13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2592

STUDY ON THE BI-NORMALIZED EARTHQUAKE ACCELERATION RESPONSE SPECTRA

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SUMMARY

The determination of current design spectral amplifications is based mainly on characteristics of normalized response spectra. Previous studies have shown that different source parameters influence normalized spectral shapes to a certain degree. Among all those factors, the influence of soil condition is significant and the site response is intentionally concentrated. However, design spectra in different building codes vary greatly due to subjective considering in their soil classification criteria and soil evaluation indexes. It is quite difficult to search for a uniform criterion to unify present different design spectra. In addition, available ground motion recordings from previous earthquakes still cannot provide satisfaction results as expected by conventionally studying methods. A concept of bi-normalized response spectra is presented in this paper. Based on the statistical analysis of a large number of earthquake records collected from the western America, the conventionally normalized response spectra and bi-normalized response spectra are studied and compared respectively. It concludes that the bi-normalized response spectra have better consistency among all strong motion records than do the conventionally normalized response spectra. Which implies that the bi-normalized response spectra can be used not only in revealing the characteristics of strong ground motions but also in unifying and simplifying the site–specific design spectra for engineering design purpose.

INTRODUCTION

Response spectrum is an important tool developed so far for expressing the excitation response relation in the seismic analysis and design of structures. In anticipating the structural response during future earthquakes two parameters are of special interest: the maximum ground motion and the manner that the motion is amplified. The maximum values of ground motion (peak ground acceleration, velocity, and displacement) for a specific site are estimated by seismic hazard analysis and empirical attenuation relations. The amplification factors of the motion are generally obtained by calculating and averaging normalized response spectra of ground motion records that with similar earthquake parameters. Earthquake parameters such as source mechanism, epicentral distance, focal depth, geological conditions, magnitude, soil conditions, damping ratio and period influence spectral shapes and amplification [1]. Recent studies [2-4] also indicated that rupture directivity and hanging-wall effects are significant in near field ground motions. Although the influence of several of these factors may be studied independently

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and results have shown definite trends, while ground motion are very complicated, most of those factors are interrelated and cannot be discussed individually. In this sense, further studies are needed before they can be considered in arriving at recommendations for design specification. Then the question rise: if all these factors are considered and evaluated in detail, are the available recorded ground motions during past earthquakes enough? In addition, whether recorded ground motions in a region of the world can be used to predict site-dependent response for regions with limited or even no strong motion recordings? Do recorded ground motions in different areas, with different magnitudes and epicentral distance have essential similarities?

As it is well know that previous studies of spectral shapes and amplification mainly underscore the discrepancies between different grouped ground motions when they have been classified, while this study, with questions mentioned above, will underscore the similarities between different grouped ground motions under the influence of earthquake parameters by proposing another response spectrum: bi-normalized response spectra. In Chinese Building Code [5], three earthquake parameters that influence the design spectra shapes have been taken into consideration: soil condition, magnitude and epicentral distance. In this paper, a large number of ground motion records selected from western America are calculated, the influence of those three parameters on bi-normalized response spectra as well as on normalized response spectra will be examined and discussed.

2. BI-NORMALIZED RESPONSE SPECTRUM CONCEPT

The maximum acceleration response *Sa* of a damped single-degree-of-freedom (SDOF) oscillator with free vibration circle frequency ω or natural period T can be represented as [6]:

$$Sa(T) = \omega' \left| \ddot{x}(\tau) e^{-\xi\omega(t-\tau)} \left[\left(1 - \frac{\xi^2}{1-\xi^2}\right) \sin \omega'(t-\tau) + \frac{2\xi}{\sqrt{1-\xi^2}} \cos \omega'(t-\tau) \right] d\tau \right|_{\max} \tag{1}$$

