A COMBINE APPROACH OF EVALUATION OF LONG-PERIOD DESIGN SPECTRUM

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SUMMARY

The need of a seismic design spectrum of long period up to 10 sec. or more is firstly discussed. The second part of the paper is a discussion of the limitation of the current data bank of the engineering-oriented accelerograms of ground motion obtained by the analogue accelerographs, which can give dependable spectra only within 3 sec. The third part gives a brief discussion of the definition of earthquake magnitude. The fourth part devotes to the authors' suggestion of a new approach to the problem by a combination of the engineering data (accelerograms) and the seismological data from magnitude definition in terms of the velocity or displacement of the ground motion. The key reasoning of the suggested approach is to make full use of this magnitude definition to derive the displacement, and thus the long-period spectrum. Numerical results are obtained from the records of the digital instruments of broad and very broad band spectrum by the seismologists, combined with those obtained by the engineers. The final results show that the results of the engineers covering the period range of 0.05 to 3.0 sec. and those of the seismologists covering the range of 1.0 to 20 sec. match with each other very well and give a smooth transition of the response spectrum. Finally, further needs of studies along this direction are briefly mentioned.

INTRODUCTION

Because of the fast development of urbanisation, transportation and communication, there are now built many very long suspension bridges of main span up to 1 km or more, and buildings or TV towers of height more than 100 m. Their natural periods are about 10 sec. or above. The current design spectra given in the world are usually not so long as required. For example, the longest period of the specified design spectrum is only 3 sec. for buildings in USA (UBC 1994) and in China (1989), which may be increased to 6 sec. in the forthcoming modified edition in China, and 7 sec. in China for industrial structures. It shows clearly the need of design spectrum of long period up to 10 sec. at least or better to 20 sec. The present paper suggest an approach to meet this need by combining the engineering data (accelerograms) and seismological approach of defining the earthquake magnitude in terms of the velocity or displacement of the ground motion. The key reasoning of the suggested approach is to make use of these magnitude definitions and to derive the displacement, and thus the long-period spectra, inversely from the above-mentioned relations. Numerical results obtained from the records of the digital instruments by the seismologists, compared with those obtained by the engineers, are given finally to illustrate the possibility and adequacy of the suggestion.

CURRENT CODE SPECIFICATIONS OF DESIGN SPECTRUM AT LONG PERIODS

Current codes of seismic design of structures derived their design spectra from the data available at the time of drafting the codes, mostly in the period of 1960's to 1980's. Table 1 shows the longest period considered in the codes listed in Regulations for Seismic Design. A World List – 1996, distributed by the International Association for Earthquake Engineering (IAEE 1996), together with some other codes at author's hand. The following definitions and terms are used in this paper. The spectral acceleration or the design spectrum is:

$$Sa(T,\zeta) = kI\psi\beta g \tag{1}$$

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where k =a/g – seismicity coefficient, given usually by a zonation map, with a for ground motion considered;

I – structural importance coefficient;

ψ -- structural coefficient, varying roughly in the range of 0.2—0.45;

β -- dynamic coefficient or the amplification spectrum, which is a function of the natural period T and the damping coefficient ζ of the structure;

g – gravity acceleration.

Table 1 Longest Period Tmax Specified in the Seismic Codes

code	year	Tmax(sec)	code	year	Tmax	code	year	Tmax
Albania	1989	Min.Sa	Dominica	1979	Min Sa	New Zealand	1992	4.0
Algeria	1988	Min Sa	Egypt	1988	2.4	Nicaragua	1983	2.5
Argentina	1983	2.4	ElSalvador	1989	?	Peru	1977	Min Sa
Australia	1993	3.0	Ethiopia	1983	?	Philippines	1992	3.0
Austria	1961	No Spec.	France	1990	2.5	Portugal	1983	Min Sa
Bulgaria	1987	2.5	Germany	1988	2.25	Romania	1977	Min Sa
Canada	1995	?	Greece	1989	No Spec.	Russia	1992	Min Sa
Chile	1993	Min Sa	India	1984	3.0	Slovenia	1994	Min Sa
China,bldg	1989	3.0	Indonesia	1983	3.0	Spain	1992	?
China,str		7.0	Iran	1988	Min Sa	Switzerland	1989	5.0
China,br		5.0	Israel	1990	Min Sa	Turkey	1996	?
Colombia	1984	Min Sa	Italy	1986	?	USA (UBC)	1994	3.0
Costa Rica	1986	10.0	Japan	1981	Min Sa	Venezuela	1994	Min Sa
Croatia		Min Sa	Macedonia	1995	Min Sa	Eurocode8	1994	Min Sa
Cuba	1995	Min Sa	Mexico	1995	Min Sa	ISO 3010	1988	Min Sa

