In the paper, to analyze the effects of sites on input energy spectra, the two kinds of input energy equivalent velocity, V_a and V_r, of elastic SDOF system with 5% damping ratio in the period (marked as T) range 0.1 to 3.0 second are considered and analyzed, for the effects of sites on elastic energy spectra and inelastic energy spectra are very similar according to the authors' study before.

4. ATTENUATION MODEL

To select a proper attenuation model is an important work in the attenuation study of strong ground motion parameters. The model must be physically meaningful, and also making the regression error to be small. The following regression model proposed by Boore *et al* (1993) as Eqn. 4.1 shows is fitted to the input energy equivalent velocity V_a and V_r.

$$\lg Y_i = a + b(M_i - 6) + c(M_i - 6)^2 + d\lg(D_i^2 + h^2)^{1/2} + eG_{ci} + fG_{di} + \varepsilon_{ri} + \varepsilon_{ei} \qquad (4.1)$$

where Y_i, M_i and D_i are the response variable (geometric mean of the two horizontal components), moment magnitude and fault distance respectively of the i-th strong ground motion record. G_{ci} and G_{di} are the site effect factors of the i-th record (G_{ci}=1 for Site C and zero otherwise; G_{di}=1 for Site 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 ε_r and ε_e are determined using the two-stage regression procedure.

The most common method to solve the coefficients of attenuation model is the two-stage regression procedure originally proposed by Joyner and Boore (1993). The method is proposed because there is some dependence between the magnitude and distance as shown in Figure 2.1. If the coefficients of magnitude, distance, and local site are solved simultaneously, errors in measuring the magnitude would affect the other coefficients. However, in the two-stage analysis procedure, the coefficients of magnitude M and distance D are solved separately and successively, and the method can be viewed as a remedy to decouple the dependence between magnitude and distance through introducing the dummy variables. In the study, the two-stage regression analysis with Gauss-Newton method is adopted to determine the unknown coefficients of the attenuation model Eqn. 4.1, and the coefficients could be found in the authors' other paper (Gong *et al*, 2005).

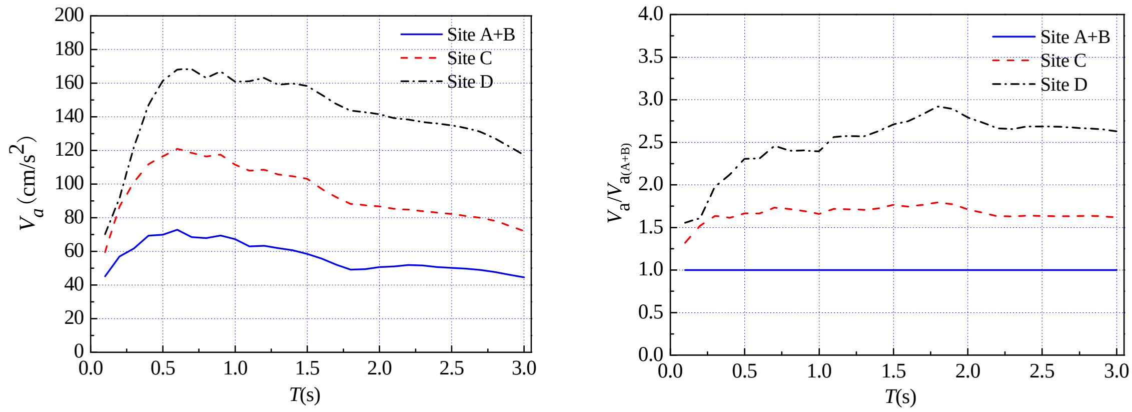
5. RESULT ANALYSIS

5.1. Results of absolute input energy spectra V_a

According to the above attenuation model, the input energy spectra can be computed for the given magnitude and distance. For example, the absolute energy spectra V_a for M=7.0 and D=5.0km on three kinds of sites are shown in Figure 5.1(a). To estimate the amplification of soil site, the energy spectra ratios of soil sites to rock site are calculated and shown in Figure 5.1(b).