Where ξ is the damping ratio $\omega' = \omega\sqrt{1-\xi^2}$ and $T = 2\pi/\omega$. If the ground motion time history and a fixed damping ratio ξ are given earthquake acceleration response spectrum can be plotted against natural period T. The acceleration response spectra for four ground motions recorded in recent earthquakes are plotted in Figure 1, which shows that the absolute acceleration responses for different ground motions vary largely. One of the earliest design spectrum was proposed by Housner [7] who calculated and then averaged the spectra by normalizing them from eight accelerograms to a given spectral intensity. However, since then the influence of earthquake parameters on normalized response spectra or amplifications have been popularly studied. To show how ground motion is amplified for different recorded ground motions, the acceleration spectral ordinate is generally normalized against the peak ground acceleration (PGA) [6]:

$$A(T) = \frac{\omega'}{PGA} \left| \ddot{x}(\tau) e^{-\xi\omega(t-\tau)} \left[\left(1 - \frac{\xi^2}{1-\xi^2}\right) \sin \omega'(t-\tau) + \frac{2\xi}{\sqrt{1-\xi^2}} \cos \omega'(t-\tau) \right] d\tau \right|_{\max} \tag{2}$$

The normalized response spectra (Amplification) for the four earthquake recordings is drawn in Figure 2, which shows that normalized response spectra for different ground motions are better regular than absolute response spectra when eliminated the influence of earthquake intensity. Even though, it is still found that the primary diversities between different ground motions lie in the varieties of their predominant periods. Nevertheless, before or after the predominant period, the profile for different normalized spectra has the similar tendency. In order to evaluate the influence of predominant period, for each normalized response spectrum, the abscissa is scaled by its predominant period *Tga* [8]:

$$A\left(\frac{T}{Tga}\right) = \frac{\omega'}{PGA} \left| \ddot{x}(\tau) e^{-\xi\omega(t-\tau)} \left[\left(1 - \frac{\xi^2}{1-\xi^2}\right) \sin \omega'(t-\tau) + \frac{2\xi}{\sqrt{1-\xi^2}} \cos \omega'(t-\tau) \right] d\tau \right|_{\max} \tag{3}$$

Then the abscissas of normalized spectral peaks are normalized and set to 1. The bi-normalized response spectra for different ground motions are shown in Figure 3. It is evident that the bi-normalized response spectra for different strong motions take on new characteristics and have even better consistency than the normalized response spectra. Which implies that the bi-normalized response spectrum can be used in revealing the characteristics of strong ground motions as well as the normalized response spectrum does.

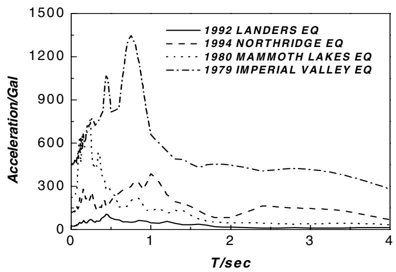


Figure 1. Earthquake response spectra ξ=0.05

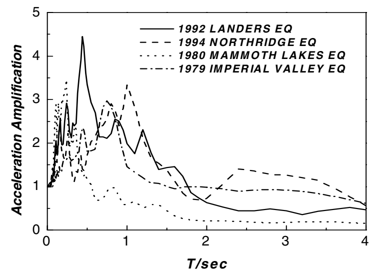


Figure 2. Normalized response spectra ξ=0.05

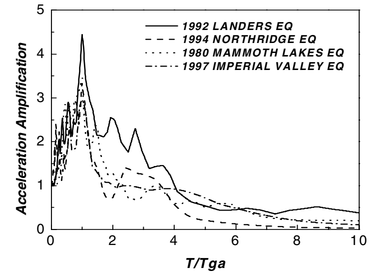


Figure 3. Bi-normalized response spectra ξ=0.05

3. EFFECT OF SOIL CONDITION ON NORMALIZED AND BI-NORMALIZED RESPONSE SPECTRA

Design spectra during present seismic design codes are site-dependent. It is generally accepted that soil condition influences spectral shapes and amplification significantly. Studies by Seed et al. [9] and Mohraz [10] indicated that acceleration amplification curves at softer soil sites are fatter and lower than that at stiffer soil sites. The Chinese Building Code [5] recommends spectral shapes and amplification for four soil categories (see Figure 4): rock and stiff soil (soil type 1), middle stiff soil (soil type 2), middle soft soil (soil type 3) and soft soil (soil type 4). The site classification is determined by two parameters: the representative average shear-wave velocity to a depth of 20 m of the over layer soil thickness (see Table 1). In this paper, the earthquake records under consideration are selected from mainly western American, many station sites characteristics are not detailedly clear, we can only classify the totally 531 selected strong-motion records (each records has two horizontal components) into four groups according to their site character description. There are 131 records for soil type 1, 128 records for soil type 2, 130 records for soil type 3 and 142 records for soil type 4. This limitation is therefore much less severe if spectral similarities is main topic of interest instead of the differences between classified ground motions, and the influences of magnitude and epicentral distance events are considered, as it is the case here.

