A NEW METHOD TO DERIVE DISPLACEMENT DESIGN SPECTRUM COMPATIBLE WITH EXISTING DESIGN CODES

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Abstract

Displacement design spectrum (S_d) provides a simple and reliable way of estimating seismic displacement demand of structures which is required for displacement-based seismic design methods. However, there is still no generally accepted methods to derive S_d. Most of the existing seismic design codes only have regulations about the acceleration design spectra (S_a). S_d is usually converted from S_a by an approximate equation, and it has been pointed out that S_d obtained by this way is extremely large at long periods. This paper presents a comprehensive study of the displacement response spectra, and proposes a reliable and practical method to derive S_d. In the existing seismic design codes, the parameters (e.g. soil, distance, and magnitude) used to determine the spectral ordinates and spectral shape of S_a are usually classified into several categories. For consistency, the ground motions used to derive S_d should also represent the properties of S_a in the same category. To solve the problem, this paper adopts BP Neural Network to select the ground motions that match with the acceleration design spectra of Eurocode 8, and then uses the selected ground motions to obtain the corresponding displacement design spectrum. Spectral displacements are significantly influenced by the long-period noise of ground motions, especially at long periods. In previous studies, the long-period noise was usually eliminated by digital filtering, and visual inspection was used to determine the filtering cut-off frequency in which subjective errors are significant. To solve the problem, this paper adopts a quantitative method to determine the filtering cut-off frequency. To be more easily applied in the existing seismic design codes, a set of code-based parameters is used to represent S_d rather than a new set of parameters.

Keywords: displacement design spectrum; BP Neural Network; displacement-based seismic design; Eurocode 8; ground motion

1. Introduction

The earthquake engineering and civil engineering communities have been progressively taking notice that the force-based design procedure may not directly and consistently reflect the damage of structures subjected to earthquakes. Displacement-based design methodologies are thought to be more rational than force-based design methods, because structural damage is more directly related to its deformation. The direct displacement-based design method (DDBD) as presented in Priestley *et al*. [1] is one of the most developed methods among displacement-based design methodologies. Many analytical investigations have been performed to apply this method to a wide range of structural types and materials (e.g., [2-4]). A reliable elastic displacement design spectrum is required in DDBD procedure just like the acceleration design spectrum to the traditional force-based design. Therefore, the researches of displacement design spectrum are highly needed.

Numerous studies have been performed to analyze the displacement response spectral characteristics, and many displacement design spectral form have been proposed. Bommer and Elnashai [5] derived the attenuation relationships of the displacement response spectral ordinates for 183 ground motions, and simplified their results into a parametric design spectral form. Bommer *et al*. [6] proposed a compatible acceleration and displacement design spectra based on the analysis results of Bommer and Elnashai [5]. Tolis and Faccioli [7] investigated the displacement response spectral characteristics of a set of digital ground motions selected from the 1995 Kobe earthquake, and several modification suggestions for the Eurocode 8 design spectra were proposed. Faccioli *et al*. [8] analyzed the salient features of displacement response spectra at long periods and derived the analytical expressions for the displacement response spectra of two ground motion pulse models. Several valuable conclusions and the limitations of Eurocode 8 spectra were summarized in their study. Guan *et al*. [9] proposed a ground motion processing procedure and the influence of several parameters on displacement response spectra were analyzed. Maniatakis and Spyrakos [10] proposed a elastic displacement spectrum used for near-fault region in form of bi-normalized response spectrum. A bi-linear displacement design spectrum used for low and moderate seismicity regions was introduced in the study of Lumantarna *et al*. [11]. Prediction equation which is obtained by regression analysis of the spectral displacements for a large number of ground motions at different spectral periods and at different damping ratio levels is another way to estimate spectral displacements (e.g., [12-13]).

An elastic acceleration design spectrum S_a has been elaborated in most existing seismic design codes. The parameters (e.g. soil, distance, and magnitude) used to determine the spectral ordinates and spectral shape of S_a are usually classified into several categories. However, the ground motions used to derive the displacement spectrum S_d cannot represent the properties of S_a of the existing seismic design codes in the above metioned studies. Not being able to apply directly in the existing seismic design codes is the main problem for the above mentioned methods. To solve the problem, this paper adopts BP Neural Network method to select the ground motions that match with the current code-based acceleration design spectra, and then uses the selected ground motions to obtain the corresponding displacement design spectrum. Long-period noise is the most critical factor affecting the reliability of spectral displacements, especially at long periods. To remove long-period noise, a quantitative ground motion processing method proposed by Xu et al. [14] is adopted in this paper. Eurocode 8 [15] provides a reasonable design spectral form in which displacement design spectrum can be converted from acceleration design spectrum, and is considered in this paper. The analysis results of this article will help in the displacement-based seismic analysis and design of structure, and are believed to be useful in the revise of Eurocode 8.

