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STUDY ON DETERMINATION METHOD OF DESIGN DISPLACEMENT RESPONSE SPECTRA BASED ON DUCTILITY FACTOR

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SUMMARY

In this paper, the earthquake ground motion records are used as inputs, which the acceleration response spectra are consistent with the Code for Seismic Design of Buildings (GB50011-2001) of China [1]. The displacement responses of the Single Degree of Freedom (SDOF) shear-type structure, with different structural yield strength factors, different nature periods and damping ratios, have been calculated by elasto-plastic time-history analysis, and the expression of design displacement spectrum is proposed by optimization method. The main conclusions are, firstly, the design displacement spectrum can be calculated with adequate precision based on input elastic displacement response spectrum, the structural yield strength factor, damping ratio and ductility factor spectrum are introduced as modify parameters in calculation; Secondly, The structural damping ratio and the yield strength factor both are the significant factors influence the elasto-plastic displacement response spectrum; Thirdly, The ductility factor spectrum is controlled mainly by the structural nature period and the yield strength factor.

INTRODUCTION

In recent years, the displacement-based design concept is a hotspot in the seismic engineering field. The representative methods include mainly the design method based on ductility factor, capacity spectrum method and the direct displacement-based design method and so on. The substance of displacement-based design method is correct the shortages of design method based on force. The method abandons the manner of describing structural nonlinear performance only by strength/force index and focus on displacement response. It is well known that the displacement-based design has been accepted in seismic codes in many countries. The capacity spectrum method is adopted by most of them [2][3]. The important but inevitable and difficult problem of both the capacity spectrum method and other displacement-based design method is how to determine the structural nonlinear displacement response spectrum. For this reason, the study on seismic structural displacement response spectrum is a basic work for developing the displacement-based design method from concept phase to execution phase.

There are many influencing factors of design displacement spectrum, such as the characteristic of earthquake ground motion, the degree of nonlinear deformation of structure, and the dynamic characteristic of structure, etc. Some qualitative conclusions have been accepted and proved, for instance the response displacement was increased with the period increasing on short period stage and medium

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period stage; the response displacement is tended to be stable on long period stage. The limited steady theory value is the peak value of the ground motions in long period stage; and the structural stiffness will reduce, period will elongate, damping ratio will increase as the development of structural nonlinear [4]. The design displacement spectrum should reflect all the structural important nonlinear performance above.

At present, the method of determinate design displacement spectrum is usually obtained by simple way [5]. For example, the displacement spectrum can be deduced in terms of standard elastic acceleration spectrum by Eq. (1),

$$S_d(T) = \omega^2 S_a(T) \tag{1}$$

It is necessary to point out that equation (1) is valid in elastic analysis, and the design displacement spectrum calculated by the formula does not suit to deal with the characteristics of nonlinear response of structure. By large number of careful nonlinear time-history analysis, the quantitative design displacement spectrum expression is obtained in the paper.

METHODOLOGY

It is noted that the acceptable and most commonly used method currently in structural nonlinear seismic response analysis is still the time-history analysis method, because nonlinear structural response can be analyzed by time-history method effectively. Based on Monte-carlo numeric analysis and statistic analysis, the nonlinear response of structure calculated by time-history analysis is the reliable data to found the design displacement spectrum, so the methodology in this paper is giving by the following.

Firstly, the ground motion records used in time-history analysis is selected in accordance similar statistic characteristics. It can be anticipated that the structural nonlinear response will be influenced obviously by the characteristics of ground motions. In this paper, the earthquake ground motion records have been chosen as inputs in time-history analysis which based on the given error criterion corresponding with the acceleration response spectrum defined in Code GB50011-2001[1].

Secondly, the time-history analysis is applied to carry out the nonlinear displacement response of SDOF structures, and the statistic results of displacement response can be used to decide the design displacement response spectrum.

Last, the ground motion characteristic parameters, the parameters of elastic structure, and the influence factors of characteristics of the nonlinear structure are introduced to determine the design displacement spectrum by regression analysis. The expression of design displacement response spectrum is proposed in this paper finally.