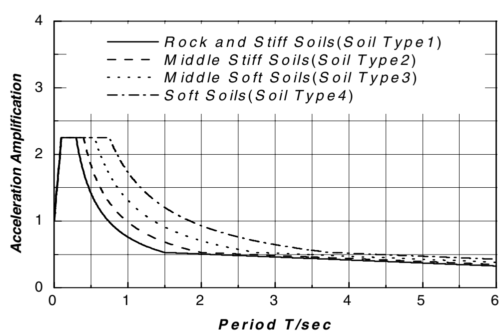
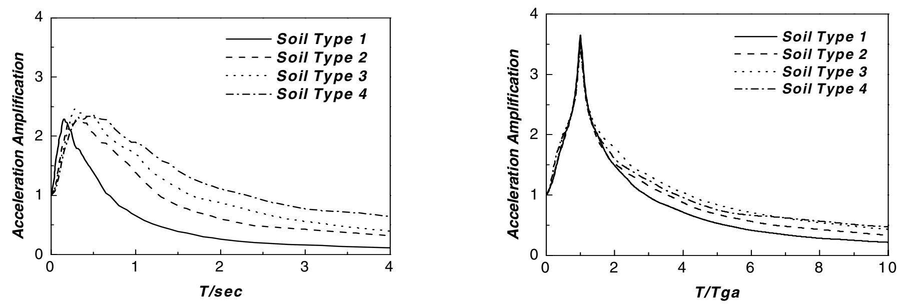


Figure 4. Normalized response spectra shapes ξ=0.05 (after Chinese Building Code 2001)

Table 1. Site classification in Chinese building code 2001

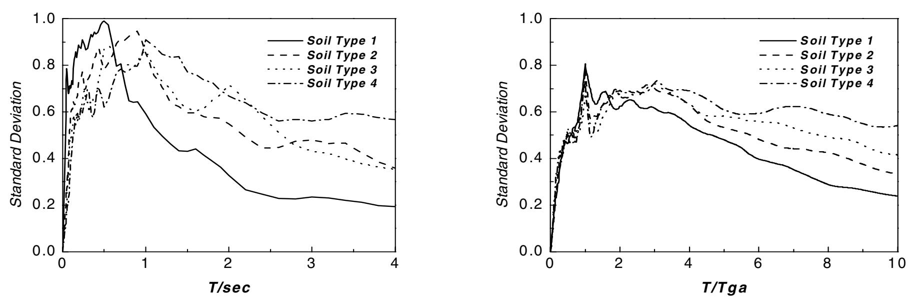
Shear Wave Velocity (m/s)	Soil Type I	Soil Type II	Soil Type III	Soil Type IV
	Over Layer Soil Thickness (m)			
Vs>500	0			
500⩾Vs>250	<5	⩾5		
250⩾Vs>140	<3	3~50	>50	
Vs⩽140	<3	3~15	>15~80	>80

The average normalized and bi-normalized response spectra with damping ξ=0.05 as well as their standard deviation and variation coefficient for each group have been calculated and presented in Figure 5, Fig. 6 and Fig. 7 respectively. Figure 5 (a) shows the effect of soil condition on normalized response spectra for all of the records. As can be seen that the soil condition affects the average normalized spectra to a significant degree. For soft soil sites, at small periods the normalized spectral ordinates are higher than those in stiff soil sites, while at middle to longer periods the spectral ordinates for stiffer soil sites are lower than those in softer soil sites. This study is better in agreement with those from previous earthquakes. The bi-normalized response spectra of all the records with respect to their corresponding soil conditions are averaged and shown in Figure 5 (b). It is found that the mean spectral curves between bi-normalized and normalized spectra differ distinctly. The shape of bi-normalized spectra is sharp with a maximum peak value at abscissa 1, for relative smaller periods the four curves are very close and differences would be a little bit increase for softer soil sites at relative longer periods. While by and large the differences of bi-normalized spectral values for various sites are much less than those of normalized spectra.