Some codes specify a limit of the longest period considered, for example Tmax =3 sec. in China building code GBJ 11-89, 5 sec. in highway code, and 7 sec. in China special structure code GB 50191-93; some give a minimum value of the design spectrum Sa (T,ζ), for example, 0.65 in Albania code, with or without limit long period; and a few codes with no limit, such as the Eurocode 8.

In Table 1, there are 20 codes specify a minimum design value for the spectrum at long period side, 17 a specific value of the end of the long period, 6 not clear to the author, and 2 no spectrum in the code. Among those specifying a limit of the longest period, one code limits it to 10 sec, one to 7 sec, and the rest to a range of 2.25 – 5.0 with an average of roughly 3 sec. There are perhaps two main reasons for this situation. Firstly, there were not so many tall buildings years ago as we have now. A building of 30 stories may have a fundamental period roughly 3 sec or less and the main cases considered in the ordinary codes are common buildings of lower height.

That is why there are seismic design codes for tall buildings in addition to building codes, such as in China. Secondly, data of strong motion records accumulated in the world now reach a huge amount, say 10,000 traces of peak acceleration, but most of them are from analogue accelerographs. People doubt their accuracy of periods long than 3 -- 5 sec. These two topics will be discussed in the following two sections before going to the authors' suggested approach of a practical method of assessment of wider spectra.

CURRENT NEEDS OF DESIGN SPECTRUM AT LONG PERIODS

In China, there are now quite a few tall buildings of more than 50 story-high and even taller ones in planning. There are also towers of height more than 100 m and bridges of main span over 1,000m. In China, among many tall buildings, a building of 88 stories above ground in Shanghai and a building of 68 stories in Shenzhen City were built in the nineties, both with a fundamental period of 6.2 sec. To meet the requirement of construction of very tall structures and other reasons in Shanghai, the mostly populated city in China had for the first time a special local seismic design code DBJ 08-9-92 in 1992, and 4 years later, followed by a partially revised edition, the 1996 edition. In this local code, a special design spectrum with the longest period up to 10 sec. was specified to Shanghai region for its special seismicity characteristics and special soft site conditions, and apparently also for the special requirement of long-period structures.

In addition to buildings, long suspension bridges of main span over one kilometre have built in many countries, including China; high televisions and other long-period structures are becoming popular in large cities in China.

An unfortunate combination in seismic structural design in this case is the long-period responses of this kind of structures will be highly amplified due to soft site condition and especially for strong earthquakes at long distance, because large cities are usually built on large alluvium plains. Experience, from strong earthquake data of damage and ground motion and theoretical studies, shows clearly that resonance effect for long period motion should be carefully considered to ensure the safety of this specially important kind of structures. They should be considered as infrastructures, and are important in the sense of commercial, communication or transportation, in addition to their very high cost of construction. A typical well-known example is the selected damage of tall buildings in Mexico City.

