ENERGY TEST OF CODE DESIGN ACCELERATION SPECTRUMS

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ABSTRACT:

Tremendous energy demand exists usually for impulsive earthquake records close to active fault zones, so it is essential to check the validity of actual seismic design codes from energy concept. By introducing of the spectrum velocity amplification factor, equivalent energy compatible with major Chinese and U.S.A. seismic codes was derived, and the extent of effective period was extracted by 214 near-fault records. The recommended energy input design spectrum (EIDS) applicable to 0~15km fault zone was quoted to check the validity of these seismic codes. Comparison analysis shows that GB50011-2001 code can just match the energy amplification effect of near-fault earthquake to a certain extent only under seldomly occurred earthquake with fortification intensity of 9 degree for soil Ⅱ,Ⅲ and Ⅳ, which means the impact of near-fault effect is not embodied in the current code acceleration spectrum. It is necessary to adjust the spectral control parameters. On the contrary, the energy spectrum compatible with UBC97 code can match well with the proposed energy input spectrum apart from the soil of hard rock (S_A). Accordingly, the correctness of proposed energy input design spectra in this paper got also certified by another way.

KEYWORDS: near-fault ground motion, energy, code acceleration spectrum, spectrum velocity amplification factor

1 INTRODUCTION

Over the last two decades, especially since the 1999 Chi-Chi earthquake in the region of Taiwan, earthquake features and seismic damage characteristics near the active fault zones have caused comprehensive attention. One of the notable features of near-fault ground motion (also known as near-field ground motion) is the massive energy demand for impulse-type velocity input with long-duration (Somerville et al, 1997), which asks for higher energy dissipation capacity for civil structures and bridges(Chou, C C, Uang C M, 2000; Gong Maosheng et al, 2003). Given this special feature of near-fault ground motion, the Unified Building Code of 1997 version (UBC97) (International Council of Building Officials, 1997) was issued after 3 years of the 1994 Northridge earthquake, which takes into account theoretically the near-fault effect by introduction of near-fault factor to adjust the standard acceleration spectrum. Figure 1 gives the comparison of standard acceleration spectrum and near-field spectrum of UBC97. Difference exists for long period scope, which is an adjustment by introduction of near-fault factor N_a and N_v, for the aim of considering the stronger earthquake demand for regions close to active faults. But it should be noted that the near-fault factor (N_a, N_v) of UBC97 was obtained from records of earthquakes with moment magnitude (M) less than7.0, and the quantity of records used at that time was limited. It is necessary to check the suitability from new records gained in recent years. Especially since the 1995 Kobe earthquake and the 1999 Chi-Chi earthquake, Japan and Chinese Taiwan have amended the original seismic design code, in order to strengthen the fortification measures and capacity for structures in near-field zones.

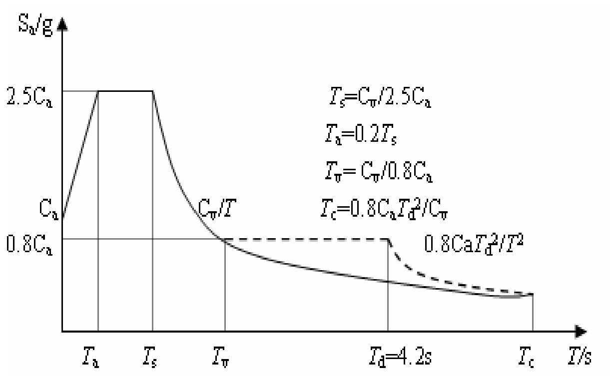

Figure 1 Comparison of Standard spectrum (solid line) and near-fault spectrum (dashed line) of UBC97 code (5% damping ratio)

