13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 341

INFLUENCE OF DESIGN SPECTRUM ON COLLAPSE PERFORMANCE OF ASEISMIC STRUCTURE

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SUMMARY

In China, the latest seismic design code, Code for seismic design of buildings (GB 50011-2001), is issued in 2001. But in the 1990's, all the buildings were built according to GBJ11-89 (Code for seismic design of buildings 1989, China). In GBJ11-89, according to the results of sites seismic hazard analysis (SSHA) completed in past more ten years, the value of corner period T_g of the design spectrum is underestimated. This results in lacked for the anti-collapse capability when a destructive earthquake hits, while it was considered sufficiently according to GBJ11-89. In this paper, we analyze the response of typical reinforcement moment frame six-story and ten-story buildings, which were constructed on the site type II with PGA 200 Gal or 300Gal (10% probabilities of exceedance in 50 years , which is corresponding to intensity VIII in the Intensity Zoning Map of China) and designed according to GBJ11-89. The IDARC 2D Version 5.0 is used to perform nonlinear time-history analysis. The artificial ground motions are seismic input of analyze. The result shows that the buildings which are familiar to the two studied buildings are not satisfied with the deformation limits in GBJ11-89. In the other words, the buildings may collapse when a deconstructive earthquake occurs.

INTRODUCTION

China is one of the countries suffering from earthquakes all over the world. Once a destructive earthquake occurs, high number of casualties and great property loss will accompany it, for example the Tangshan earthquake on July 28, 1976. The first one of the causes of the losses is building collapses.

In Code for seismic design of buildings of China (GBJ11-89), a tow-level seismic design criterion is adopted. The first level is based on the operational performance objective after frequent earthquake (63% probabilities of exceedance in 50 years) occurs, and the second level is based on the life safety performance, i.e. anti-collapse after rare earthquake (2-3% probabilities of exceedance in 50 years) occurs[1]. According to the tow levels, the Code gives tow sets of design spectra respectively. The difference between the tow sets of design spectra is the peak acceleration only, the corner periods of spectra (T_g) are same. The value of T_g is assigned according to the strong ground motion records. But

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there is a problem about this. Because of the non-linear mechanics characteristic of soil, the spectrum signatures of soil responses are different when peak acceleration of ground motions are different. So, the value of T_g should be different too. In the GBJ11-89, there is no different between the values of tow design levels.

In 1990's, many tall buildings were built in China. The first mode periods of these buildings are usually larger than the corner periods in the Code. So the 5% damped spectral acceleration at the first mode period of building is very sensitive to the value of T_g. If the corner period of the site related spectrum is larger than the one of design spectrum, the earthquake effects which act on buildings are greater than those be considered during design, which may result in insufficiency of resistance when a destructive earthquake occurs.

A comparison between corner periods of related spectra and design spectra will be done in this paper. The comparison includes statistical analysis on values of T_g of site related spectra ascertained by site seismic hazard analysis (SSHA). Then tow model will be built and their s, which inputs are artificial ground motion with the peak acceleration 400/540 gal with the corner periods from 0.30s to 0.70s of their target spectra, will be analyzed. From the results of analyses, we can get a building's damage state when it suffers an earthquake action greater than the action considered during its design process.

1. THE CORNER PERIODS OF SITE RELATED SPECTRA

In GBJ11-89, the design spectra are given according to the large numbers of seismograms. In these records, there are few near field records of great shocks. There are many differences on spectrum signature of ground motion among records when the magnitude and/or epicentral distance of seismostation are different, results in that the value of T_g of response spectrum varies throughout in a wide range. If the first mode period of a building is greater than T_g of response spectrum, the earthquake action obtained from the response spectrum varies with different site, e.g. different value of T_g. Fig.1 and Fig.2 show the comparison among Chinese(GBJ11-89), Japanese[2] and American[3] design spectrum. We can find from the figures that value of T_g influence the value of spectral acceleration greatly when T is greater than T_g. At the same time, we can see that the value of T_g of GBJ11-89 is smaller than those of Japan and USA, which may results in that the anti-seismic performance of buildings designed and constructed according to GBJ11-89 is relative insufficiency to those in Japan or USA.