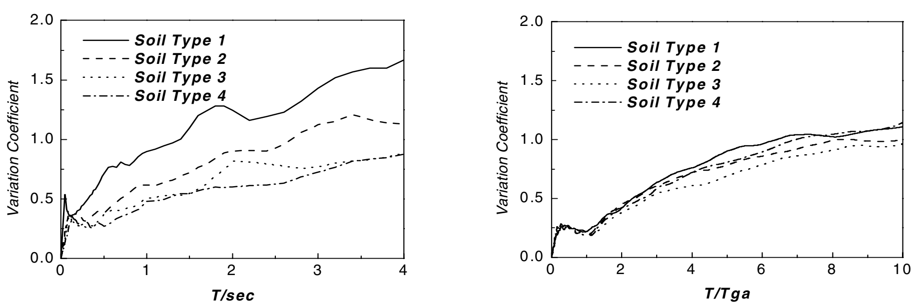
(a) Normalized spectra (b) Bi-normalized spectra

Figure5. Average response spectra for all soil types



(a) Normalized spectra (b) Bi-normalized spectra

Figure 6. Standard deviation for all soil types



(a) Normalized spectra (b) Bi-normalized spectra

Figure 7. Variation coefficient for all soil types

Figure 6 (a) and (b) show the standard deviation for normalized and bi-normalized response spectra of all the grouped recordings. Compared with Figure 5, the standard deviation curve shapes have the similar tendency to their mean curve shapes. However, the standard deviation values of normalized spectra vary largely between different soil types, but the standard deviations of bi-normalized spectra between different soil types differ much less than those of normalized spectra. Figure 7 (a) and (b) show the variation coefficient curves for normalized and bi-normalized response spectra of all the records. The variation coefficient curves also show that bi-normalized response spectra for different soil types have much common characteristics. Figure 5, 6 and 7 all indicate that bi-normalized response spectra have better consistency among strong motion records at different soil types than do the conventionally normalized response spectra. Which implies that the site-dependent design response spectra can be simplified and unified if only site characteristic period for any seismic environment has been determined accurately. As it is defined that the bi-normalized response spectra expresses the profile tendency for the shape and amplification of earthquake normalized spectra, its abscissa is relative period after it has been scaled by predominant period *Tga* and thus cannot be used for design directly. While on the other hand, predominant period for a specified site environment can be evaluated by other method such as theoretical method [11], microtremor method [12,13] etc. So if the abscissa of mean bi-normalized spectra multiplies the site-specific predominant periods for different site conditions, then the bi-normalized spectra would be site-specified and could be practically used for structural design.

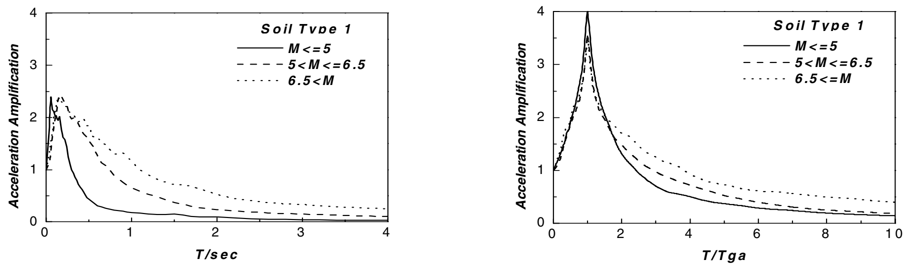
4. EFFECT OF EARTHQUAKE MAGNITUDE ON NORMALIZED AND BI-NORMALIZED RESPONSE SPECTRA

The earthquake magnitude influences the normalized response spectral shapes and values. A study by Mohraz [14] on the influence of earthquake magnitude on response amplification for alluvium shows larger acceleration amplifications for records with magnitudes between 6 and 7 than for those with magnitudes between 5 and 6. In this study, the records are grouped based on their magnitude and soil condition. Table 2 shows the grouped records range and number. Figure 8, 9, 10 and 11 show the influence of earthquake magnitude on normalized and bi-normalized spectral shapes of each soil type. In order to show the effect of magnitude individually, Figure 12 represents the effect of magnitude on spectra for three groups disregarding the influence of soil condition. From those figures it can be seen that magnitude for short period smaller than 0.2s, the normalized spectral values increases slightly with the decrease in earthquake magnitude. While for middle and long periods normalized spectral values increase substantially with the increase in earthquake magnitude.