However, the current code for seismic design of buildings of China (GB50011-2001) (Ministry of Construction of the People's Republic of China, 2001) takes the measure of smallest giving way distance from active fault to deal with near-fault effect on the structure, and lacks special design spectrum for these regions. But some of China's major cities such as Chengdu, Urumqi, Lanzhou and Xining are located at the near-fault regions of potential earthquakes, and how to conduct a reasonable seismic fortification and seismic design has become prominent problems. Particularly since the outbreak of the 1999 Turkish Kocaelia earthquake, Duzce earthquake, and the 1999 Chi-Chi earthquake, a considerable number of records near the active faults have been accumulated; it is time to be re-awareness of the applicability of seismic codes of GB50011-2001 and UBC97. Based on the earthquake records close to faults obtained all around the world, the equivalent energy compatible with code acceleration spectrum was derived by the introduction of spectrum velocity amplification factor. The range of effective period was extracted. And finally the applicability of these two codes was checked and discussed in this paper.

2 ENERGY SPECTRUMS COMPATIBLE WITH CODE ACCELERATION SPECTRUMS AND ITS RANGE OF EFFECTIVE PERIOD

2.1 Data base of earthquake records

Because the seismic response of the structure is directly related to the distance from fault, then fault projection distance should be selected as one of the main qualifications for selecting earthquake records. The three criterions are as follows:

(a) Fault projection distance: $R \leq 15$km; (b) Peak ground acceleration: $PGA \geq 0.05$g; (c) Moment magnitude: $M \geq 5.0$

According to the above criteria, a total of 214 horizontal records from 16 major earthquakes were selected (Jiang Hui, 2007). These records are mainly from the earthquakes of the United States and the 1999 Chi-Chi earthquake, but the classification criterions of site soil are not the same for the U.S. Geological Survey (USGS) and the Taiwan Central Weather Bureau (CWB). And even some near-fault records have no detailed soil information, so it's difficult to classify these records accurately in response to the current seismic design code. Therefore the classification criterions of site soil for USGS and CWB have to be combined: the soil S_A, S_B of USGS and rock soil of CWB are taken as soil S1; the soil S_C of USGS and median soil of CWB are taken as soil S2; the soil S_D of USGS and soft soil of CWB are taken as soil S3 in this paper. Meanwhile, in order to consider the impact of fault distance, all the 214 records are divided into three categories in accordance with the fault distance from 0~5km, 5~10km to 10~15km. And the records for three distance range are respectively 29, 22, and 32 for soil S1; 16, 18 and 10 for soil S2; 30, 27 and 30 for soil S3.

2.2 Derivation of equivalent energy from design acceleration spectrum

In order to test the code response spectrum from energy concept, it is needed to seek the relationship between spectrum acceleration and equivalent velocity of input energy. Based on the spectrum velocity amplification factor proposed by the author (Jiang Hui, 2007), a procedure to derive equivalent velocity of input energy compatible with the code design spectrum was developed as follows:

(1) It can be drawn from the integral analysis of SDOF differential equation that when damping ratio of the structure is less than 0.10, the influence of damping could be ignored. And then the following relationship exists between absolute spectrum acceleration PS_A and pseudo spectrum velocity PS_V:

$$PS_A(T,\xi) = \omega PS_V(T,\xi) \Rightarrow PS_V(T,\xi) = PS_A(T,\xi)/\omega \tag{2.1}$$

In eqn.2.1, T is the natural vibration period; ξ is damping ratio; ω is natural vibration frequency of the structure. And thus the pseudo-spectrum velocity PS_V could be obtained.

(2) According to the research of Hudson (Hudson, 1962), with the exception of particularly long period, there is minute difference between relative spectrum velocity S_V and PS_V, and then the following equation exists:

$$PS_V(T,\xi) \cong S_V(T,\xi) \Rightarrow S_V(T,\xi) = PS_A(T,\xi)/\omega \tag{2.2}$$

(3) For damping ratio of 5%, input energy equivalent velocity V_E can be calculated from spectrum velocity S_V, by the introduction of spectrum velocity amplification factor Ω_{SV} (Jiang Hui, 2007):

$$V_E = S_V \cdot (1/\Omega_{SV}) \Rightarrow V_E = (PS_A(T,\xi)/\omega)\cdot(1/\Omega_{SV}) \tag{2.3}$$

In which, the expression of Ω_{SV} is as follows:

$$\Omega_{SV} = \begin{cases} a_1 T/T_1 & 0 < T \le T_1 \\ a_1 + a_2(T - T_1) & T_1 < T < 5.0\text{s} \end{cases} \tag{2.4}$$

In eqn.2.4, T_1 is the control period of inflection point; a_1 and a_2 are regression parameters. Once the parameters in eqn.2.4 are determined, the input energy equivalent velocity V_E compatible with the code design acceleration spectrum can be calculated by eqn.2.3.