Up to now, hundreds of site seismic hazard analyses (SSHA) have been completed in China. One of

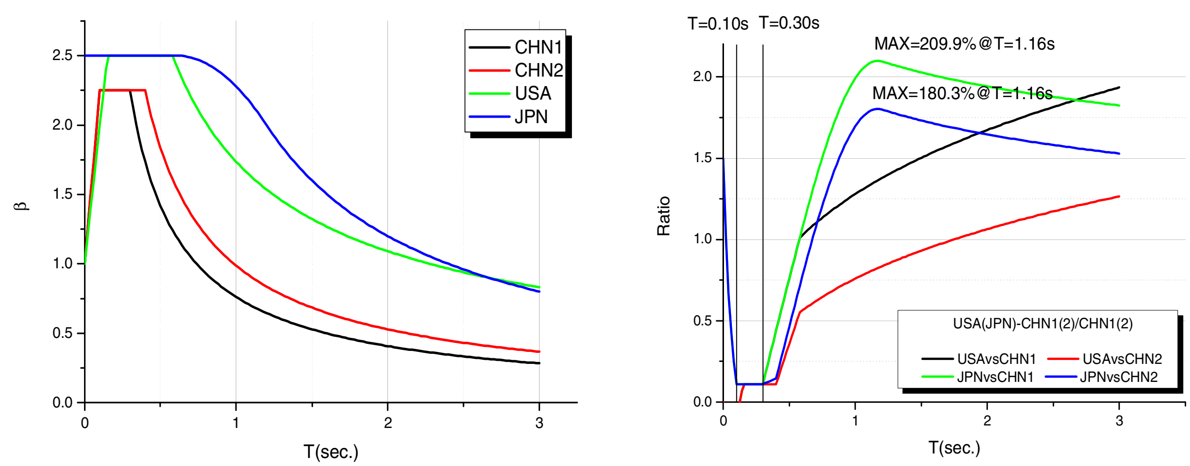

Figure 1. Comparison among China (GBJ11-89), Japan (earthquake resistant design method for civil engineering constructions, 1981) and USA (UBC1994) on design spectra (Magnification spectra). The left: magnification spectra of three countries; and the right: quantitative compare, for example, the Red curve = (USA-CHN2)/CHN2

results of SSHA is an absolute acceleration response spectrum related with seismicity, seismogeology, and soil dynamics of construction site, called site related spectrum[4]. Because of processes of SSHA, we can conclude that site related spectrum reflects more accurately earthquake action, which will apply to a building in its working life, on a specific site than design spectrum given in the Code.

Table 1. the statistical characterizations of T_g of site related spectra on site class II (Sec.)

Probabilities of exceedance in 50 years	Sample size	Average	Variance	Maximum	Minimum
2-3%	95	**0.567**	0.0587	1.20	0.20
10%	95	**0.457**	0.0247	0.90	0.20
63%	95	**0.373**	0.0090	0.70	0.18

Table 2. T_g of design spectra in GBJ11-89 (Sec.)

Near/ Distant earthquake	Site class			
	Ⅰ	Ⅱ	Ⅲ	Ⅳ
near earthquake	0.20	**0.30**	0.40	0.65
distant earthquake	0.25	**0.40**	0.55	0.85

In this statistical analysis, we collect 130 spectra at each of three probability levels (63%, 10% and 2-3% probabilities of exceedance sin 50 years) on 130 sites. Among them, 95 sites of all samples are site class Ⅱ with design-based intensity from less than Ⅵ to Ⅸ. In table 1, we can see the statistical characterization of the 95 sites.

And we give the values of T_g of China code for seismic design of buildings (GBJ11-89) in table 2.

And we give the histograms and probabilities of distribution of T_g at three probability levels respectively in Figure 2.

From the tow tables (Table 1.and Table 2.) above and the figure (Figure 2.), we can see the difference between the tow sets of value of T_g. We will discuss what the difference results in.

