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Construction of a design response spectrum from evolutionary spectra of seismogram

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ABSTRACT: The evolutionary power spectra (EPS) of seismic accelerograms are estimated from the multifilter technique. The peak factor, which is the maximum value of the EPS at a specific frequency, is served as a normalization factor to build up the shape function of the EPS. An expected EPS is then determined from the shape function and appropriate peak factor , which is a function of the peak ground acceleration (PGA). Based on the expected EPS, the simulated acceleration time histories for a design PGA are generated to calculate the response spectral values.

1 INTRODUCTION

The response spectrum method is widely employed in the aseismic design analysis for many reasons. A design response spectrum usually incorporates the spectra for several earthquakes and represents a kind of average spectrum (Newmark et al., 1973). Before performing the statistical analysis, each response spectrum is generally normalized for a maximum ground acceleration of 1.0 g. Such a normalization, although is simple, is far from reasonable as the normalization factor is implicitly fixed for all components with different frequencies in a particular earthquake. It is the objective of this study to propose an alternate approach in which a more realistic normalization factor is used to construct a design response spectrum.

Since both its frequency contents and mean square values vary with time, an earthquake acceleration time history can be regarded as a nonstationary random process. A useful stochastic model to describe such a process is the evolutionary power spectrum (EPS) proposed by Priestley (1965), which is a time dependent function and has a physical interpretation as local energy distribution over frequency. This paper applies the multifilter technique (Kameda, 1975) to estimate the EPS from any single earthquake record. The peak factor is defined as the maximum value of the EPS at a specific frequency. Using such a peak factor as a normalization factor, we build up a shape function of the EPS. The relationship between the peak factor and the peak ground acceleration (PGA) is also investigated. Consequently, under a given design PGA, the expected EPS is yielded by multiplying the shape function with appropriate peak factors. Based on the expected EPS, the simulated acceleration time histories are generated to calculate the response spectral values.

The data base includes 159 accelerograms recorded from strong-motion seismographs in Taiwan with PGAs being larger than .05 g (Wu, 1989). The data are divided into several categories on the basis of the site condition and the record duration. The numerical result shows that the response spectral values above the mid-period range obtained from the proposed approach is greater than those from the previous approach.

2 EVOLUTIONARY POWER SPECTRUM

A zero-mean random process, X(t), may admit a representation of the form (Priestley, 1965)

$$X(t) = \int_{-\infty}^{\infty} e^{i2\pi ft} B(t,f) \, dZ(f) \qquad (1)$$

in which B(t,f) is the amplitude modulating function and dZ(f) the differential of the orthogonal random process Z(f). The evolutionary power spectrum of X(t), S(t,f), is given by the following equation

$$S(t,f) = E\{ B^2(t,f) \, dZ^2(f)\}/df \qquad (2)$$

where E{·} denotes the expected value.

According to the multifilter technique developed by Kameda (1975), the squared envelop $R^2(t)$ of the displacement of a single degree of freedom (SDOF) system subjected to a random base acceleration, $X(t)$, can be represented by

$$R^2(t) = Y^2(t) + \dot{Y}^2(t) / (2\pi f_0)^2 \tag{3}$$

in which $Y(t)$ = random relative displacement response and f_0 = natural frequency. The mean square response of $Y(t)$ and $\dot{Y}(t)$ is given approximately by

$$\sigma_Y^2(t) = \frac{S(t,f_0)}{4\xi_0(2\pi f_0)^3}\left(1 - e^{-4\pi\xi_0 f_0 t}\right) \tag{4}$$

$$\sigma_{\dot{Y}}^2(t) = \frac{S(t,f_0)}{4\xi_0(2\pi f_0)}\left(1 - e^{-4\pi\xi_0 f_0 t}\right) \tag{5}$$

when the damping factor of the SDOF system, ξ_0, is small.

From Eqs. (3) - (5), it follows that

$$S(t,f_0) = \frac{2\xi_0(2\pi f_0)^3}{\left(1 - e^{-4\pi\xi_0 f_0 t}\right)} E\{R^2(t)\} \tag{6}$$

The value 0.05 is used for ξ_0 in this study.

3 CLASSIFICATION OF DATA

The data base used in this study includes 159 accelerograms recorded from strong-motion seismographs in Taiwan with horizontal peak values being greater than 0.05 g. These data are divided into two categories based on the site condition at recording stations. The alluviam site is classified as the soft site. Except this, all are deemed as hard sites.