THE INPUTS

At present, the seismic action specified in the Seismic Code in many countries is usually in the way of acceleration response spectrum. So as a method of structural seismic analysis, the work of determining the design displacement spectrum should be consistent with the relevant regulations of current seismic code. In this paper, the inputs of time-history analysis are selected by the rule of the acceleration response spectra corresponding with the standard acceleration response spectrum presented in the Code GB50011. The error criterion is defined as the relative error which is less than 20% between standard response spectrum and the sample's response spectrum. The time interval is 0.005s, and each group consists of 30 samples.

The objective acceleration response spectrum is considered as the standard response spectrum given by the Code (GB50011-2001) under intensity 7, site category 2 and the first category of design seismic (characteristic period value T_g=0.35s). The acceleration response spectra, of single ground motion, the average of group and the object, are shown in Fig. 1.

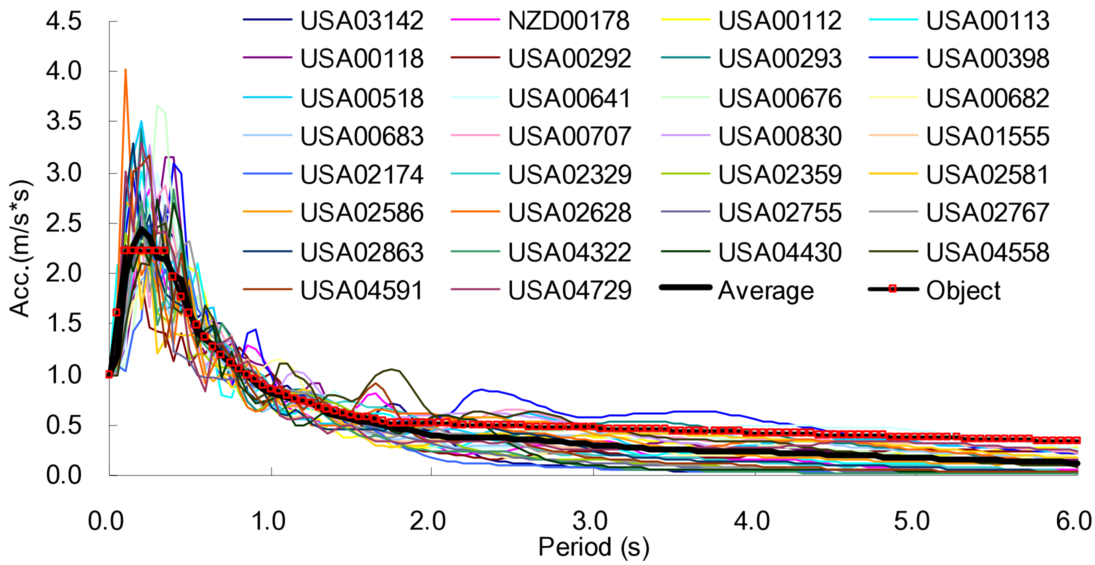


Fig. 1 The acceleration response spectrum of inputs and the object

It is illustrated that the average values of the acceleration response spectrum of inputs are correspond well with the objective response spectrum (Fig.1), and the lever of fit is much better especially when period is less than 1.5s. The result is because of the error weight is developed in the short period stage at the program of selecting inputs. The reason to do so is that the acceleration response spectrum is raised artificially in the Code in the long period stage, so it is reasonable to control the relative error for response spectra at short period stage is more strictly than that in the long period stage. Certainly, regarding 1.5s as the dividing point of error weight is a kind of personal adjudication in this paper. It needs detailed researches to prove its rationality, and hoping that it will not affect the conclusions of this paper.

THE STRUCTURAL PARAMETERS

As a fundamental study, the structural dynamics analysis model does not need to be too complex. So the SDOF shear-type model is chosen as analysis model, the hysteretic model adopted is three-line-type model, and the other structural parameters are defined as follows in this paper.

Considering that the design displacement spectrum should overlay enough range of frequency domain, the structural nature period is assigned from 0.2s to 6.0s with the interval 0.1s.

The yield point of hysteretic curve is defined by the yield strength factor (ξ_y), the yield strength factor $\xi_y = F_y/F_e$. F_y is the yield shear force, and F_e is the maximum elastic shear force. The range of ξ_y is from 0.25 to 0.9 with the interval 0.05 in this paper.