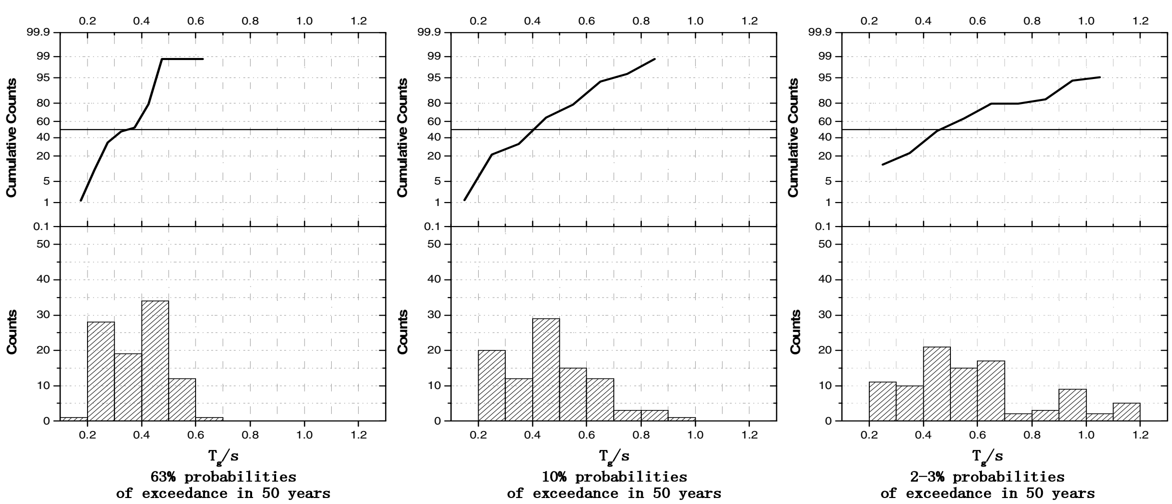

Figure 2. The histogram and probabilities of distribution of T_g at three probability levels.

2. SAMPLE STRUCTURE MODELS

In this paper we build tow building structure models to analysis their earthquake response. The tow models are both located on site class Ⅱ and their design-based intensity are both Ⅷ (Seismic Intensity Zonation Map of China-1990, equivalent to the regions with ground motion acceleration 200 gal. or 300 gal. in Zoning Map of Peak Acceleration of Ground Motion of China- GB18306-2001). The tow models are taken from Anti-Seismic Design of Buildings (in Chinese, Gao Zhenshi et. al., China Architecture & Building Press, 1995: 247-261) and Brachylogy Design Manual of High-Raise Reinforcement Structures (in Chinese, Li Guosheng, China Architecture & Building Press, 1995: 195-218) and modified slightly respectively. Both are frame structures, six stories and ten stories respectively.