The strong-motion duration suggested by Trifunac (1975) can be used as a basis for classification. The strong-motion duration is the excitation period in which 5% to 95% of the total energy is covered. Therefore, the data in each site condition are further divided into seven groups. For those in the soft site, they are denoted as S5, S10, S15, S20, S25, S30, and S35. The Arabic numerals in above notations refer to the strong-motion duration in second. For instance, S10 represents the groupwwhich has a duration ranging from 7.5 seconds to 12.5 seconds. In addition, the duration associated with S35 is over 32.5 seconds. The number of accelerograms collected in each group is 3, 12, 10, 5, 5, 6, and 10, respectively. Similarly, for the hard site, the number in H5, H10, H15, H20, H25, H30, and H35 is 17, 27, 24, 10, 10, 2, and 18, respectively.

A typical recorded accelerogram from S25 and its EPS are shown in Fig.1.

4 EXPECTED POWER SPECTRUM

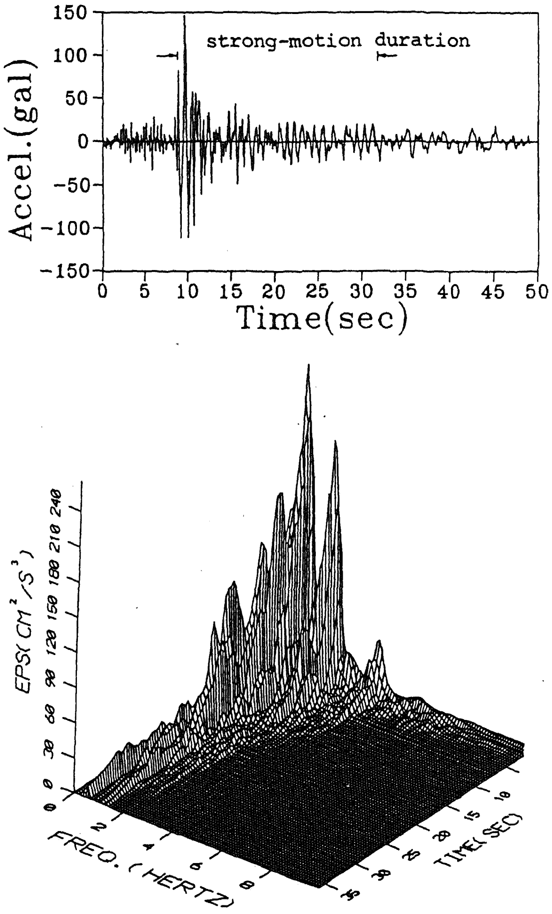

Figure 1. Typical accelerogram from S25 and its EPS

Once the EPS of any single earthquake record in a particular group is obtained by Eq.(6), the expected EPS for this group can be constructed on the average sense.

First, the shape function of the expected EPS for a specific set of records is defined by

$$G(t,f) = \sum_{i=1}^{N} \frac{S_i(t,f)}{A_i(f)\ N} \tag{7}$$

where N is the number of records in this group, $S_i(t,f)$ the EPS of the i-th record with the PGA being p_i, and $A_i(f)$ the peak factor. The factor is defined as the maximum value of the EPS at a specific frequency.

The relation between $A_i(f)$ and p_i can be obtained by carrying out a linear regression analysis. As an example, for S10 and f = 3.5 Hz, their relationship is shown in Fig.2. If the design PGA is 100 gals, the corresponding peak factor is estimated to be 53 cm^2 / s^3.

When similar estimation for other frequencies is made, the design peak factor $A_x(f)$ is obtained and is delineated in Fig.3.