ACCURACY OF CURRENT DATA BANK OF STRONG MOTION RECORDS

Two types of analogue accelerographs, from which the design response spectra were derived, mostly recorded the popularly used strong motion data of accelerograms. Accelerogram means the time-history of acceleration for motion in one given direction at a point on or under ground or on structure. There are now in the world more than 10,000 accelerograms accumulated from past strong earthquakes. Roughly one third is in the USA, one third in Japan, and another one third in Taiwan of China, Europe and other places. Most of the existing accelerograms were obtained from the analogue accelerographs, of which the dependable part of the spectrum is usually in the range of 0.1 – 1 sec. That means those components of motion with periods out of this range will be filtered out or strongly reduced by the lower amplification in periods greater than 1 or 3 sec of the engineering accerleragraphs. Corrections may be made for this bandwidth filtering effect, but the main point is if the noise/signal ratio is still low enough to guarantee a meaningful accuracy of the results. Noise may be introduced in several steps, such as recording, processing, digitising, scaling, and analysing the time history of accelerograms. The first serious study of this problem was carried out about 20 years ago by Professor M.D.Trifunac of USC in the United States. His conclusion is somewhat on the happy side that useful information may be obtained for components of motion with period up to 15 sec. But modern studies seem to agree that confident results may only be obtained for periods up to 3 -- 5 sec. My group in the Institute of Geophysics studied also this problem in recent years (Lu, 1995; Yu, Hu and Wang 2000) and obtained similar conclusion.

DEFINITION OF EARTHQUAKE MAGNITUDES AND THEIR ACCURACY

In 1935, Richter first introduced the idea of magnitude to give a quantitative measure of an earthquake through instrumental records. Since then there are several magnitudes defined in almost the same way as the following two cases

$$M = \log A(\Delta) - \log A_0 (\Delta) \qquad (2)$$

$$M = \log(A/T)\max - Q(\Delta) \qquad (3)$$

Equation (2) is used to define the local magnitude M_L and surface wave magnitude M_S and equation (3) for body wave magnitude m_b and also surface magnitude. In Eq. (2), A is the average of the maximum displacements (in μm) of two horizontal components at epicentral distance Δ=100 km and A_0 is an empirical correction for the effect of local geological conditions on attenuation of ground motion. Eq.(3) may be used for any type of waves; when used for surface wave, the maximum ratio (A/T) of the surface wave of period about 20 sec at a distance of about 2000 km is used, where A is defined as the amplitude and T is the time duration between two zero-crossings directly before and after this amplitude A, and Q(Δ) is a correction term. Recently, a moment magnitude is defined as

$$M_W = (2/3)\lg M_0 - 10.7$$

where M_0 is the earthquake moment, which is a measure of the energy released by the earthquake wave. In the range of $3 \le M_L \le 7$, $M_W = M_L$; in the range of $5 \le M_W \le 7.5$, $M_W = M_S$.

No matter what kind of magnitude is used, it is expressed in terms of amplitude or a ratio of amplitude to a time interval. It is well known that earthquake ground motion, acceleration or displacement, is of random nature, because the earthquake wave propagates in a complex stratified medium and cut irregularly in the earth crust by faults during the long history of the earth. In the definition of magnitudes, the only parameters are the distance Δ and a correction term also in terms of Δ. It is then quite natural that the difference or error in measurements of several stations, after correction for local geological background, is 0.2 at least in average, with individual measures varying in a range of 0 to 1.0 or even higher. Taking the 1976 Tangshan Earthquake as an example, roughly in average, the difference in ground motion will be roughly 80% for a difference 1.0 in magnitude or 25% for a difference of 0.3 in magnitude.

The earthquake magnitude is defined by the seismologists and used by engineers and seismologists in the seismic hazard assessment or zonation map. In seismic hazard assessment or earthquake zonation, the ground motion parameters used as the basic requirement to ensure the safety of structures are evaluated through ground motion attenuation relations. Whatever the attenuation relation may be, there are at least two earthquake parameters, the magnitude M and the distance R; and the general form is as follows

$$\lg Y(M,R)= C_1+C_2*M+ C_4*\lg[R+ C_5*\exp(C_6*M)] + C_7*R \qquad (4)$$

where C_i (i=1,2,…..) are numerical coefficients. There are other modifications, such as to include another term of M^2 to consider the magnitude saturation of the ground motion Y, especially when y represents some short-period parameter such as acceleration. The C_6 term is used to represent the effect of finite source dimension, especially when the distance R is very small. The C_7 term is used to represent the geometrical attenuation of ground motion, but many engineers prefer to ignore it because two terms of the same variable R in one equation is not easy to estimate the related coefficients by regression only and part of this attenuation may be included in another term C_4 when R is less than 100km at least. That is why the seismologists used to take a theoretical value for C7*R and select the coefficient of the other term by regression.