2.3 Discussion of the range of effective period

Just as Hudson has ever pointed out, eqn.2.2 exists just for a certain range except for very long period. But Hudson did not give a clear quantitative scope of effective period. It is necessary to study the application range of this formula, which is the core foundation for calculation of energy equivalent velocity from spectrum acceleration. For the design acceleration spectrum of GB50011-2001 and UBC97, there exists a minimum requirement of shear capacity for long period structure, and thus a second platform was specified in these codes. If the acceleration spectrum value of this platform was transferred by eqn.2.2, then the resulted pseudo velocity would increase rapidly as the augment of structure period, which is obviously irrational. In order to solve this problem, Eurocode8 (CEN: European Committee for Standardization, 1996) limited the spectrum displacement for long period scope, and the spectrum value of the second platform was not admitted to be larger than the maximum ground motion displacement $d_{g,max}$:

$$d_{g.\max} = 0.05 * a_g * S * T_C * T_D \tag{2.5}$$

In eqn.2.5, a_g is the design earthquake acceleration; S is parameter related to the type of site soil; T_C is the second period of turning point for the first platform in acceleration design spectrum.

Figure 2 gives the time history of pseudo spectrum velocity and spectrum velocity of two earthquake records (Table 1), and t_d in Table 1 is effective duration of strong earthquake within 95% intensity domain (Trifunac, Brady, 1975).

Table 1 two records of near-fault ground motion for confirmation

Station	Events	*M*	d_f/km	*PGA* /cm^2/s	*PGV* /cm/s	Duration t_d/s	T_g/s	T_p/s
Pacoima Dam	1971 San Fernando	6.7	0	1201.5	112.5	7.05	0.6	1.8
Rinaldi	1994 Northridge	6.7	0	821.2	166.1	7.04	1.3	1.7

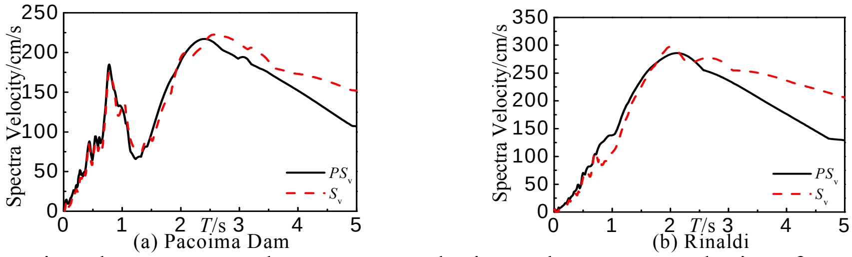

Figure 2 Comparison between pseudo spectrum velocity and spectrum velocity of earthquake records (5% damping ratio)

In order to explore the range of effective period for eqn.2.2, the 214 records were divided into three groups according to the types of site soil for calculation of the ratio of pseudo spectrum velocity to spectrum velocity. The range of effective period was confirmed in accordance with the 80 percent of confidence interval (0.8~1.2) for average ratio. It can be seen from Figure 3 that pseudo spectrum velocity meets well with spectrum velocity for the short-middle period range, and the ratio of these two physical quantities distributes around 1.0. With the increment of structure period, the ratio fluctuates obviously. As the site soil softens, the border of effective period becomes longer. Specifically, the turning point periods for soils of S1, S2 and S3 are respectively 2.4s, 2.8s and 4.0 s. And the discussion in this paper would focus on the above period scope.

