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A SIMPLIFIED METHOD FOR ESTIMATING MAXIMUM CREDIBLE EARTHQUAKE RESPONSE SPECTRUM

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SUMMARY

Based on the paper (Ref. 1), a simple procedure for estimating the maximum credible earthquake response spectrum has been derived. The spectrum is of high reliability, and it may make a contribution to predicting the safe shutdown earthquake (SSE) in nuclear power plant designs. Therefore, structures checked with this spectrum are safer than those with the traditional average response spectrum. Finally, the problem how to classify a site is studied for practical purposes , and a corresponding method is proposed by means of the concept of fuzzy set in fuzzy mathematics.

INTRODUCTION

Important structures, such as dams, offshore platforms and nuclear power plants, built in active seismic areas, have to be designed to withstand strong ground motions. From this point of view, it is imperative to check the reliability of these structures with the maximum credible earthquake response spectrum (MCERS) rather than with the conventional average earthquake response spectrum (AERS). For practical purposes, a new method for evaluating MCERS is suggested in this paper.

In order to protect nuclear power plants from being failure , the designs of them should be allowed for unforeseen circumstances. Therefore, in many countries, there are two steps during design. In the first step, they should be designed with the OBE in the United States or the S1 METHOD in Japan, while in the second step, checked with the SSE or S2 METHOD. The approach proposed here may provide an effective path to get the SSE or S2.

STATEMENT OF PROBLEMS

It is well known that there are serious variances among ground motion response spectra, even those obtained from the entirely same observational stations may exhibit great differences, as shown in Fig. 1. Therefore,it is apparent that the traditional aseismic design of structures based upon the AERS is not reliable, and introducing MCERS to the aseismic design of important structures has become a subject of growing importance.

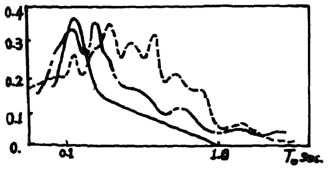

Fig.1

By analyzing the data presented in Ref. 2, the following conclusions can be drawn, as clearly demonstrated in Fig.2(a) through Fig.2(d). The expectancy, $E[\beta_d(T_0)]$, of earthquake response spectra taken from different samples will vary in a wide range, and the variation between a spectrum $\beta_d(T_0)$ and its expectancy is small. For instance, in case of the site of type II, based on ground motion records from China, $E[\beta_d(0.1)]$, $E[\beta_d(0.3)]$, $E[\beta_d(1.0)]$ are equal to 2.44, 1.23, 0.28 respectively while , based on ground motion records in the United States and in Japan, these values correspond to 1.55, 2.43, 1.04 respectively. That is, when T_0=1.0 sec., $E[\beta_d(1.0)]$ of the later case is 3.71 times as large as that of the former case, but the ratio of variance to the mean of ERS is small. It appears that the maximum of $E[\beta_d(T_0)]$, i.e. MCERS, may be more appropriate to use than AERS.

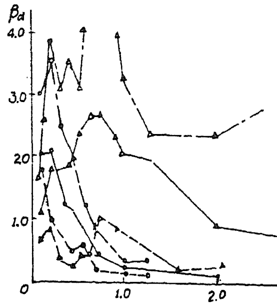

Fig. 2a Response Spectrum (II)

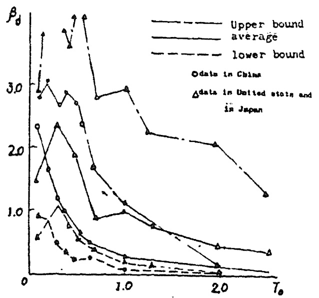

Fig. 2b Response Spectrum (III)

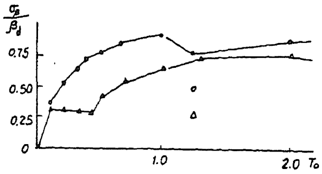

Fig. 2c Ratio of Variance to Mean

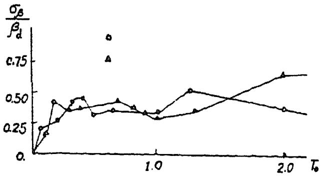

Fig. 2d Ratio of Variance to Mean

BASIC THEORY

Affected by site conditions, wave propagation paths and source parameters, ground motions can be represented by three essential factors, i.e. maximum acceleration, the duration of earthquake and power spectrum. In the past decades, the maximum acceleration is considered as the most important factor and has been studied a lot . The duration is of less importance to elastic structures. Thus, the power spectrum can be uniquely applied to express ground motions when only the amplified ratios of acceleration responses are taken into consideration.