From Figure 5.1, it can be concluded that the site class has a significant effect on absolute input energy spectra V_a, and the absolute input energy spectra V_a of Site C and Site D are much higher than that of Site A+B for a given period, magnitude and distance. The amplification of absolute input energy spectra V_a from Site A+B to Site C and Site D is shown in Figure 5.1(b). It can be observed that the mean increase of V_a is about 66.7% and 151.6% for Site C and Site D respectively for all the periods. That is to say, the strong motion ground motion is amplified about 1.67 times and 2.52 times for Site C and Site D respectively compared with Site A+B rock site. The maximum increase of V_a is about 79.6% and 192.1% for Site C and Site D respectively at period 1.8s, and the amplification coefficients are a little bit small for the short periods (T<0.3s) as shown in Figure 5.1(b).

Furthermore, the amplification factor is same for other magnitude and distance because the effect of soil site in Eqn. 4.1 only depends on the factor e and f for Site C and Site D respectively. The conclusion can be proved by using the exponent transformation to the both sides of Eqn. 4.1 and then calculating the ratio of different site conditions to Site A+B.



(a) Absolute input energy spectra (*M*=7.0, *D*=5.0km)

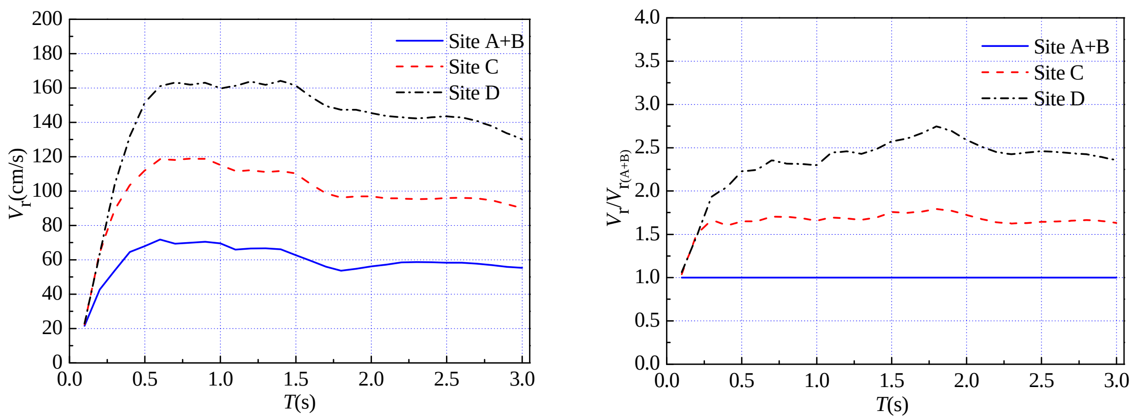
(b) Spectra ratio to rock site (*M*=7.0, *D*=5.0km)

Figure 5.1. Effects of site conditions on absolute input energy spectra V_a

5.2. Results of relative input energy spectra V_r

The effect of site class on relative input energy spectra V_r is very similar to that on absolute input energy spectra V_a as Figure 5.2 shows. Figure 5.2(a) shows the relative energy spectra for M=7.0 and D=5.0km on three kinds of site classes and Figure 5.3(b) shows the amplification factors for different period. From Figure 5.2, we can see that V_r spectra of Site C and Site D are much higher than that of Site A+B for a given period, magnitude and distance. It can be observed that the mean increase of V_r is about 65.4% and 134.4% for Site C and Site D respectively for all the periods. It means that the strong motion ground motion is amplified about 1.65 times and 2.34 times for Site C and Site D respectively compared with Site A+B rock site. The maximum increase of V_r is about 79.2% and 174.5% for Site C and Site D respectively at period 1.8s as shown in Figure 5.2(b).

As same as absolute energy spectra, the amplification factor is same for other magnitude and distance because the effect of soil site in Eqn. 4.1 depends on the factor e and f for Site C and Site D respectively. Considering the two kinds of input energy spectra V_a and V_r together, the average amplification factors are 1.66 and 2.43 from the Site C and Site D to site A+B respectively from the point of input energy spectra. That means the site conditions must be considered very well when the site seismic hazard analysis, structural seismic design and related works are carried out.