Table 2. Classification of records account for magnitude and soil condition

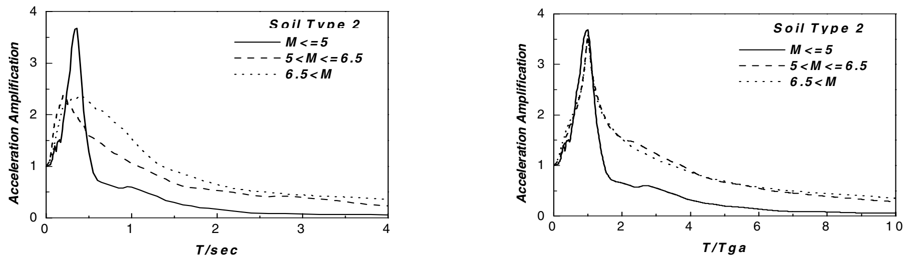
Soil Type	$M \leq 5$	$5 < M \leq 6.5$	$6.5 < M$
S1	26	80	25
S2	1	39	88
S3	5	14	111
S4	8	54	80
Total	40	187	304

The earthquake magnitude has minor influence on bi-normalized response spectra even that the effect of magnitude on it shows the similar trends as the influence on normalized response spectra. The maximum acceleration amplification of bi-normalized spectra increases with the earthquake magnitude decreases in very stiff and very soft soil sites. Compared with the effect of magnitude on normalized spectra, the bi-normalized response spectra have better consistency among all strong motion records under the influence of earthquake magnitude.



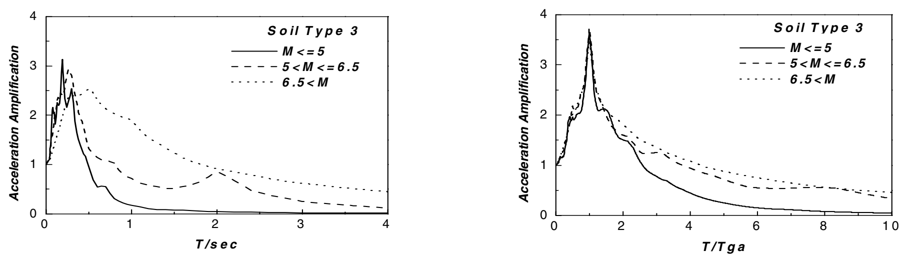
(a) Normalized spectra (b) Bi-normalized spectra

Figure 8. The influence of magnitude for records of soil type 1



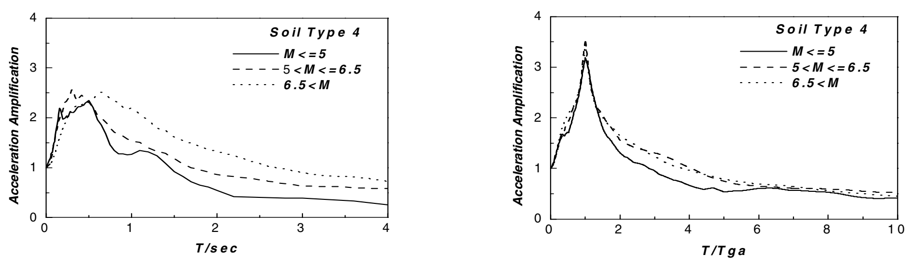
(a) Normalized spectra (b) Bi-normalized spectra

Figure 9. The influence of magnitude for records of soil type 2



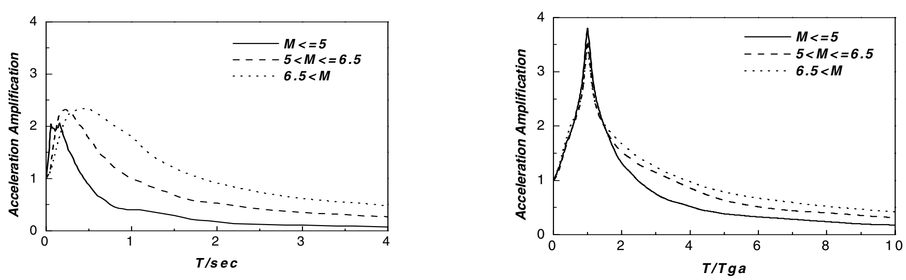
(a) Normalized spectra (b) Bi-normalized spectra