The values of structural critical damping ratio ζ are 0.05, 0.10, 0.15, respectively.

Putting the above-mentioned parameter values together, there are 74340 calculation examples are used in this paper.

RESULTS AND ANALYSIS

Based on the results of time-history analysis, the average values of structural maximum displacement responses are calculated. The total results of the calculated displacement response spectra are shown in Fig. 2 to Fig. 4, and the characteristics of displacement response spectra can be describe as follows.

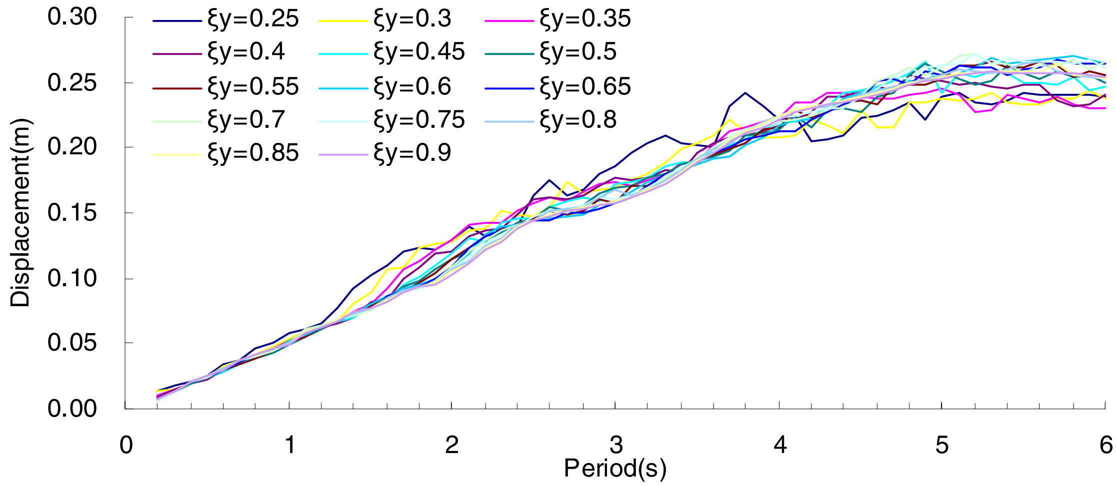


Fig. 2 The calculated displacement response spectra with varying ξ_y as ς =0.05

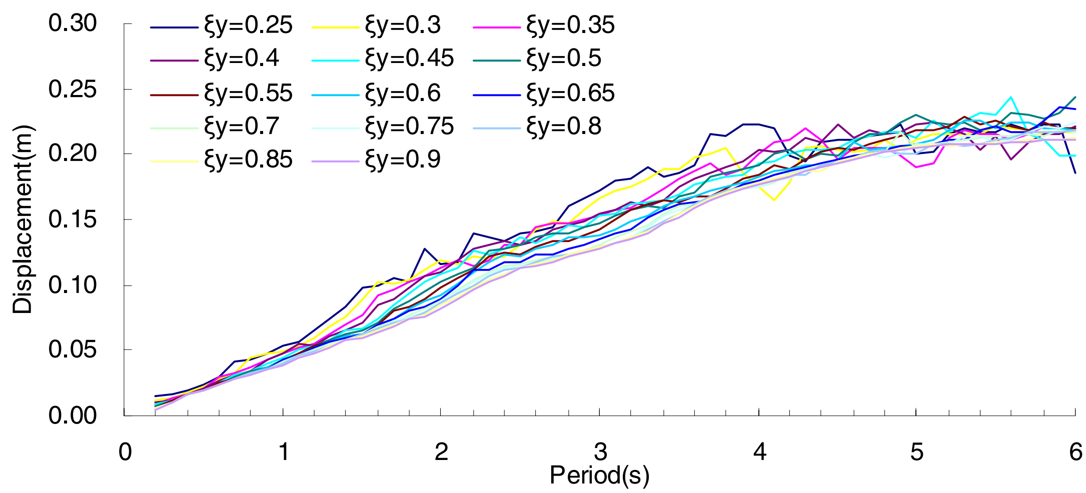