Different earthquakes can produce entirely different power spectra , and variations of them are very sophisticated. But, some simple analytical models still can be applied to represent them , and complicated variations of power spectra can be transferred into changes of model parameters.

Let $\{x_g(t)\}$ be the random process of ground motion and $\{y(t)\}$ be the absolute acceleration response process of single degree of freedom system (SDOF), it is then reasonable to regard their maximum values X_m , Y_m and the amplified ratio $\beta_d(=|Y_m|/|X_m|)$ as random variables. According to Ref. 1, $E[\beta_d]$ can be deduced simply.

$$E[\beta_d]=E[\,|Y_m|\,/\,|X_m|\,]\doteq E[\,|Y_m|\,]/E[\,|X_m|\,]\doteq \sigma_Y/\sigma_X \qquad (1)$$

$$\sigma_X^2=\int_0^\infty S_{X_g}(\omega;x_1,x_2,\ \dots,\ x_n)d\omega\ ; \quad \sigma_Y^2=\int_0^\infty |H(\omega,\omega_0)|^2\ S_{X_g}(\omega;x_1,x_2,\ \dots\ ,x_n)d\omega$$

where σ_x^2 and σ_Y^2 are variances of $\{x_g(t)\}$ and $\{y(t)\}$; $x_1, x_2, \ldots, x_n$ are model spectral parameters determined by Ω, δ and ε ; and $|H(\omega;\ \omega_o)|^2$ represents the frequency response function of SDOF system. The various value of $E[\beta_d]$ can be obtained by inputting different $S_{x_g}(\omega;\ x_1, x_2, \ldots, x_n)$. For a given model there must be a group of $x_1, x_2, \ldots, x_n$ which makes $E[\beta_d]$ be maximum, i.e., MCERS.

POWER SPECTRUM MODELS

Four power spectrum models are selected for analysis, i.e.,truncated white noise, KANAI ,modified KANAI and modified white noise spectra. The effects of ground motion nonstationarity on power spectra can be neglected (Ref. 3).

Spectral Parameters of Ground Motion Records As the preliminary estimations of MCERS, spectral parameters are considered to be a function of only site conditions.

The Fourier transforms have been made for 14 selected accelerograms whose power spectra are then denoted by $|X_g(\omega)|^2$,and their spectral parameters are listed in Table.1. The spectral parameters Ω , δ and ε are defined as

$$\Omega = \sqrt{\lambda_2/\lambda_0} \quad ; \quad \delta = \sqrt{1-\lambda_1^2/(\lambda_0 \cdot \lambda_2)} \quad ; \quad \varepsilon = \sqrt{1-\lambda_2^2/(\lambda_0 \cdot \lambda_4)} \qquad (2)$$

$$\lambda_i = \int_0^\infty \omega^i |X_g(\omega)|^2 \, d\omega$$

Selection of Proper Parameters for Spectral Models The spectral parameters of four selected models are calculated by using Eq.(2), and the numerical results are given in table 2 in which the spectral parameters corresponding to the code response spectrum (Ref. 4) are also listed. By choosing the parameters properly and comparing the parameters of known ground motion records with those supported by four models, the desired power spectrum models can be determined.