2. Ground motion selection based on BP Neural Network

BP Neural Network is a kind of feed forward neural network which is the most popular networks, as show in Fig.1. It consists of three layers: the input layer, the hidden layer and the output layer. BP Neural Network can classify input vectors in an appropriate way as defined by you. Equations 1a, b and c show the mathematical expressions of the acceleration and displacement design spectrum of Eurocode 8. The design spectra are mainly determined by five period parameters T_B, T_C, T_D, T_E and T_F. To selecte the ground motions that have the simlar spectral shape with Eurocode 8, a comprehensive set of ground motions utilized in Xu et al. [14] is used in this paper. The dataset consists of 2271 ground motions generated by 173 large earthquakes ($5 \leq M_w < 8$, epicentral-to-site distance $\leq$ 200 km). Each ground motion consists of two horizontal components. To avoid the influence of the amplitude of ground motions, the peak ground acceleration PGA of each ground motion is scaled to 1 g.

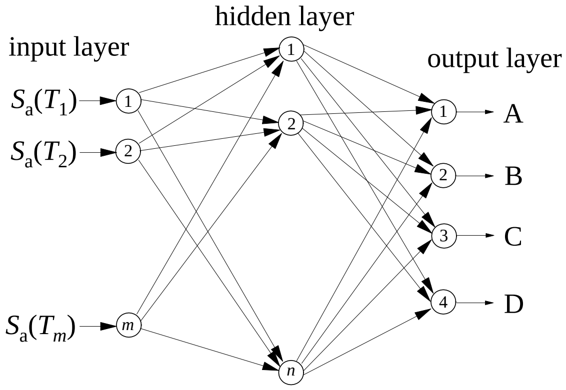

Fig. 1 – A three layers BP Neural Network

$$S_a(T_n,\xi)=\begin{cases} a_g S[1+\frac{T_n}{T_B}(2.5\eta-1) & 0 \leq T_n < T_B \\ 2.5a_g S\eta & T_B \leq T_n < T_C \\ 2.5a_g S\eta\frac{T_C}{T_n} & T_C \leq T_n < T_D \\ 2.5a_g S\eta\frac{T_C \times T_D}{T_n{}^2} & T_D \leq T_n \leq 4\text{ s} \end{cases} \tag{1a}$$

$$S_d(T_n,\xi)=\begin{cases} S_a(T_n,\xi)(\frac{T_n}{2\pi})^2 & T_n < T_E \\ 0.025a_g ST_C T_D[2.5\eta+(\frac{T_n-T_E}{T_F-T_E})(1-2.5\eta) & T_E \leq T_n < T_F \\ 0.025a_g ST_C T_D & T_n \geq T_F \end{cases} \tag{1b}$$

$$\eta=\sqrt{\frac{10}{5+\xi}} \tag{1c}$$

where, S_a = acceleration design spectrum; S_d = displacement design spectrum; T_n = vibration period of a linear single-degree-of-freedom system; η = damping correction factor; ξ = viscous damping ratio and is expressed as a percentage; S = soil factor and equals 1.0, 1.2, 1.15, 1.35, and 1.4 for A ~ E ground types respectively; a_g = design ground acceleration on type A ground; T_B = 0.15 s, 0.15s, 0.2 s, 0.2 s, and 0.15 s for A ~ E ground types respectively; T_C = 0.4 s, 0.5 s, 0.6 s, 0.8 s, and 0.15 s for A ~ E ground types respectively; T_D = 2 s for all ground types; T_E = 4.5 s, 5 s, 6 s, 6 s, and 6 s for A ~ E ground types respectively; T_F = 10 s for all ground types.