Fig. 3 The calculated displacement response spectra with varying ξ_y as ς=0.10

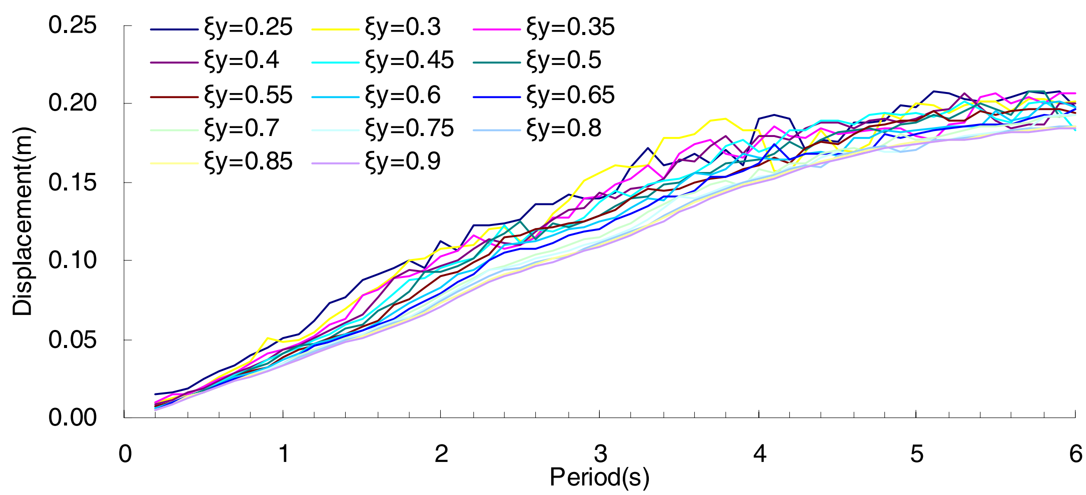


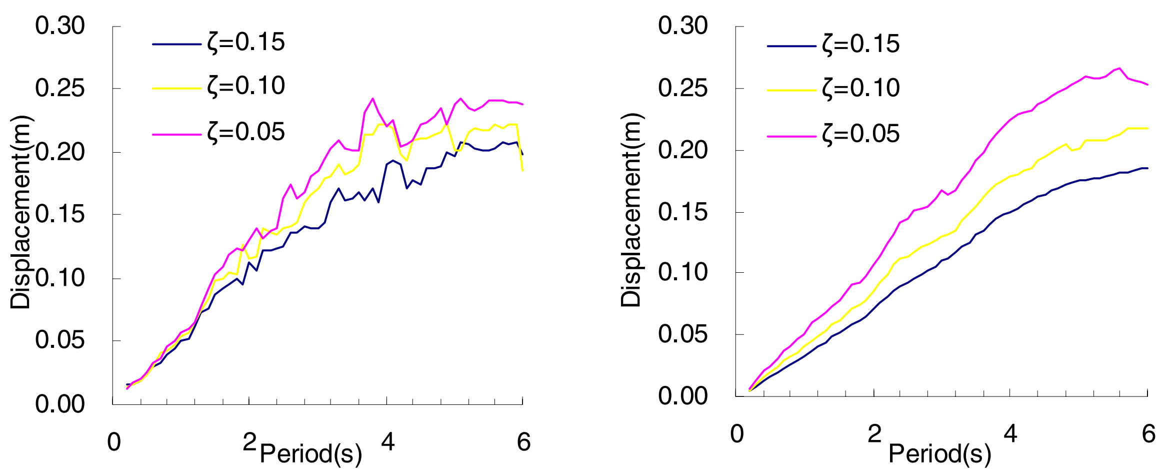
Fig. 4 The calculated displacement response spectra with varying ξ_y as ς=0.15

(1) The values of the calculated displacement response spectra increase with the increase of structural nature period, but the increase of amplitude is varying with different period stages. When the period is

shorter than 4s, the values of calculated displacement response spectra tend to increase linearly with periods. When the period is longer than 4s, the increasing of the calculated displacement response spectra tends to be stable.