Figure 10. The influence of magnitude for records of soil type 3



(a) Normalized spectra (b) Bi-normalized spectra

Figure 11. The influence of magnitude for records of soil type 4



(a) Normalized spectra (b) Bi-normalized spectra

Figure 12. The influence of magnitude for all records

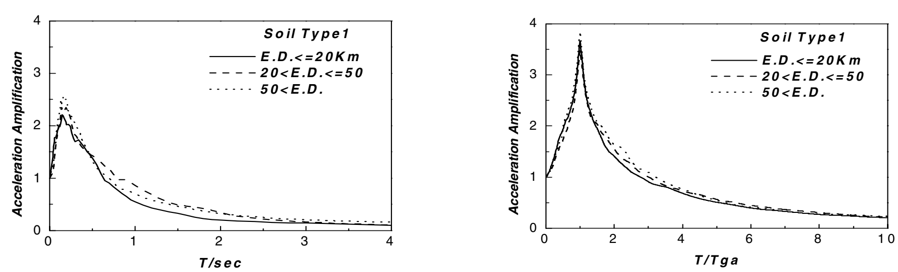
5. EFFECT OF EPICENTRAL DISTANCE ON NORMALIZED AND BI-NORMALIZED RESPONSE SPECTRA

In order to investigate the effect of epicentral distance to normalized and bi-normalized response spectra, the selected ground motion records are grouped and shown in Table 3. The average normalized response spectra of the horizontal components for each grouped records have been calculated and plotted in Figure 13, 14, 15 and 16 accounting for the influence of soil conditions. Figure 17 show the influence of epicentral distance for all the records disregarding the influence of soil condition. At short periods the normalized spectral values of near field are bigger than those of far field, but at middle and long periods the normalized spectral values of near field are smaller than those of far field. This result was not in accord with the study by Mohsen [15] in Iran, but some similarities with the results studied by Mohraz [16] who used Loma Prieta records. Although the influence of distance on amplification and normalized spectral shapes show definite trends, further studies are needed because the influences of several factors are interrelated and cannot be discussed individually. In near field cases, the rapture distance should be well considered instead of epicentral distance.

Table 3. Classification of records account for epicentral distance and soil condition

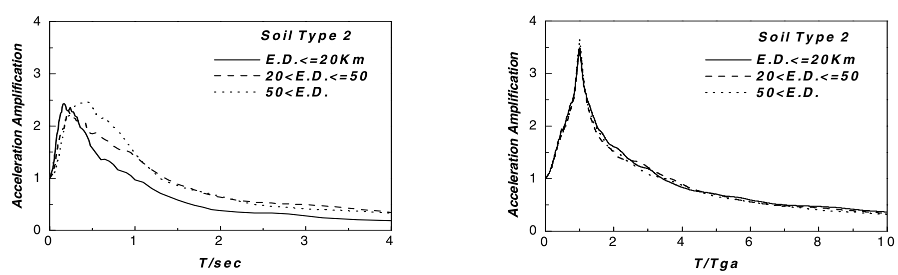
Soil Type	Near Field E.D. ≤20	Middle Field 20<E.D. ≤50	Far Field 50<E.D.
S1	73	42	16
S2	19	51	58
S3	30	35	65
S4	20	55	67
Total	142	183	206

The figures for bi-normalized response spectra of the horizontal components taking account of the effect of epicentral distance indicates that in all relative periods the mean spectral values vary slightly. The differences of bi-normalized spectral ordinate between different fields are much less than those of normalized spectra.