A COMBINED APPROACH OF ENGINEERING DATA AND SEISMOLOGICAL DATA

Comparing Eq. 2 or 3 with Eq.4, we may say that they are principally the same. The difference comes from the near field term C_6 and the implicitly included form of distance term in Eq.2 or 3. The engineers used to emphasise the shorter period motion, say 1 sec or less, which is controlled mostly by the near field motion, say less than 100 km away; and on the other side, the seismologists paid more attention to the far field motion, say more than 100 km away, which is usually of longer periods, say more than 1 sec. It is natural then trying to combine them together with emphasis of the engineering approach on the near field motion, and the seismological approach on the far field motion, to have a better estimate of design spectrum in a wide period band, say from 0.1 sec to 10 sec. This is the basic idea of the present paper.

NUMERICAL RESULTS OF A WIDE RESPONSE SPECTRUM

Since the main part of engineering data of ground motion is obtained in the United States, the short period spectrum is then estimated on the US data. Dr. Huo had obtained such spectrum attenuation for rock sites, as given by solid lines in Fig.1 by solid lines for periods smaller than T=1.7 sec and by dotted lines greater than T=1.7 sec, and his coefficients of Eq.4 are given in Table 1, but the coefficients of the spectra S_a for periods T smaller than T=1.7 sec. are not shown in Table.

Table 2 Comparison Attenuation Coefficients of S_a (T, ζ=0.05)

$C_5 = 0.327$, $C_6 = 0.327$, $C_7 = 0$							
(from seismological data)				(from engineering data)			
T	C_1	C_2	C_4	T	C_1	C_2	C_4
1.7	-1.783	0.983	-1.760	1.7	-1.534	0.927	-1.700
2	-2.017	1.039	-1.783	2	-1.575	0.892	-1.621
3	-2.709	1.106	-1.821	3	-1.409	0.742	-1.302
4	-3.048	1.120	-1.776	4	-1.692	0.747	-1.256
5	-3.282	1.144	-1.792	5	-1.963	0.734	-1.136
6	-3.471	1.158	-1.789	6	-1.879	0.654	-0.928
8	-3.832	1.204	-1.832	8	-1.463	0.509	-0.751
10	-4.115	1.247	-1.888	10	-1.055	0.405	-0.717
12	-4.598	1.262	-1.737	12	-1.089	0.383	-0.688
14	-4.848	1.298	-1.815	14	-1.548	0.451	-0.754
17	-.5.031	1.338	-1.895	17	---	---	---
20	-.5.199	1.381	-1.985	20	---	---	---

To have a good estimate of the long-period spectrum, two sets of data are obtained from the points of view of the seismologists. The first set is obtained directly from the definition of magnitude

$$M_S = \lg(A/T)_{max} + 1.66\lg\Delta - 3.3 \qquad (5)$$

The limit of the data of this definition is for periods greater than 3 sec and distance Δ in a range roughly greater than 100km. This limitation on period is too strong for the present case. To overcome this limitation, a second set of data are obtained from 130 horizontal components of digital broad band (Yu, Hu and Wang 2000) and very broad band records recorded in China. The acceleration spectrum is taken as $S_a = 2.5A$, where A is the recorded displacement in Eq.4 and the factor 2.5 is the amplification of the ground motion to response, which is related to a damping of 0.05 for the spectrum.