(2) As the yield strength factor changed, the varying regular of displacement response spectra in the short period stage is different from the regular in medium period stage and long period stage. The main characteristic in the short period stage (<1.8s), is that the displacement responses spectra decrease with the increase of yield strength factor, and curve of the displacement response spectra with different yield strength factor almost has no intercross. The value of displacement response spectra in the medium period stage (1.8s~4.2s) related not only to the yield strength factor, but also to the value of damping ratio of structures. The figure shows that, when the damping ratio is small (ζ=0.05), the curve of displacement response spectra has a lot of intercrosses among different yield strength factors, viz. the displacement response of intense nonlinear characteristic structure with low damping ratio has the more discreteness result. When the damping ratio is larger (ζ=0.10, 0.15), the curve of displacement response spectra with smaller yield strength factors (ξ_y<0.4) still has the phenomenon of intercross among different yield strength factors. When the yield strength factor ξ_y is greater than 0.4, the values of displacement response spectra reduce obviously as ξ_y increases. In the long period stage (>4.2s), the varying rule of the displacement response spectra values is not obvious as ξ_y changing, and the curve of displacement response spectrum have some intercrosses among different yield strength factors. According to the distribution characteristics of these curves showed in this paper, it is easy to find that the structural nonlinear displacement response considering random inputs is influenced not only by the structural nature period and yield strength factor, but also by the damping ratio.

(3) When the value of yield strength factor does not vary, the values of structural displacement response spectra tend to reduce with the increase of the value of damping ratio. In order to show this rule clearly, the calculated displacement spectra of which ξ_y=0.25, ξ_y=0.8 and the damping ratios equal to 0.05, 0.10 and 0.15 are shown in Fig.5, respectively. It is easy to find that the structure with the larger yield strength factor (ξ_y=0.8) or the smaller yield strength factor (ξ_y=0.25) have the same rule that the displacement response spectra tend to reduce with the increase of damping ratio. On the other hand, because of the nonlinear characteristics tend to be obvious with the smaller yield strength factor, the displacement response spectra are shown in Fig 5 (a) in a discrete and zigzag pattern.



(a) ξ_y =0.25 (b) ξ_y=0.8

Fig.5 Comparison of displacement response spectra with varying damping ratios

The average values of the maximum displacement ductility factor (called ductility factor in the following text) have been counted in this paper. The varying rule of ductility factor with different structural nature periods and damping ratios is shown in Fig.6 to Fig.8.

The ductility factor spectra change of with the structural nature period, the yield strength factor and damping ratio are shown in Fig.6 to Fig.8. The main rules are,

(1) When the damping ratio does not vary, the ductility factors decrease rapidly as the structural nature period increase in short stage (<1.5Tg). It accords with the conclusion in reference [6]. When the structural nature period is greater than 1.5 T_g, the ductility factor spectra are stabile approximately as the nature period varying.

(2) When the damping ratio does not vary, the ductility factor spectra decrease as the increase of yield strength factor. When the structural characteristic is approximately elastic (ξ_y tend to 1), the ductility factor spectra is approaching to 1. The result is consistent with the conclusion in the meaning of theory.

(3) Fig.9 shows the ductility spectra with ξ_y=0.25 and the damping ratio equal to 0.05, 0.10 and 0.15, respectively. When the yield strength factor is unchanged, the figure shows that the ductility factors increase apparently in the short period stage as the increase of damping ratio, and it is almost invariant when the period is longer than 1.5T_g.