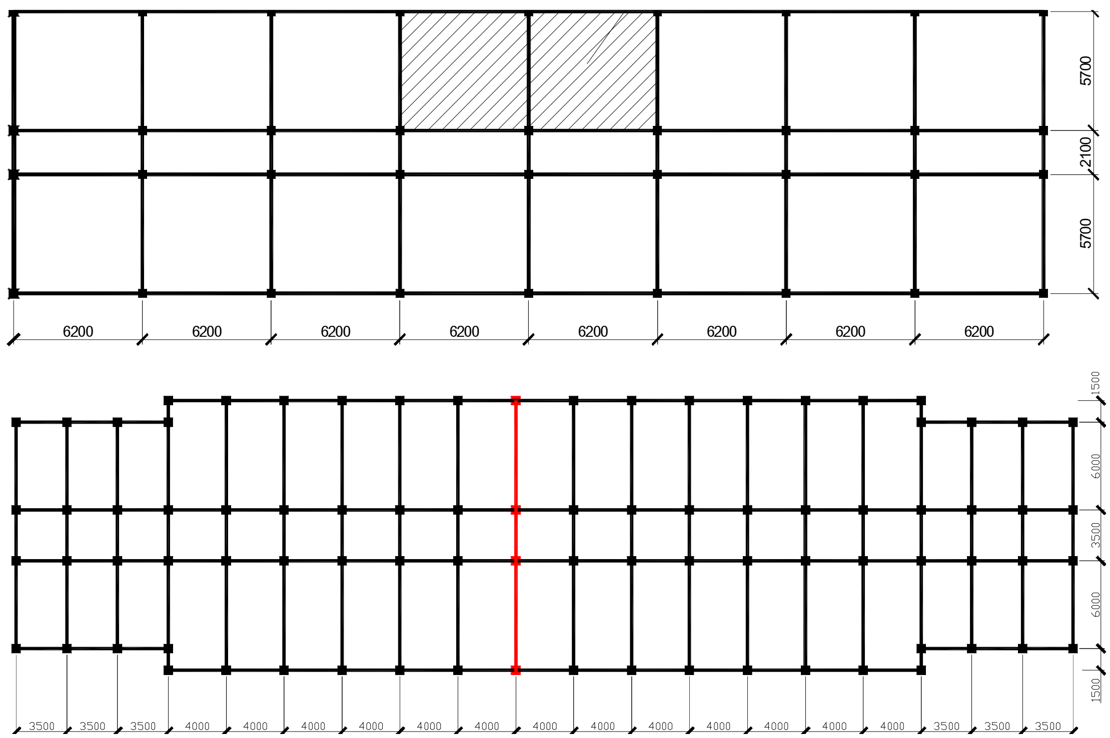

Figure 3. Plans of tow structures. The upper: Model 1[5], the lower: Model 2[6]. In plan of Model 2, the red is regular frame to be calculated. The dimension in mm.

Because of disregarding for the effect of the infill panels to structure lateral stiffness, we modify the original design of two structures. Being same as the most reinforcement structure buildings existing in Chinese cities, the tow models are designed and constructed complying with the GBJ11-89l. The first mode period of two models modified are 1.014 seconds (Model 1, the 6 stories one) and 1.303 seconds (Model 2, the 10 stories one) calculated by IDARC, respectively. The plans are showed in Figure 3. To simplify process, in model 2 we select one regular frame (the red in Figure 3 lower) as sample one to analysis.

3. INPUT OF ANALYSIS

In this paper, nonlinear dynamic response analysis method is applied to the models with the IDARC. Input of analysis is artificial ground motion acceleration time-histories. Considering the long-period components of ground motion, adopt the design spectra of GB50011-2001 as the target spectra of artificial ground motion, but their T_g are modified to embody variation of sites. The design spectrum with 5% damp of GB50011-2001 is defined by the equation (1):

$$S_a(T)=\begin{cases} a_m + a_m(\beta_m - 1.0)\dfrac{T}{T_0} & 0.0 < T < T_0 \\ a_m\beta_m & T_0 < T < T_g \\ a_m\beta_m(\dfrac{T_g}{T})^{0.9} & T_g < T \le 5T_g \\ a_m\beta_m\left[0.2^{0.9} - 0.02\left(T-5T_g\right)\right] & 5T_g < T \le 6.0\,\text{sec}. \end{cases} \qquad (1)$$

where S_a is spectral acceleration, a_m is peak ground motion acceleration, β_m is maximum of amplification coefficient of soil, T is the first mode period of structure, T_g is the corner period of soil, and the T_0=0.10 seconds.

The design spectrum in GBJ11-89 defined by the equation (2):

$$S_a(T)=\begin{cases} a_m + a_m(\beta_m - 1.0)\dfrac{T}{T_0} & 0.0 < T < T_0 \\ a_m\beta_m & T_0 < T < T_g \\ a_m\beta_m(\dfrac{T_g}{T})^{0.9} & T_g < T \le 3.0\,\text{sec}. \end{cases} \qquad (2)$$

where the meanings of characters are same to equation (1).