T_B and T_C are the most critical parameters to determine the acceleration design spectral shape. Even Eurocode 8 provides the values of T_B and T_C for all ground types, however, the T_B and T_C of ground type E are equal to those of ground type B. For this, this paper only considers the ground types of *A* ~ D, and classifies the acceleration design spectra are 1 ~ 4 for the ground types of A ~ D respectively. In this paper, each input data is a vector of 200 spectral accelerations with T_n = 0.02 s to 4 s at a interval of 0.02 s. Equation 2 is used to obtain the training data. The analysis results indicate that setting r = 0.03 could result in preferable results. Fig.2 shows the training data utilized in this paper. As stated above, the selected ground motions are scaled to 1 g. To maintain consistency, for the design spectrum $S \times a_g$ is assumed as 1 g. Fig.3 shows the selected ground motions for the ground types of A ~ D. It can be seen that the averaged spectrum of the selected ground motions is on the whole similar with the design spectrum of Eurocode 8.

$$S_{\text{a, train}}(T_n,\xi) = S_{\text{a}}(T_n,\xi)(1+r\varepsilon) \tag{2}$$

where, ε is a standard normal random variable (with zero mean and unit standard deviation); r is a parameter with value less than 1.

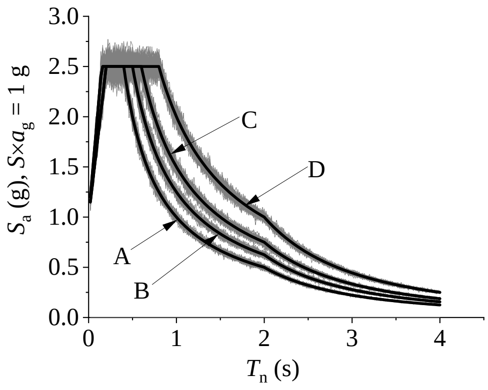

Fig. 2 – Training data utilized in the BP Neural Network of this paper

3. Ground motion processing based on a quantitative method

Ground motion processing usually has little effect on acceleration response spectrum, but has significant effect on displacement response spectrum. To obtain reliable displacement design spectra, special attention must be given to the processing of ground motions. Long-period noise is the main factor affecting the reliability of spectral displacements, especially at long periods. To remove long-period noise, many ground motion processing methods have been proposed (e.g., [5, 16]). In these studies, the filtering cut-off period was determined by visual inspection to ensure that the velocity and displacement time-histories of the filtered ground motion have physically reasonable features. As a consequence, the effects of subjectivity were significant. To solve the problem, Xu et al. [14] proposed a quantitative method to determine filtering cut-off period for the analysis of displacement response spectra. In this approach, the long-period noise of a ground motion is represented by the wavelet multi-resolution method, and then a iterative method was used to calculated the final filtering cut-off period. In Xu et al. [14], the acceleration amplitude of long-period noise is assumed as the 4% of the acceleration amplitude of original ground motion. This method is adopted in this paper to process the selected ground motions. Fig.4 shows the filtering cut-off periods of the selected ground motions. It can be seen that only one ground motion with the filtering cut-off period less than 4 s, and nearly half are greater than 10 s. It means that abundant long-period contents are reserved.