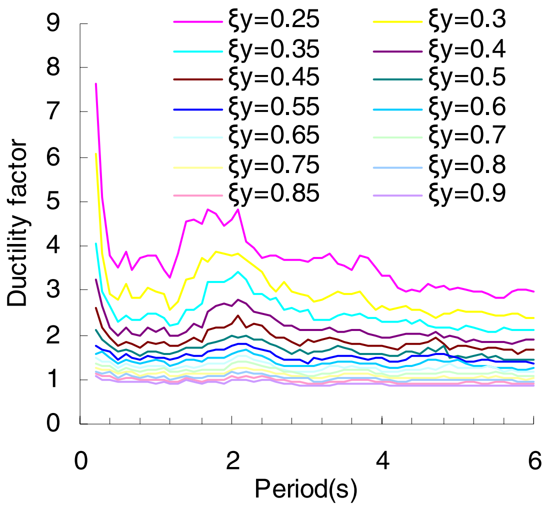


Fig.6 The ductility factor spectra under ξ_y=0.25~0.9 and ζ=0.05

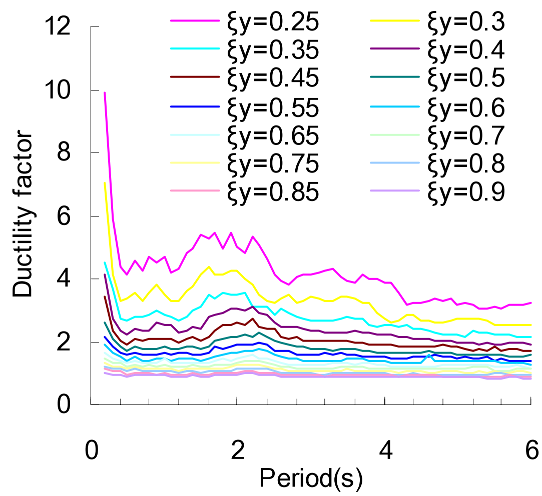


Fig.7 The ductility factor spectra under ξ_y=0.25~0.9 and ζ=0.10

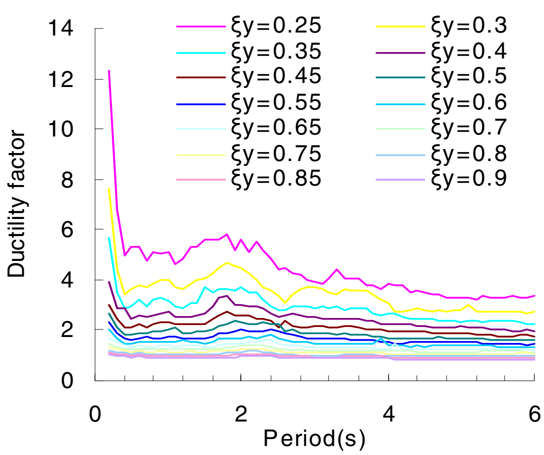


Fig.8 The ductility factor spectra under ξ_y=0.25~0.9 and ζ=0.15

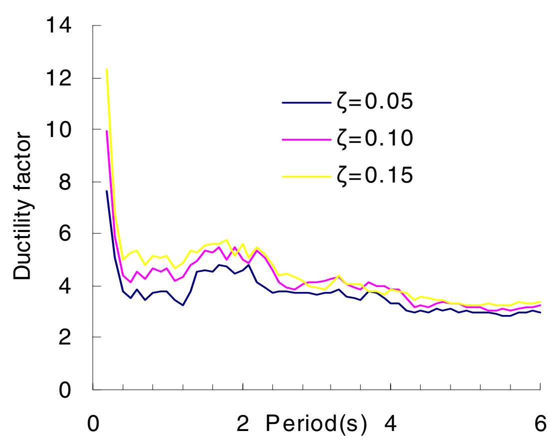


Fig.9 Comparison of ductility factor spectra with different ζ under ξ_y=0.25

In a word, the determination of design displacement spectrum not only needs to consider the random characteristics of the inputs, but also needs to reflect exactly the structural nature period, the yield strength factor, damping ratio and other vary factors.

THE DETERMINATION OF THE DESIGN DISPLACEMENT SPECTRA

According to the similarity between calculated displacement spectrum and input displacement spectrum, for example, both of them approximately increase linearly in short period stage and tend to the peak value of response displacement of the ground motion in long period stage, it is suitable that the design displacement spectrum is determined by introducing inputs displacement spectrum. The formula of design displacement spectrum proposed in this paper is,

$$S_d(T) = \alpha \xi_y \zeta^{\beta} \mu(T) S_w(T) + \gamma \tag{2}$$

Where, α, β, and γ are unknown coefficients, $S_d(T)$ is the design displacement spectrum, $\mu(T)$ is the ductility factor spectrum, $S_w(T)$ is the displacement spectrum of input earthquake ground motion. The unknown coefficients are found by the method of complex optimization.