Table 1

site \ earthquake records \ spectrum parameters	Ω rad/sec.	δ	ε
I	HELENA,MONATANA CARROLL COLLEGE NOOE 1935	48.42	0.58	0.84
	PACOIMA DAM, CAL. S16E 1971	32.20	0.65	0.90
	PACOIMA DAM, CAL. S74N 1971	32.75	0.61	0.88
	GOLDEN GATE PARK N10E 1957	32.93	0.44	0.65
	GOLDEN GATE PARK S80E 1957	38.58	0.26	0.47
II	EL CENTRO N-S 1940	31.35	0.73	0.97
	EL CENTRO E-W 1940	25.51	0.64	0.96
	OLYMPIA N10W	36.07	0.65	0.93
	OLYMPIA N80E	30.85	0.62	0.94
	TAFT N69W	27.71	0.66	0.96
	TAFT S21W	27.46	0.64	0.96
III	SOUTHERN PACIFIC BLAG. N45E 1957	22.04	0.63	0.89
	SOUTHERN PACIFIC BLAG. N45W 1957	20.35	0.60	0.85
	SOUTHERN PACIFIC BLAG. VERT 1957	36.76	0.55	0.80

Table 2

models \ spectrum parameters		Ω rad/sec.	δ	ε	adjustable parameters
truncated white noise		$\simeq 0.58\,\omega_s$	0.50	0.66	ω_s
Kanai spectrum $=0.6,\ \omega < 4\omega_g$		$\simeq 2.1\,\omega_g$	0.67	0.96	ω_g , ξ_g
modified Kanai spectrum $\xi_1 = \xi_g = 0.6$ $K = \omega_g/\omega_1$	K=1.43	$3.28\,\omega_g$	0.61	0.92	ω_g , ξ_g K , ξ_1
	K=2.00	$2.72\,\omega_g$	0.66	0.94	
	K=6.00	$2.24\,\omega_g$	0.67	0.96	
modified white noise spectrum $K = \omega_2/\omega_1 = 1$	=0.05	$28.85\,\omega_1$	0.69	0.91	ω_1, α, K
	=0.10	$14.72\,\omega_1$	0.68	0.91	
	=0.355	$4.59\,\omega_1$	0.61	0.88	
code spectrum 4	type I	66.80	0.58	0.84	
	type II	58.65	0.64	0.87	
	type III	45.38	0.72	0.92	

From table 2 ,it can be seen that for the selected models except truncated white noise spectrum, the parameters (Ω, δ) can be adjusted to those of ground motion records, and the modified white noise model is the most flexible one. Therefore , it reveals that modified white noise, KANAI and modified KANAI Spectra can be respectively employed to describe ground motions in sites of type I, II, III.

ESTIMATION OF MCERS

The Upper Bound of Response Spectra Drenick has formulated an expression for the upper bound of response spectra (Ref .5).

$$(S_A/I)_{upper} = 1.25/\sqrt{\xi}\,T_0 \qquad (3)$$

Where S_A, I are respectively the acceleration spectrum and the intensity of ground motion. It can be easily calculated that $(S_A/I)_{upper}$ =3.2275 when damping ξ =0.05 and period T_0 =3.0 sec.

To test Drenick's formula, the upper bound of AERS has been estimated (Ref. 1) where E[β_d] is found to be 9.56 for ξ (=0.05). Comparing this with β_{max}(= 10.05) corresponding to harmonic motion shows that the estimation in Eq(3) is much greater than that of the actual ground motion.

Proposed MCERS Different MCERS can be estimated according to Eq.(1) by inputting the KANAI, modified KANAI and modified white noise spectra. After comparing estimated results with measured values, the suggestions about the parameter selections in models can be summarized as following:

site types	MCERS models	values of parameters
I	modified white noise spectrum	α =0.355, K=1, $\omega_1 \in$[6.537,7.409]
II	KANAI spectrum	ξ_g =0.6, $\omega_g \in$[12.562,15.843]
III	modified KANAI spectrum	ξ_1=0.8, =0.6, $\omega_1 \in$[1.114,2.228] $\omega_g \in$[6.684,13.369]

Based on the above proposals, the calculated MCERS are shown in Fig.3, compared with (E[β_d]+ σ_{β_d}) (Ref. 2), code values β_s (Ref. 4) in table 3.