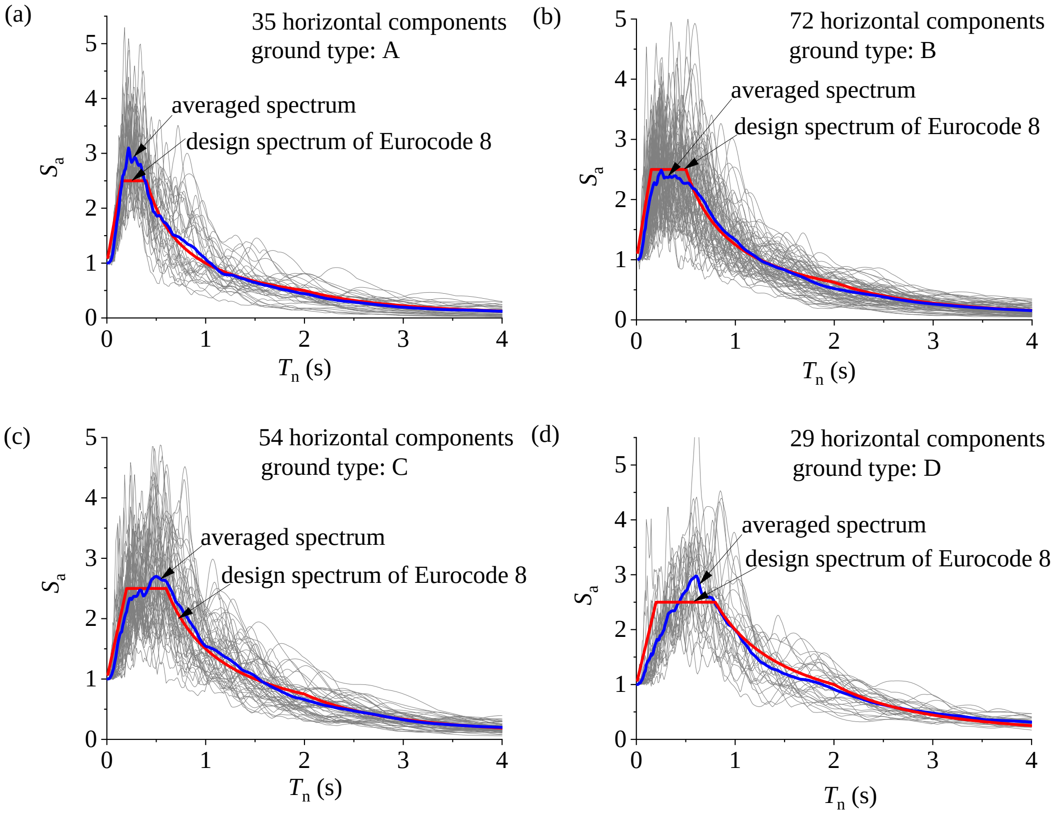

Fig. 3 – Comparison of the acceleration spectra of the selected ground motions to the design spectra of Eurocode 8 for different ground types

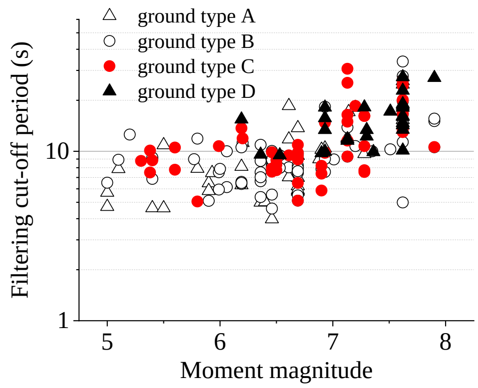

Fig. 4 – Scatter plot of filtering cut-off period to moment magnitude for different ground types

4. Determining the displacement design spectral parameters

Eurocode 8 provides a reasonable design spectral form, however, the values of the control periods have some problem, such as, it is unreasonable to set T_D at a fixed value. This paper adopts BP Neural Network to select the ground motions that match with the acceleration design spectra of Eurocode 8. This section uses the selected ground motions to calculate the control periods of the corresponding displacement design spectrum. This paper adopts equations 4a and 4b proposed by Bommer *et al*. [6] to calculate T_C and T_D, as shown in Table 1. It is known that the spectral displacements for all damping levels increase with period from zero to some maximum value and then descend to converge at the value of the peak ground displacement (PGD) at long periods. As defined by Eurocode 8, the spectral displacement converges to PGD at T_F. However, due to the influence of long-period noise and the defects of digital strong motion instruments, the spectral ordinates are not reliable at very long periods. Some studies indicated that the spectral ordinates at the periods less than 0.7 ~ 0.8 times of the filtering cut-off period are usable (e.g. [16]). As shown in Fig.4, a relative large cut-off filtering cut off period is used for most ground motions. Thus, the values of T_C and T_D computed by this paper is believed to be usable. T_E determines the terminal point of the platform region of the displacement design spectrum of Eurocode 8. This paper recommends using Equation 4c to calculate T_E.

Fig.5 shows the comparison of the displacement design spectrum of this paper to Eurocode 8. It can be seen that the displacement design spectrum of Eurocode 8 is less than the averaged spectrum because Eurocode 8 adopts a small value of T_D. Based on current data, it is impossible to obtain an accurate value of T_F. Eurocode 8 sets T_F at a fixed value of 10 s. It can be seen that from Fig.5 that the true value of T_F should be much greater than 10 s. This paper takes a conservative value 40 s for T_F in Fig.5. It can be seen from Fig,5 that the design spectrum derived by this paper can reflect the main feature of the averaged spectrum.