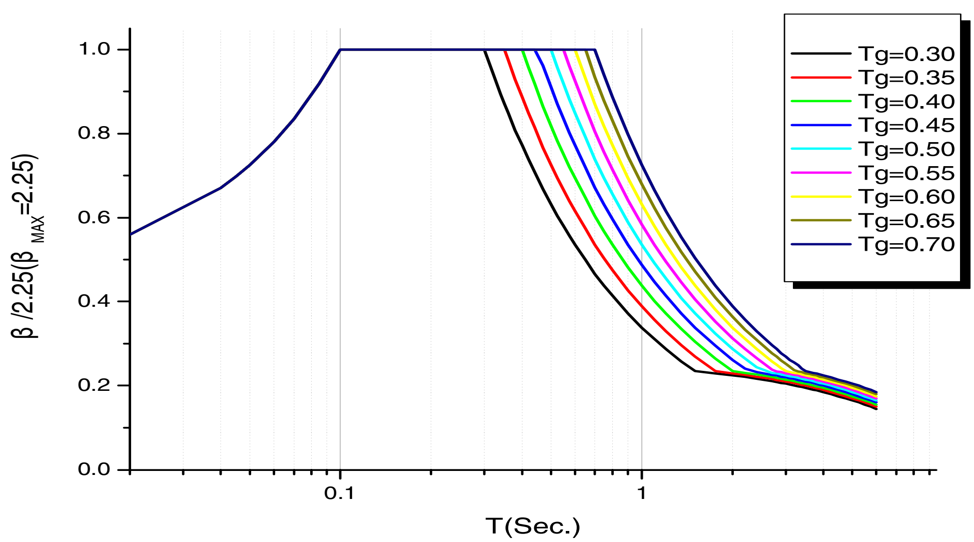

Figure 3. Target spectrums of artificial ground motions. Y-axis is normalized amplification coefficient of soil, i.e. β/β_{max} (in Chinese code, β_{max} =2.25).

We redefine the value of T_g from 0.30 seconds to 0.70 seconds to embody the characteristics of different sites, the increment is 0.05 seconds. Figure 3 illustrators the target spectra. To reduce the effects of randomness of seismic ground motions as possible, we form four ground motion acceleration time-histories according to each target spectrum with a specific value of T_g, then we take the average of four analysis results (interstory drift ratios) according to the four time-histories as the result of structure response acted by a specific target spectrum. And the same time, we specify tow values of peak ground motion accelerations, 400gal and 540gal respectively, as am in the equation (1). Because we are only concerned with reactions of structures under rare earthquake (2-3% probabilities of exceedance in 50 years), so we don't try to get the reactions under other tow probability levels earthquakes (63% or 10%

probabilities of exceedance in 50 years).

4. ANALYSIS FOR SAMPLE STRUCTURE MODELS

In this analysis, we use the IDARC VERSION 4.0 (Inelastic Damage Analysis of Reinforced Concrete structures, beta version, by Department Of Civil Engineering, State University of New York at Buffalo)[7]. In the program, we turn on options for P-Delta effects and linear flexibility distribution. The figure 4 illustrators the results of model 1 with peak ground motion accelerations 400gal and 540gal, and the figure 5 illustrator the results of model 2 with peak ground motion accelerations 400gal and 540gal.

Both in figures 4 and figure 5, the X-Axis is the value of T_g, and the Y-Axis is story numbers of models, the polygonal line means the average interstory drift ratios of each story corresponded to each value of T_g.

In Chinese Code [8, 9], if the interstory drift ratio of any story of a building is lager than 0.02 for frame structure, it can be considered that this structure has been collapsed. It has been verified by experiments and theory analysis. From the figure 4 and figure 5, we can see that the tow models collapsed when the T_g increase to some value smaller than 0.60 seconds. To model 1, when T_g is 0.45 seconds or 0.35 seconds the structure collapses as PGA = 400gal or PGA = 540gal respectively. This means that the model building designed according to GBJ11-89 is life-safe (i.e. not collapse) only on about 50% or 20% sites (see figure 2) as PGA = 200gal or PGA = 300gal zone of Zoning Map of Peak Acceleration of Ground Motion of China respectively. Similar to the model 1, the model 2 is life-safe only on 70% and 20% sites (see figure 2). Because of the model 1 is softer than model 2 (the ratio of first mode period to height of model 1 is obviously larger than that of model 2) laterally, the peak response (maximum interstory drift ratio) of model 1 is relative larger than that of model 2, so its safe-range is smaller than that of model 2 in some degree. At same time, we can see from the figure 4 and figure 5 there is an approximate linear relation between interstory drift ratio and the value of T_g. Maybe this is by accident, but we can not exclude the possibility of internal relation between them. If so, the probable reason is increasing of spectral acceleration due to increasing of value of T_g.