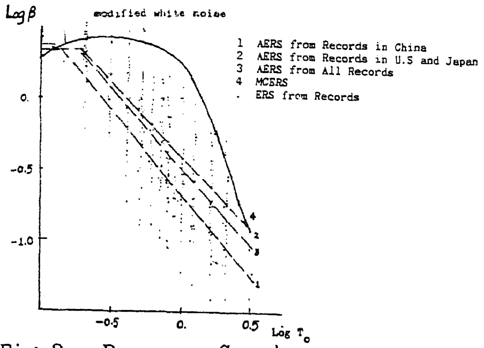

Fig.3a Response Spectrum in Site of Type I

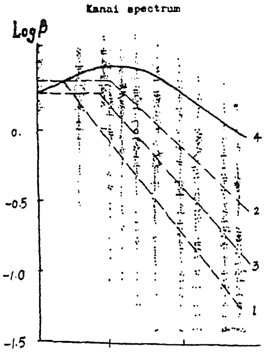

Fig.3b Response Spectrum in Site of Type II

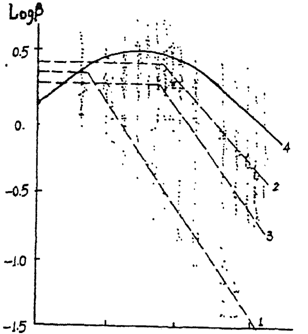

Fig.3c Response Spectrum in Site of Type III

Table 3

site	value \ To sec	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	1.0	2.0	2.5
I	$(E[\beta_d])_{max}$	1.96	2.69	2.78	2.75	2.66	2.56	2.46	2.36	2.01	0.36	
	$\beta_d + \sigma_{\beta_d}$	2.95	2.61	2.12	1.75	1.47	1.11	0.89	0.82	0.74	0.34	
	β_s	2.25	2.25	1.50	1.13	0.90	0.75	0.64	0.56	0.45	0.45	0.45
II	$(E[\beta_d])_{max}$	1.88	2.48	3.03	3.12	3.08	2.85	2.57	2.31	1.93	1.18	1.04
	$\beta_d + \sigma_{\beta_d}$	2.83	2.80		2.38	2.26				1.35	0.66	0.28
	β_s	2.25	2.25	2.25	1.69	1.35	1.13	0.96	0.84	0.68	0.45	0.45
III	$(E[\beta_d])_{max}$	1.32	2.02	2.64	3.02	3.02	2.99	2.96	2.93	2.86	1.73	1.42
	$\beta_d + \sigma_{\beta_d}$	1.89	2.66	2.66	2.45	2.99				2.60	1.33	1.41
	β_s	2.25	2.25	2.25	2.25	2.25	2.25	2.25	1.97	1.58	0.79	0.63

The Reliability of Proposed MCERS The response spectrum (β_d) approximately satisfies the logarithmic normal distribution, the probability $P\{\beta_d \leqslant \beta_o\}$ can be written as

$$P \doteq 1-0.5\exp\{-0.022078u(u+3)(u+12)\} \qquad (4)$$

$$u=0.5\sqrt{\ln[1+(\sigma_{\beta d}/\beta_d)^2]}+\ln(\beta_o/\beta_d)/\sqrt{\ln[1+(\sigma_{\beta d}/\beta_d)^2]}$$

where β_d and $\sigma^2_{\beta_d}$ are the mean value and variance of the sample respectively (Ref. 2).

The calculated probabilities $P\{\beta_d<(E[\beta_d])_{max}\}$ are listed in table 4. These results show that the reliability of the proposed MCERS is greater than 0.9 for all cases with the period T equal to or greater than 0.5 sec.

Table 4

site	P \ To sec	0.1	0.3	0.5	1.00	2.0	3.0
I	Modified white noise	0.412	0.653	0.999	1.000	1.000	0.881
II	Kanai spectrun	0.508	0.612	0.972	0.977	0.995	0.996
III	modified Kanai spectrum	0.495	0.879	0.879	0.963	0.986	0.989

STANDARD FOR CLASSIFYING A SITE

The above discussions are all based on the qualitative method of classifying a local site (Ref. 2). The following method gives a quantitative description of a site in which the predominant frequency is used to realize the local site geology.