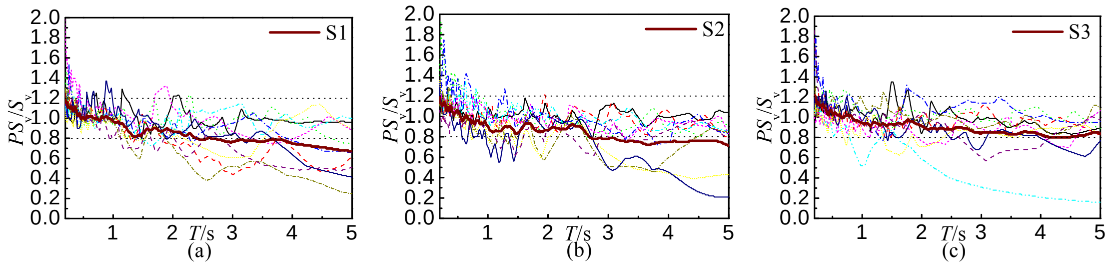

Figure 3 Ratio of pseudo spectrum velocity to spectrum velocity for different type of site soil (5% damping ratio)

3 ENERGY TEST OF SEISMIC CODE ACCELERATION SPECTRUMS

3.1 Advised energy input design spectrum (EIDS) from near-fault ground motion

With the collection of strong earthquake records throughout the world, an energy input design spectrum (EIDS) applicable to 0~15km of fault distance and peak acceleration *PGA*=0.4g was advised with the semi-theory and semi-empirical method (Jiang Hui, Zhu Xi, 2006). The design parameters such as turning point period and height of platform were determined according to the types of site soil (S1, S2, S3) and fault distances(0~5km, 5~10km, 10~15km). Figure 4 describes the contrast of the proposed energy design spectrum (EIDS) and 84 percent envelope curve of all records for different types of site soil and fault distances. It can be drawn that the EIDS could cover the energy demand with high enough credibility, thus this design energy spectrum can be used for representation of actual energy demand of earthquakes near faults. Based on the advised EIDS, an energy test was conducted for China's current code for building seismic design (GB50011-2001) and UBC97 code of U.S.A., in order to discuss whether they are applicable to the seismic design of structures in near-fault regions.

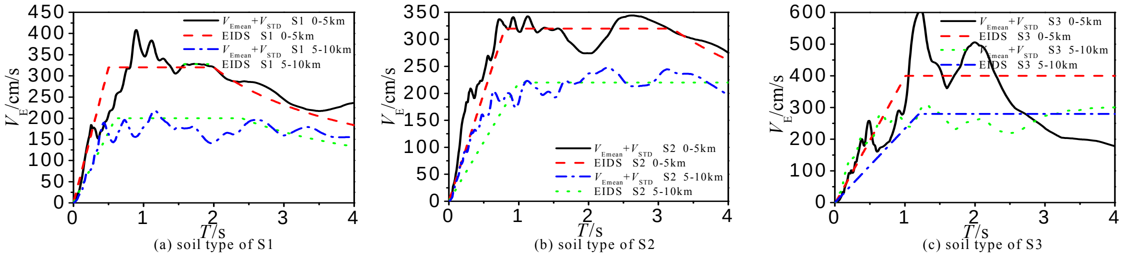

Figure 4 Comparison between the proposed EIDS and $V_{Emean}+V_{STD}$ curve of input energy (V_{Emean} is the mean value of input energy equivalent velocity; V_{STD} is the responded standard deviation.)

Since the classification methods of site soil for the codes of U.S.A (such as NEHRP, UBC97) are different from the codes of China (such as GB50011-2001): the average velocity of shear wave in soil below 30m from ground surface is used as the classification indicator for the former; the average velocity of shear wave in soil below 20m from ground surface and the thickness of covering soil with shear wave velocity larger than 500m/s are taken as dual indicators for Chinese codes. Comparison of the soil classification indicators by exploration test data (Lü Hongshan, Zhao Fengxin, 2007) shows the soil I of China covers soil A, B and a part of soil C of U.S.A, soil Ⅱ is between soil C and D, soil Ⅲ is between soil D and E, and soil Ⅳ of China is under soil E of U.S.A. Therefore, based on the classification principle mentioned above for earthquake records, the soil I of GB50011-2001 and S_A, S_B of UBC97are taken as S1; the soil Ⅱ, Ⅲ and S_C, S_D are taken as S2; the soil Ⅳ and S_E are taken as S3 in this paper.