Finally, the expected EPS, $S_x(t,f)$ is yielded by

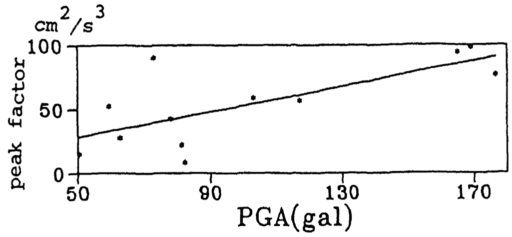

Figure 2. Relationship between peak factor and the PGA for S10 and f = 3.5 Hz

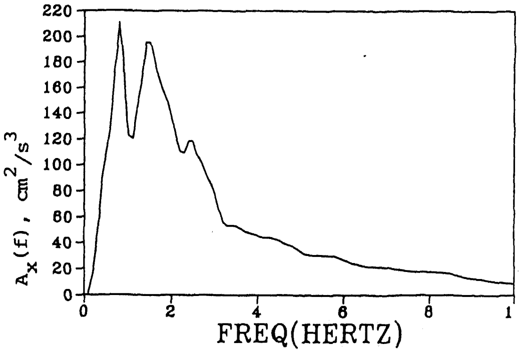

Figure 3. Peak factor for S10 when design PGA is 0.1 g

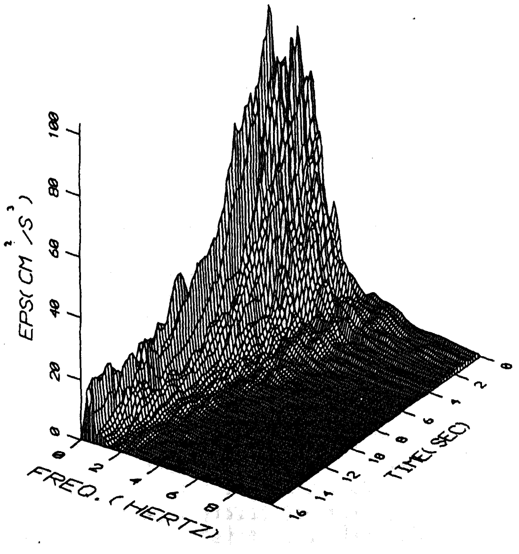

Figure 4. Expected EPS for S10 when design PGA is 0.1 g

$$S_x(t,f) = G(t,f)\,A_x(f) \tag{8}$$

Fig. 4 presents the expected EPS for S10 when the design PGA is 0.1 g.

5 RESPONSE SPECTRUM

Based on the expected EPS, the simulated accelerogram can be generated (Shinozuka and Jan, 1972) by the following equation

$$x(t) = \sum_{j=1}^{m} 2\sqrt{S_x(t,2\pi j\Delta f)\cdot 2\pi\Delta f}\cdot\cos(2\pi j\Delta f t+\phi_j) \tag{9}$$

where Δf= interval of frequency chosen to be 0.04 Hz, m = number of superposed harmonic components, which is 250 in this study, and ϕ_j = independent random angle distributed uniformly between 0 and 2π.

N simulated accelerograms are obtained to construct the response spectrum. As a demonstration, the spectral acceleration, $S_a(T)$, for S10 with design PGA 0.1 g, estimated by the proposed EPS method (solid line in Fig.5) is contrasted with its estimation through previous method (dashed line in Fig.5). The latter is obtained from correcting the average spectrum normalized to 1.0 g by a factor of 0.1. When period T is greater than .7 sec. the spectral values from the EPS method is larger. Similarly, the spectral acceleration for S25 is shown in Fig.6. Two curves are relatively close. We note that certain spectral values from the previous method are higher. Furthermore, that for S35 is presented in Fig.7. It is seen that when different methods are employed for estimating the response spectrum, the influence of