$$T_C = 5\frac{PGV}{PGA} \tag{4a}$$

$$T_D = 8\frac{PGD}{PGV} \tag{4b}$$

$$T_E = 3 \times T_D \tag{4c}$$

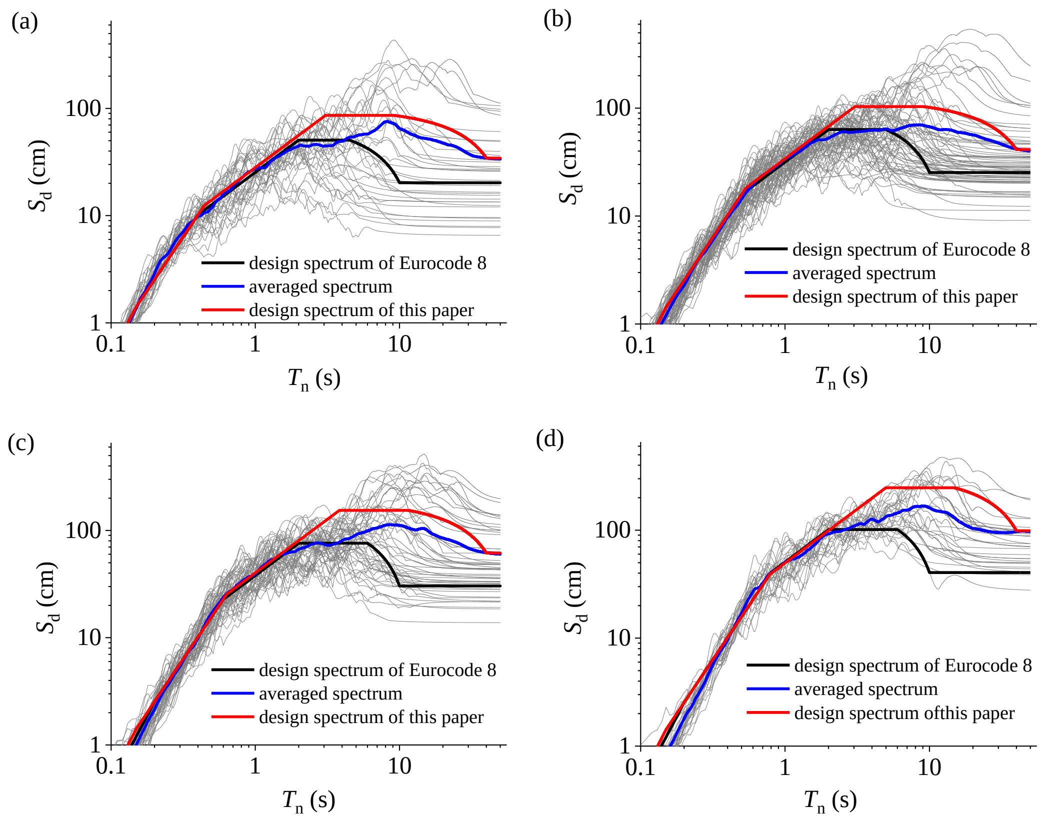

Fig. 5 – Comparison of the displacement spectra of the selected ground motions to the design spectra of Eurocode 8 for different ground types

Ground motions recorded at large earthquakes would be more likely to have abundant long-period contents. Even a ground motion has abundant long-period contents, the spectral acceleration is usually very small at long periods. However, the influence of the long-period contents on the spectral displacement is significant. Xu et al. [14] indicated that displacement spectral ordinates converge to PGD at different period locations for different earthquake magnitudes. In Eurocode 8, the control periods are only related to site condition, and the effects of earthquake magnitude are not considered. At least, T_D, T_E, and T_F should be related to earthquake magnitude.

Table 1 – Values of the control periods for the design spectrum calculated by this paper

Ground type	T_B (s)	T_C (s)	T_D (s)	T_E (s)
A	0.15	0.44	3.0	9.0
B	0.15	0.54	3.0	9.0
C	0.20	0.63	3.8	11.5
D	0.20	0.78	5.0	15.0

5. Conclusions

BP Neural Network is used to select the ground motions that match with the acceleration design spectra of Eurocode 8, and then the selected ground motions are used to obtain the corresponding displacement design spectrum. To be more easily applied, a set of code-based parameters is used to represent S_d rather than a new set of parameters. The results indicate that the T_D of Eurocode 8 is relatively small, and this will underestimate the spectral displacement at long periods (> T_D). Based on current data, it is difficult to obtain an accurate value of T_F. However, the true value of T_F should be much greater than 10 s as defined by Eurocode 8. A new set of design spectral parameters is calculated based on the selected ground motions and are presented in tabular form. This paper uses Eurocode 8 as the reference seismic design code. The method can also be applied to other seismic design codes.

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