3.2 Energy test of code acceleration spectrums

Figure 5 reflects the contrast results between the proposed EIDS and equivalent velocity of energy spectrums compatible with the codes of GB50011-2001 and UBC97.

For seldomly occurred earthquake with intensity of 8 and 9 degree, as well as frequently occurred earthquake with intensity of 9 degree, the equivalent energy compatible with acceleration design spectrum of soil I of GB50011-2001 is obviously less than the proposed energy spectrum (EIDS) for each fault distances, which means the GB50011-2001 code underestimates the seismic demand of near-fault pulse in this region (Figure 5 (a)). For soil Ⅱ of GB50011-2001, under seldomly occurred earthquake with intensity of 9 degree, the equivalent energy demand is close to the proposed spectrum for fault distance of 10~15km. But there exists an apparent underestimation of actual energy for seldomly occurred earthquake with intensity of 8 degree and frequently occurred earthquake with intensity of 9 degree (Figure 5 (b)). From Figure 5(c) and Figure 5(d), it can be seen the equivalent energy of soil Ⅲ and Ⅳ under seldomly occurred earthquake with intensity of 9 degree from GB50011-2001 is close to the proposed energy design spectrum of soil S2 and S3 under fault distance of 5~10km, which illustrates the code spectrum could consider the energy demand in this condition. However, the equivalent energy is obviously lower than the design spectrum under fault distance of 0~5km, especially for seldomly occurred earthquake with intensity of 8 degree and frequently occurred earthquake with intensity of 9 degree, therefore it can not be effectively applied to seismic design within this scope. In general, Spectra test shows that GB50011-2001 code can just match the energy amplification effect of near-fault to a certain extent only under seldomly occurred earthquake with intensity of 9 degree for soil Ⅱ,Ⅲ, Ⅳ and far away from 5km of fault, which indicates the impact of fling or pulse effect is not embodied suitably in the current code acceleration spectrum curve.

For soil S_A of UBC97, although the near-fault factor N_a and N_v was introduced, the equivalent energy is still less than the proposed design spectrum of soil S1 (Figure 5 (e)). The perhaps reason is because the weight of N_a and N_v for soil S_A is the smallest among all the types of site soil, and at the same time the data base of this paper includes mainly the records from the 1999 Chi-Chi earthquake, which is void for UBC97. For soil S_B, S_C and S_D of UBC97, the equivalent energy of fault distance of 0~2km, 2~5km and 5~10km is very close to the corresponded EIDS under the distance of 0~5km, 5~10km and 10~15km (Figure 5 (f), (g), (h)). For soil S_E of UBC97, the platform value of equivalent energy for fault distance of 0~2km, 2~5km is higher than the EIDS under the distance of 0~5km and 5~10km respectively (Figure 5 (i)). And the equivalent energy of fault distance of 5~10km is nearly concurrent with the corresponded EIDS under the distance of 10~15km.

Generally, since the UBC97 code takes into account the near-fault effects by the introduction of N_a and N_v, the control parameters such as the height and width of platform, the control period of turning point are more reasonable than GB50011-2001 code. It shows the UBC97 can effectively reflect the energy demand of near-fault, and some modification is needed for GB50011-2001 to be applicable to near-field regions. At the meantime, the control parameter of proposed energy input design spectrum (EIDS) can be proved to be reasonable by comparison.