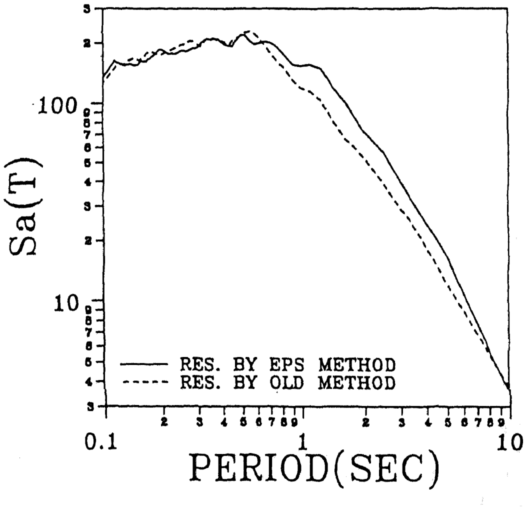

Figure 5. Response spectra for S10 when design PGA is 0.1 g

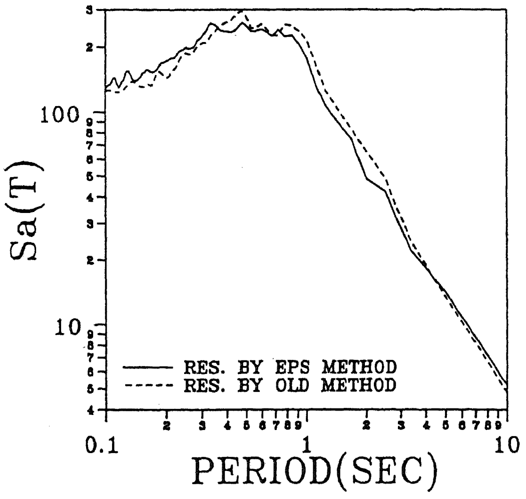

Figure 6. Response spectra for S25 when design PGA is 0.1 g

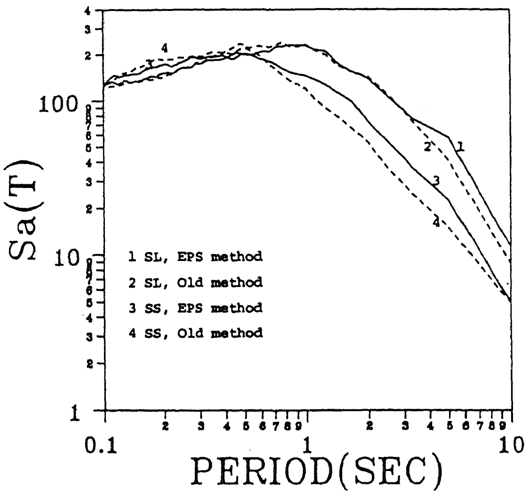

Figure 8. Response spectra for SS and SL when design PGA is 0.1 g

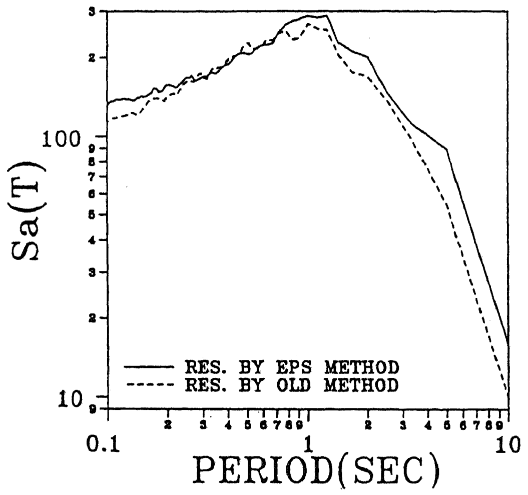

Figure 7. Response spectra for S35 when design PGA is 0.1 g

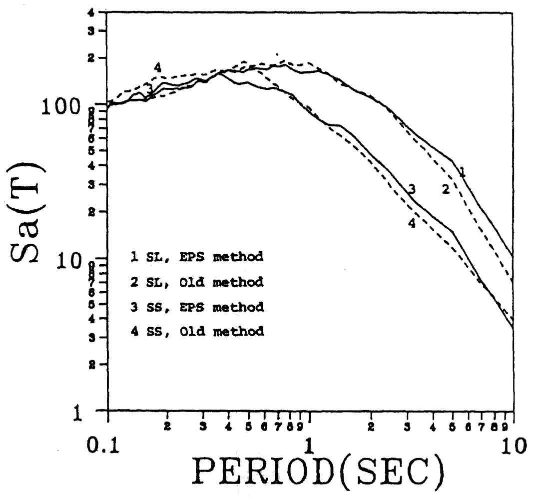

Figure 9. Response spectra for SS and SL when design PGA is 0.08 g

duration is not the same. To reduce the associated uncertainty, it will be of help when more data for each group are available. As a note, the number of records for S10, S25, and S35 is 12,5, and 10, respectively, in this study.

To circumvent the scarity of data, the records from the soft site are classified into two categories only, namely short-duration record and long-duration record, which are denoted as SS and SL, respectively. In this regard, SS consists of S5, S10, S15, and S20, while SL consists of S25, S30, and S35. Their spectral accelerations can be obtained by averaging the associated spectra and are shown in Fig.8. For SL, when T is less than 1.1 sec., although the difference between two curves in not very significant, that from the previous method is generally conservative except in a few frequencies. Same situation occurs for SS when T is less than 0.6 sec. Otherwise, that from the EPS method is rather conservative. This is even more apparent in the long-period range.

When the design PGA is other than 0.1 g, corresponding spectra can be built up by the same procedure. Fig. 9 shows the spectral acceleration when the design PGA is 0.08 g. While the division of critical period is slightly shifted, i.e. T is 1.2 sec. instead of 1.1 sec. for SL and is 0.7 sec. instead of 0.6 sec. for SS, the general trend is similar.

When it comes to the spectra for the hard site, Fig. 10 shows the spectral acceleration for H10. It is observed that the spectral values from the EPS method are significantly smaller in periods ranging from 0.3 sec. to 0.7 sec. However, the spectra for H25 (Fig.11) and H35 (Fig.12) show another type of variation. To reach a more conclusive result, only two categories are grouped, i.e. HL, long-duration record and HS, short-duration record. Fig.13 presents the spectra for HL and HS. It is noted that the spectral value from the EPS approach is generally larger for HL. This holds true for HS if the period is not within 0.3 - 0.8 sec.