$$S_d(T) = 0.489 \xi_y \zeta^{-0.336} \mu(T) S_w(T) - 0.00078 \tag{3}$$

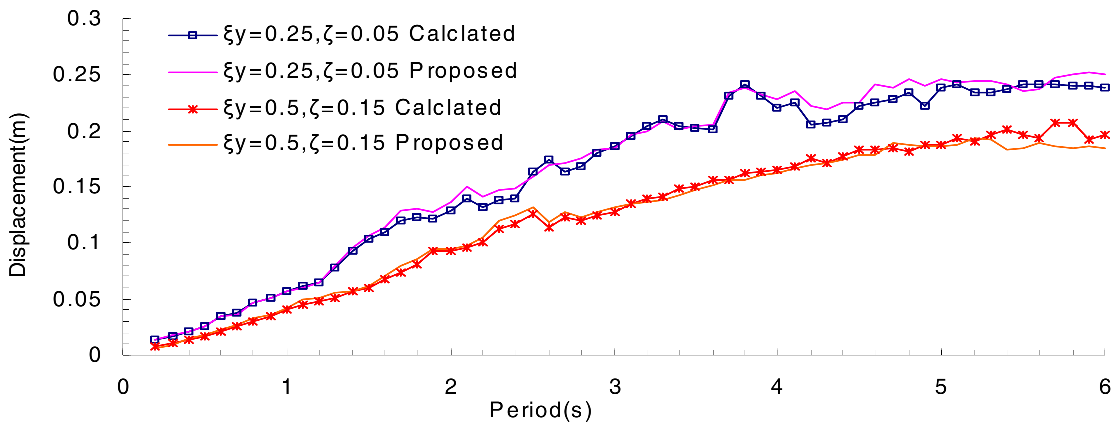


Fig.10 Comparison of the displacement spectrum proposed by the formula (3) and calculated by time-history analysis

Fig.10 shows that the displacement spectrum obtained by Eq.(3) is agreed well with the displacement spectrum calculated by time-history analysis. According to calculation, the average relative error is about 4%, and the largest relative error is only 8%.

CONCLUSIONS

In this paper, the earthquake ground motions records, which acceleration response spectrum are consistent with the Code of Seismic Design of Buildings (GB50011-2001) of China, are used as inputs. The displacement responses of SDOF shear-type structure, with different strength, nature periods and damping ratios, have been calculated by elasto-plastic time-history analysis, and the expression of design displacement spectrum is proposed by optimization method. The main conclusions are,

First, while the yield strength factor, damping ratio, ductility factor spectrum are employed as parameters, the design displacement spectrum are obtained with adequate precision based on elastic displacement response spectrum of input ground motions.

Second, the structural damping ratio and the yield strength factor both are significant factors influencing the elasto-plastic displacement response. The influence of the factors on structure increases as the increase of damping ratio and the yield strength factor.

Third, The ductility factor spectrum is controlled mainly by the period and the yield strength factor of structure. The value of ductility factor is larger in the short period stage than that in medium and long period stage, and it tends to 1 while the structural period and the yield strength factor increase gradually.

Finally, the yield strength factor and ductility factor in the formula drawn in this paper are both physical quantities describing the structural nonlinear performance. In order to apply the design displacement spectrum to engineering conveniently, the further research work is needed.

REFERENCES

1. GB50011-2001, "Code for Seismic Design of Buildings."(in Chinese) Beijing: China Architecture& Building press, 2001.
2. Eurocode 8, "European Prestandard." CEN, ENV 1998-1-1, 1994.
3. FEMA 273, "NEHRP Guidelines for the Seismic Rehabilitation of Buildings." Federal Emergency Management Agency (FEMA), 1997.
4. Xia Hongliu, Li Yingmin, Yang Pu. "Analysis of the statistic characteristics of displacement responses of SDOF system under rare earthquake." (in Chinese) Journal of Chongqing Jianzhu University. 2000, 22(s):139-143.
5. Priestley JN. "Displacement-based approach to rational limit states design of new structure." Working Group 2, International Concrete Association (Fib), Pavia, Italy, 1999.
6. Xiao Mingkui, Wang Yaowei, Yan Tao. "The response spectrum of elastro-plastic displacement for seismic structure." (in Chinese) Journal of Chongqing Jianzhu University. 2000, 22(s): 34-40.