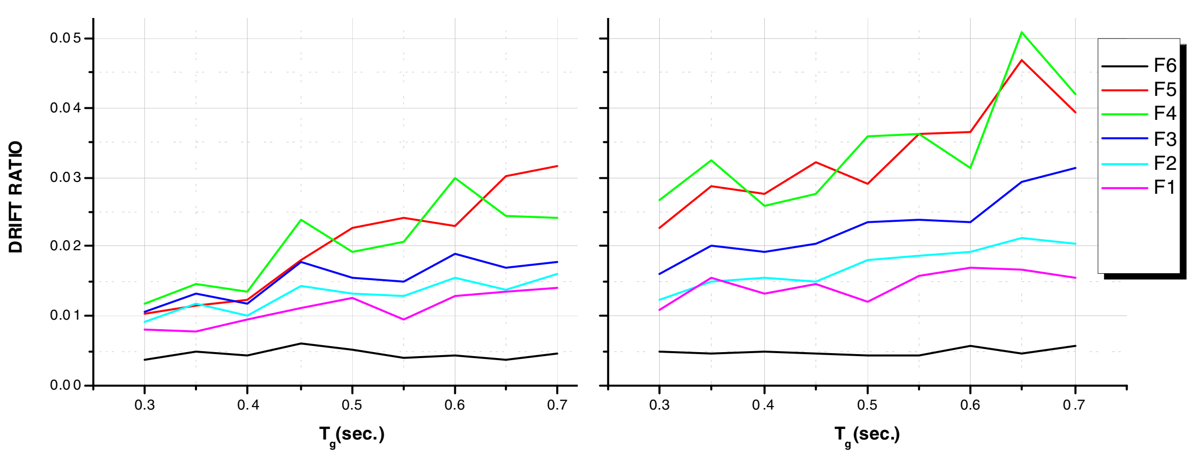

Figure 4. Results of model 1. Left: Peak Ground Motion = 400gal; Right: Peak Ground Motion = 540gal

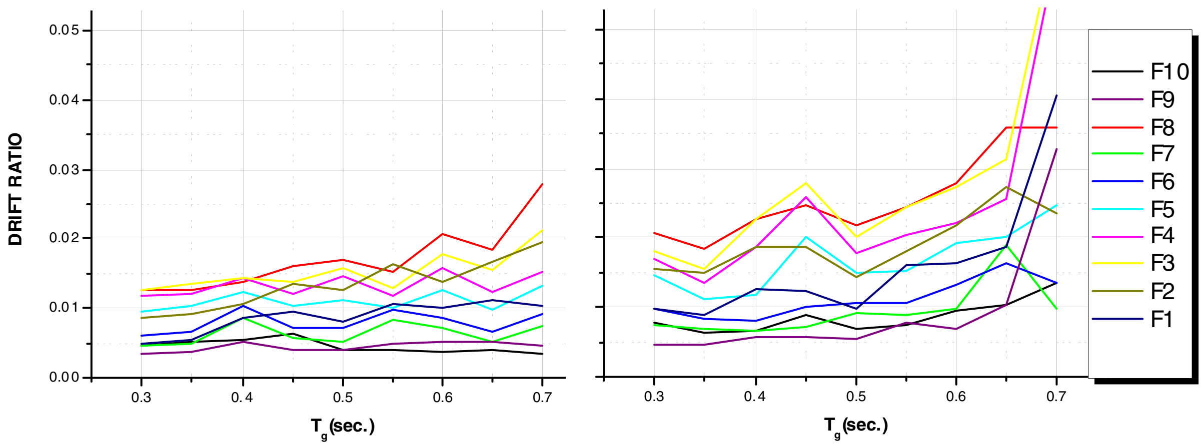

Figure 5. Results of model 2. Left: Peak Ground Motion = 400gal: Right: Peak Ground Motion = 540gal.

In figure 5 (Left), when the T_g is 0.70 seconds, tow interstory drift ratio (F3 and F4) is dramatically increase, maybe because the structure has collapsed under this earthquake action. So this tow results are both untruthful.

5. DISCUSSION

In this analysis, we exclude some factors which may affect the structures' response. These factors are listed below:

1) Soil-structure interaction;
2) Peak motion acceleration decrease due to depth of bottom of foundation increasing;
3) The decrease exponent of target spectrum when T is larger than T_g. In this paper, we assume this exponent is 0.9, but according to results of soil dynamic response, the exponent usually is smaller than 0.9, i.e. the site relative spectrum acceleration may smaller than that of design spectrum. When the first mode period of structure is larger than T_g, the spectral acceleration adopted in this paper may larger than the real one (the value according to site relative spectrum);
4) Effects of structures' details; And
5) Quality of construction and installation of buildings and/or its equipments.