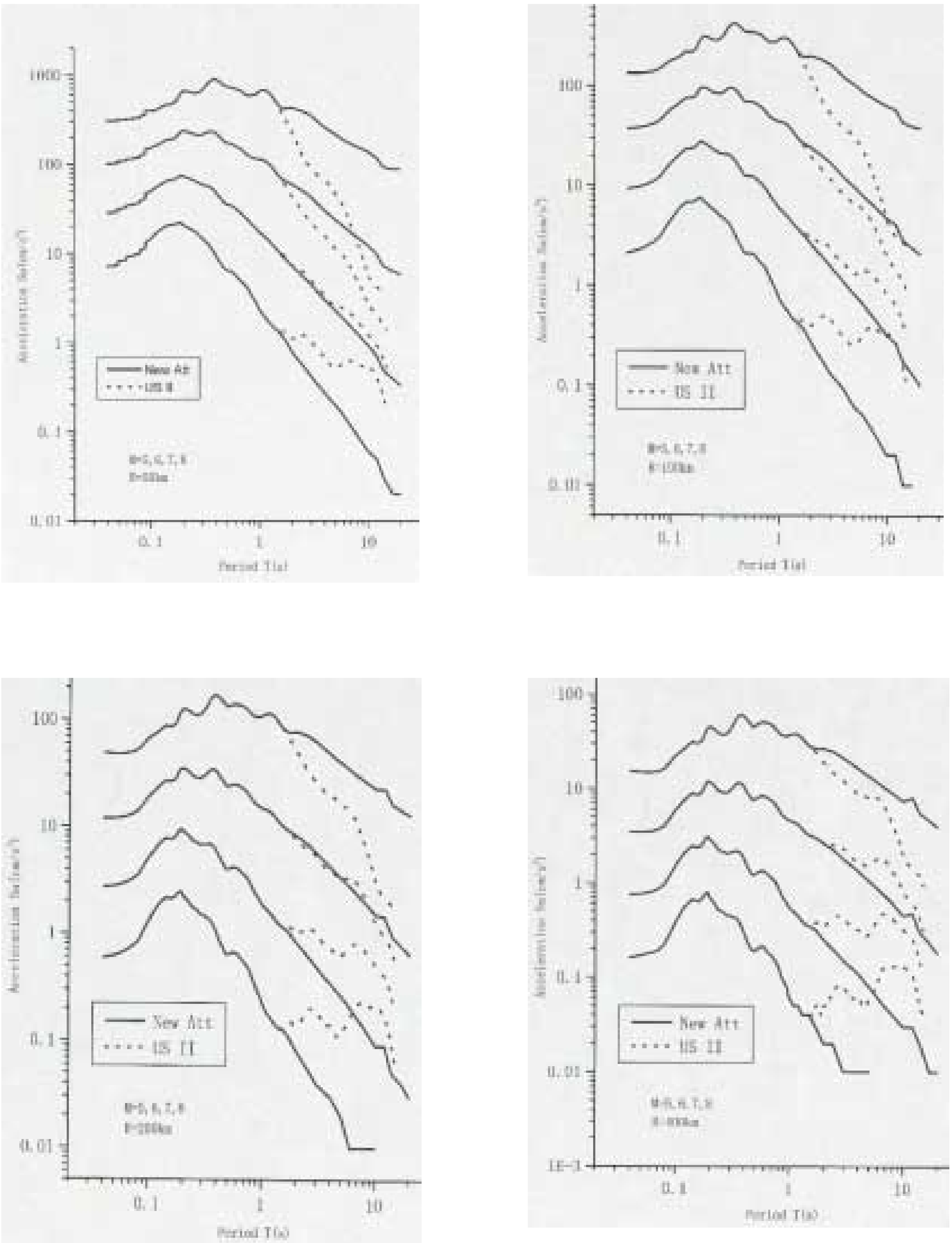

Fig.1 Acceleration Response spectrum S_a (T, ζ=0.05) up to T= 20 sec.
US II ----- Huo's result based on US data
New Att. ---- Spectra obtained by the suggested approach

With these two sets of data, a regression is made to obtain the long-period part (T=1.7 - 20 sec.) of the response spectrum. Using also the same Eq.4, the coefficients obtained are given in the right part of Table 3 and the results are plotted also in Fig.1 in solid lines. Similar results for other magnitudes and distances show the same trend. It can be seen clearly that the spectra obtained by Huo, based solely on engineering data, given in dotted lines for periods T greater than 1.7 sec, show irregular results and not dependable in the long-period range, say after T greater than 2 sec. and that the new results presented in this paper show a much better smoothness at least.

CONCLUSIONS

To meet the urgent need of a wide-band design spectrum for very tall buildings and very long-span bridges, a combined approach of both the engineering acceleration data and the seismological data of magnitude definition and the broadband displacement data is suggested. The engineering data cover rightly the shorter period (0.05 – 1 or 2.0 sec) and the seismological data cover the longer period (1.0 – 20 sec), and the transition is smooth. Further researches on noise/signal ratio, error analysis, the selection of the amplification factor of 2.5 and other data analysis are under way.

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