The predominent frequency can be obtained either from the expression $\pi V_s/(2H)$ (where H, V_s are respectively the thickness of the soil layer and the shear wave velocity) or from the spectrum analysis of in-site microtremors.

The frequency distribution curves with period are presented in Fig.4 (Ref.6). It can be observed that the predominant period of a local site approximately satisfies the normal distribution.

It would be more suitable to use the so-called "membership" value of ω_g to the sites to identify the type of a local site because the type of site itself is a fuzzy concept. Denoting the type (I,II,III) of a site by fuzzy sets whose domain of definition is in the range of a site predominant period, i.e., T_g (= $2\pi/\omega_g$), the "membership" can be defined in reference to Fig.4 as follows:

$$\mu_i(T_g)=e^{-[\frac{(T_g\ -\ T_{ci})^2}{2\sigma_i^2}]} \qquad (5)$$

where T_{ci} , σ_i^2 are the average period and the variance of period distribution in type I.

The type of a site can be defined as J providing that J makes the $\mu_i(T_g)$ be maximum. The related parameters in formula (5) are chosen as follows

$T_{c1}=0.2$, $\sigma_1=0.15$ sec.

$T_{c2}=0.3$, $\sigma_2=0.30$ sec.

$T_{c3}=0.7$, $\sigma_3=0.60$ sec.

By setting $\mu_i(\bar{T}_g)=\mu_j(\bar{T}_g)$, $\bar{T}_g$ can be found out. This is considered to be the juncture value of predominant period between I and J adjacent site types.

$$\bar{T}_g=\frac{T_{cj}\,\sigma_i\ +\ T_{ci}\,\sigma_j}{\sigma_i\ +\ \sigma_j} \qquad (6)$$

It should be noted that the geological condition of a site is generally irregular and sophisticated, and using the single parameter ω_g to determine the type of a site may cause some errors. Therefore, other factors should be considered together with $\overline{T}_g$. Reasonable criteria for classifying the type of a site corresponding to the code (Ref. 4) are suggested in table 5.

Table 5

prodominent frequancy in site ω_g rad/sec.	thickness in covered layer h_c(m)			qualitative discription
	$h_c < 7$	$7 < h_c < 50$	$h_c > 50$	
	type in site			
$27 < \omega_g$	I	–	–	rock, shallow layer
$14.5 < \omega_g < 27$	II	II	III	thin for alluvium
$\omega_g < 14.5$	II	III	III	thick for alluvium

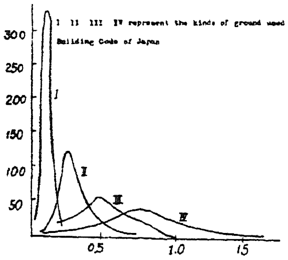

Fig.4 Period Distribution of Microtremors

CONCLUDING REMARKS

Several conclusions can be drawn from the above work as below:

1. By properly choosing spectrum parameters (Ω, δ , ε), MCERS can be determined by the power spectrum of ground motion. The equivalent frequency decreases with the soil softened, such as ω_g =32.50 rad/sec. for type I site, ω_g =29.83 rad/sec for type II site and ω_g =21.20 rad/sec. for type III site.

2. Checking important structures with the MCERS is more reliable than with the AERS.

3. The theoretical models of white noise , KANAI and modified KANAI spectra can be respectively selected to simulate the ground motions of type I, type II and type III sites, which produce satisfactory results of MCERS. The reliability of the proposed spectra in Fig.3 is more than 0.9 for all cases with T_0 equal to or greater than 0.5 second.

4. Employing ω_g(or T_g) as the main parameter, it is easy to decide the type of a site with the fuzzy distinguished method. Being lack of actual in-site information, however, the standards of classifying a site listed in table 5 need further studying.

5. It may appear more reasonable to consider the parameters (Ω,δ,ε) to be a function of the Magnitude M and epicenter D in the further study, and the error analysis caused by approximate equation $E[\beta_d] \approx \sigma_Y/\sigma_X$ will be proved desirable.

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