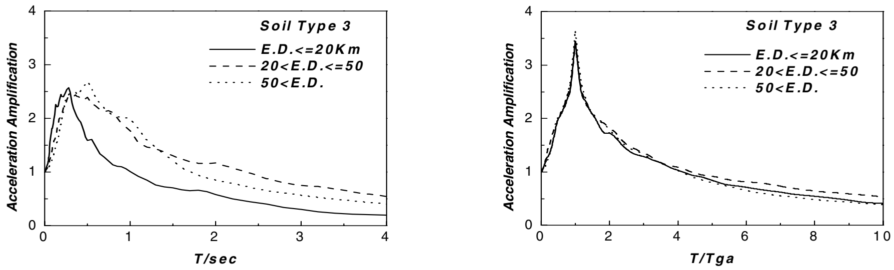
(a) Normalized spectra (b) Bi-normalized spectra

Figure 13. The influence of epicentral distance for records of soil type 1



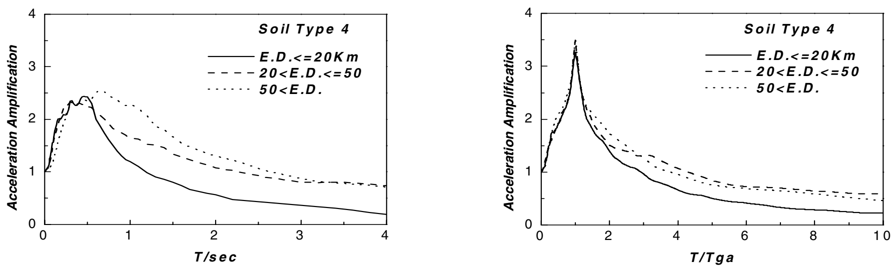
(a) Normalized spectra (b) Bi-normalized spectra

Figure 14. The influence of epicentral distance for records of soil type 2



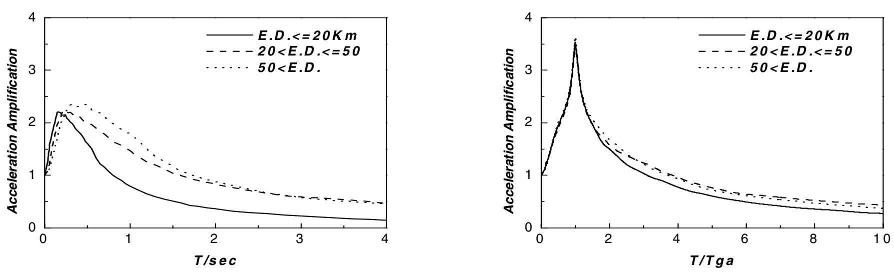
(a) Normalized spectra (b) Bi-normalized spectra

Figure 15. The influence of epicentral distance for records of soil type 3



(a) Normalized spectra (b) Bi-normalized spectra

Figure 16. The influence of epicentral distance for records of soil type 4



(a) Normalized spectra (b) Bi-normalized spectra

Figure 17. The influence of epicentral distance for all records

6. CONCLUSIONS AND RECOMMENDATIONS

The study of the characteristics of normalized response spectra is conventional method to add new recommendations and guardlines for earthquake resistance design. Based on this method, ground motion recordings are classified into groups taking account of the effects of earthquake parameters such as site geology, the earthquake magnitude and the distance of the site to the source of energy release. Which will require an abundance of records that make it possible to study the influences of various parameters on ground motions. Hence the question rises: do recorded ground motion have essential common characteres besides the influences of parameters and can recorded ground motions in a region of the world be used to predict site-dependent response for another region? We attempt to answer the question by proposing a new concept: bi-normalized response spectra. From findings some conclusions can be made that soil condition, earthquake magnitude and epicentral distance all affect the normalized spectral shapes and amplifications to a substantial degree. However, the bi-normalized response spectra, as being of a new tool used to analyze and revealing characteristics of ground motions has unique merits for that soil condition, earthquake magnitude and epicentral distance all influence its shape and spectral ordinates slightly, besides which the maximum amplification of the bi-normalized response spectra is most prominent and up to 3.5 instead of 2.25 or 2.5 which have been accepted in most specifications. Above all, the bi-normalized response spectra have better consistency among all strong motion records than do the conventionally normalized response spectra, which implies that the bi-normalized response spectra can be used not only in revealing the characteristics of strong ground motions but also in simplifying the site–specific design spectra for engineering design purpose.

7. ACKNOWLEDGMENTS

The article represented herein was supported by Heilongjiang Natural Science Foundation. Project: Bi-Normalized Design Response Spectra Based on Uniform Site Conditions, and the project no. ZJG03-03.

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