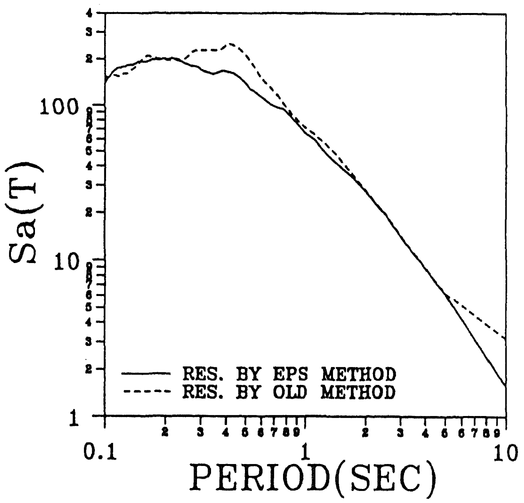

Fig. 10 Response spectra for H10 when design PGA is 0.1 g

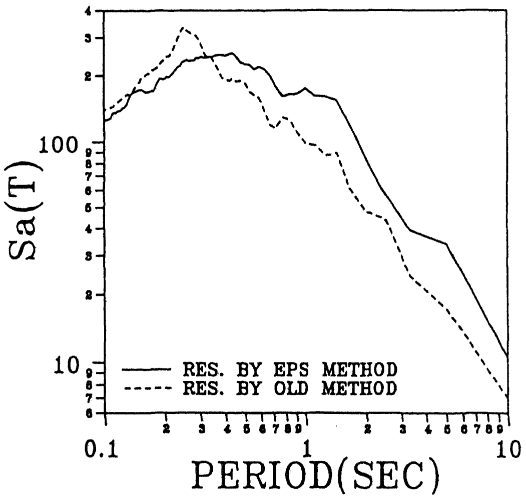

Figure 11. Response spectra for H25 when design PGA is 0.1 g

6 CONCLUSIONS

On the basis of recorded accelerograms, this study utilizes the evolutionary power spectrum and a frequency-dependent normalization factor to construct a design response spectrum. The proposed method takes into account the variation of motion amplification among different excitation components by a systematic manner. The method has a better physical interpretation than the previous method in which each individual response spectrum is normalized for a PGA of 1.0 g before performing the statistical analysis, and implicitly the motion amplification for all components is the same.

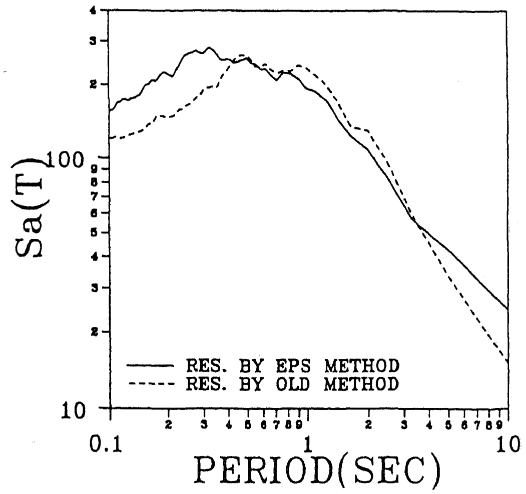

Figure 12. Response spectra for H35 when design PGA is 0.1 g

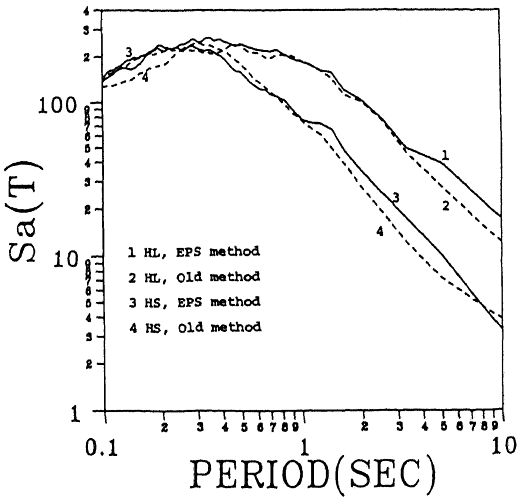

Figure 13. Response spectra for HS and HL when design PGA is 0.1 g

The numerical result shows that the discrepancy between the spectra estimated from two methods depends on the site condition, the strong-motion duration, and the design PGA level. For most cases, the spectral values from the EPS method are somewhat larger than those from the previous method. We come to a tentative conclusion that, from the viewpoint of safety design, the previous normalized spectrum is not conservative. This is particularly apparent for a structure with a long period. The spectrum from the EPS method is preferred to the previous one for the design of tall buildings and some important or critical structures.

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