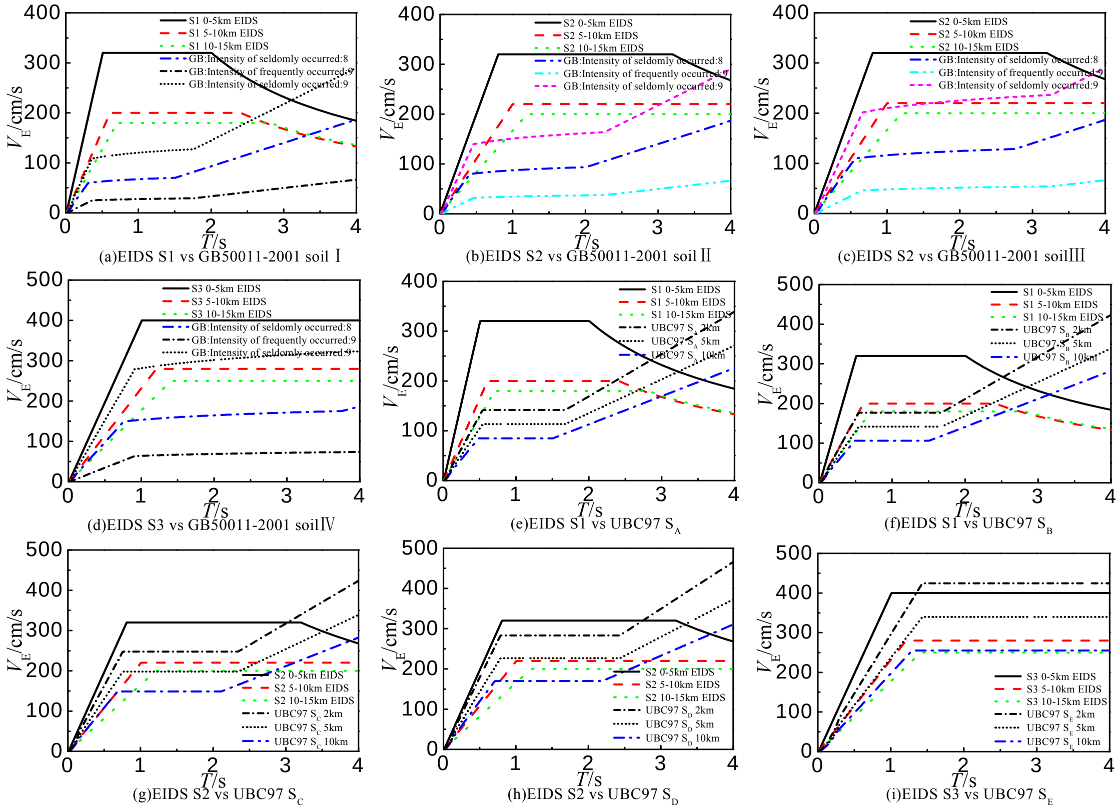

Figure 5 Comparison between advised EIDS and equivalent energy spectrum from GB50011-2001 as well as UBC97 code

4 CONCLUSIONS

Based on the research, some conclusions can be drawn as follows:

Earthquake disaster close to the active fault zones brings forward bran-new challenge. Since tremendous energy demand exists for impulse-type records, it is essential to check the validity of actual seismic design codes by energy concept.

Firstly, spectrum velocity amplification factor was introduced to compute equivalent energy from acceleration spectrum and the accuracy and effective period extent was verified and discussed by near-fault records all around the world. From the proposed simplified calculation model, the equivalent input energy spectrums compatible with major Chinese and U.S.A seismic codes were deduced. The proposed energy input design spectrum (EIDS) applicable to 0~15km fault zone was used to check the validity of these seismic codes. Spectra test shows that GB50011-2001 code can just match the energy amplification effect of near-fault to a certain extent only under seldomly occurred fortification earthquake with intensity of 9 degree for soil Ⅱ, Ⅲ and Ⅳ, which indicates the impact of fling or pulse effect to structural damage is not embodied. It is necessary to adjust the spectral parameters in order to apply to near-fault regions.

On the contrary, for distinct fault distance and soil condition, the energy spectrum compatible with UBC97 code can match well with actual energy demand of earthquakes close to active faults except soil S_A. It means the near-fault factor (N_a, N_v) by UBC97 code is essential for structure design within 0~15km fault region. And the proposed energy input design spectra can be proved to be reasonable once again from another aspect.

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