In above five factors, the first four factors are of advantage to structures under earthquake actions, only last one is disadvantageous to structures. But in Chichi earthquake, Taiwan, the bad quality of construction and installation induces many buildings collapsed which were designed complied with the anti-seismic code available in Taiwan. So we don't think the five factors affect the conclusions of this paper greatly, and it is hard to estimate which the effect of sum of the five factors is of advantage to structures or not.

6. CONCLUSION

The statistical interpretation and the analysis of tow model structures under earthquake action show that they may not accomplish their purposes that they would stand rather than collapse after a rare earthquake (2-3% probabilities of exceedance in 50 years) occurs, though they comply with the anti-seismic design codes available when they are designed and constructed. The uppermost one of all possible causes is that the platform of design spectrum prescribed in the anti-seismic design codes is too narrow to characterize the reaction of soil when soil is excited by earthquake ground motions, in another words, the value of T_g adopted in the anti-seismic design codes when a building is designed is smaller than actuality in a certain extent. And if the peak ground motion acceleration is different, the value of T_g is not same. So when compute the reaction of buildings under rare earthquake action during design prosess, which to get interstory drift ratio to avoid buildings' deformation too large to stand, we should use the different T_g to the value which used in strength prove. But in GBJ11-89, the tow values used in the tow processes respectively are same.

In China, a new edition of anti-seismic design code, Code for seismic design of buildings (GB 50011-2001), has been issued in 2001. In this edition of Code, the value of T_g is increased about 0.05 seconds generally, and the T_g used in deformation prove is greater than the one used in strength prove about 0.05seconds too when the buildings locate in a high intensity region whose peak ground motion acceleration is not less than 200 gal in Zoning Map of Peak Acceleration of Ground Motion of China. So in the years before the next edition anti-seismic code is issued, the new build buildings will be more solid than those designed and constructed according to GBJ11-89 when they suffer a destructive earthquake. But comparing to the buildings which are constructed in seismic regions of America or Japan, Chinese earthquake resistant structures, including buildings, bridges and other engineering structures in seismic regions, are still less earthquake resistance after GB 50011-2001. Because of the most important effect of anti-seismic regulations on earthquake disasters mitigate, we should improve our seismic design standards in company with the progress of theoretical researches and practical experiences, decrease sensitivity to direct costs of buildings' construction process in steps to adopt conservative values of design parameters in the next anti-seismic design code.

REFERENCES

1. Gao X.W., "Anti-seismic level and values of 'moderate' and 'major' earthquakes for various types of building in aseismic design", Earthquake engineering and engineering vibration 1989, 9(2): 58-66 (In Chinese)
2. IAEE, "Regulations for seismic design: A world list-1996", Tokyo, Japan, 1996,26:1-53
3. IAEE, "Regulations for seismic design: A world list-1996", Tokyo, Japan, 1996,40:1-50
4. HU Y.X., "Technical course of seismic hazard analysis", Beijing: Seismological Press, 1999 (In Chinese)
5. Gao Z.S., "Anti-Seismic Design of Buildings", Beijing: China Architecture & Building Press, 1995 (In Chinese)
6. Li G.S., "Brachylogy Design Manual of High-Raise Reinforcement Structures", Beijing: China Architecture & Building Press, 1995 (In Chinese)
7. R. E. Valles, A. M. Reinhorn, S. K. Kunnath, C. Li, A. Madan, "IDARC 2D Version 4.0: A Program for the Inelastic Damage Analysis of Buildings", Technical Report NCEER-96-0010, Buffalo, 1996
8. Ministry of Construction of the People's Republic of China, "Code for seismic design of buildings (GBJ11-89)", Beijing: China Architecture & Building Press, 1989 (In Chinese)
9. Ministry of Construction of the People's Republic of China, "Code for seismic design of buildings (GB 50011-2001)", Beijing: China Architecture & Building Press, 2001 (In Chinese)