(a) Relative input energy spectra (*M*=7.0, *D*=5.0km)

(b) Spectra ratio to rock site (*M*=7.0, *D*=5.0km)

Figure 5.2. Effect of site conditions on relative input energy spectra V_r

5.3. Comparison of two kinds of input energy spectra

Uang and Bertero (1990) had already explained, the absolute input energy spectra and relative input energy spectra are very different at the very short or very long period range by using single strong motion record. The differences of absolute input energy spectra V_a and relative input energy spectra V_r constructed from the attenuation model are compared in the study as shown in Figure 5.3. It can be observed that the absolute input energy spectra V_a are almost equal to the relative input energy spectra V_r at periods in the range of 0.5-1.5s for all the site classes (for Site A+B, the cross point of two kinds of input energy spectra is at around 0.6s, for Site C, the cross point is at around 0.7s, and for Site D, the cross point is at around 1.1s). The absolute input energy spectra V_a is much larger than relative input energy spectra V_r in very short period range and some less than relative input energy spectra V_r in long period range. The difference trend is similar as the results computed by using single strong ground motion, for the attenuation law is obtained from large number of energy spectra of strong ground motions. The difference between absolute and relative input energy spectra for single strong ground motion must result in the similar difference trend between the two kinds of energy spectra constructed from the attenuation law.

The input energy spectrum is the most important parameter of strong ground motion, and it should be the most appropriate parameter for structure seismic design, seismic hazard analysis and related works. However, considering almost all of the seismic design methods are based on strength presently, the seismic design method based on energy is still needed to be studied and discussed in future, and there are too many scientific and technical problems needed to be solved urgently. If the input energy were adopted as a parameter for seismic design and similar works, the difference between absolute input energy spectra and relative input energy spectra in short and long period range should be considered very well by the seismic engineers, earthquake engineering researchers and structure designers.

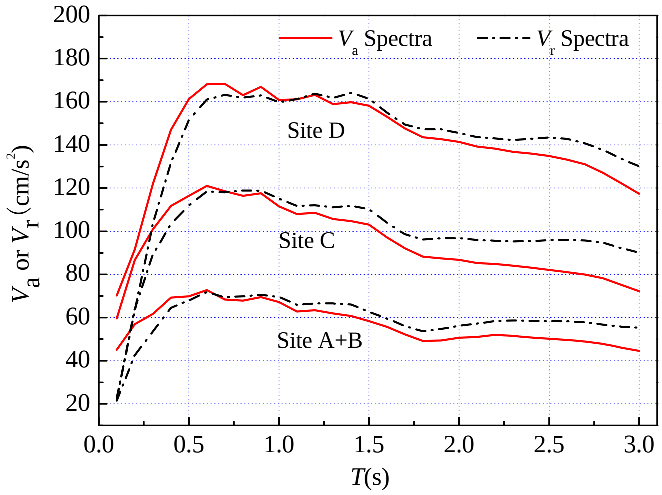


Figure 5.3. Comparison of V_a and V_r spectra (M=7.0, D=5.0km)

6. CONCLUSIONS

The effects of site conditions on two kinds of input energy spectra constructed from attenuation law are analyzed, and the differences between the absolute and relative input energy spectra are compared in the paper. The main conclusions are summarized as below.

(1) The absolute input energy spectra of strong ground motion is amplified approximately about 1.67 times from Site C to Site A+B, and 2.52 times from Site D to Site A+B in the period range 0.1-3.0s, and the components with period of 1.8s are amplified maximally about 1.80 times and 2.92 times for Site C and Site D respectively.

(2) For the relative input energy spectra, they are amplified approximately about 1.65 times from Site C to Site A+B, and 2.34 times from Site D to Site A+B in the period range 0.1-3.0s, and the components with period of 1.8s are amplified maximally about 1.79 times and 2.75 times for Site C and Site D respectively.

(3) The site class has significant effect on strong ground motion, and almost all components of different periods are amplified by soil site, and the mean amplification factors are 1.66 and 2.43 for very dense soil site (Site C) and stiff soil (Site D) site from the direction of input energy spectra. The site conditions must be considered very well in the work of seismic hazard analysis, seismic regionalization, and other related seismic disaster reduction programs.

(4) The absolute input energy spectra are almost equal to relative input energy spectra at periods in the period range of around 0.5-1.5s for all the site classes, but much larger than relative input energy spectra in very short period range, and less than relative input energy spectra in long period range. The similar point is that the peak values of absolute input energy spectra and relative input energy spectra appear at the period around 0.5 second for all the site classes.

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