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THE INFLUENCE OF STRONG GROUND MOTION DURATION ON STRUCTURAL DISPLACEMENT DUCTILITY DEMAND

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Abstract

The amplitude, frequency content and duration are the basic parameters to characterize the strong ground motions, and the structural seismic damage is mainly determined by the three contents besides the structural seismic capacity. The amplitude and frequency characteristics are studied and analyzed intensively and detailedly in the past, and considered maturely in the seismic design and the nonlinear time history analysis of structures in the earthquake prone countries. However, the duration of strong ground motion is seldom considered in the related work, especially without consideration in most seismic design codes. In fact, the existing researches and earthquake events have shown that the duration of strong ground motion has great influence on the seismic damage of structures. To improve the seismic design of structures, and help selecting the proper strong ground motions as the inputs for time history analysis of structures, the influence of the strong ground motion duration on the structural seismic response is investigated in this paper. Firstly, by matching the response spectra to eliminate the effects of frequency content and amplitude, 114 pairs of long-duration and short-duration strong ground motions are chosen and obtained from the NGA-West 2 database, China Seismological Network and Japan K-Net and Kik-net databases. Then, based on the 114 pairs of long-duration and short-duration strong ground motions, the equal strength ductility demand spectra of SDOF (single-degree-of-freedom) structures with four strength reduction factors are calculated, and the ductility demand spectra ratio between long-duration and short-duration strong ground motions are obtained by statistical analysis. At last, the influence of strong ground motion duration on structural displacement ductility demand are analyzed from the ductility demand spectra ratio. The results show that the displacement ductility demand of the structure under long-duration strong ground motion is significantly greater than that under the short-duration strong ground motion. For most structures with different periods, the ductility demand of long-duration ground motion is 1.3 times than that of short-duration ground motion, and the maximum value reaches 2.5 times. It is suggested that the influence of duration should be considered carefully when the time history analysis of structure is performed as well as in the seismic design of structure.

Keywords: strong ground motion duration; displacement ductility demand; strength reduction factor

1. Introduction

The differences of strong ground motions are generally characterized by the amplitude, frequency spectrum and duration. The seismic responses and damage phenomena of one structure under the different strong ground motions depend on the three contents directly. That is to say, all the three contents must be considered carefully in the seismic design and time history analysis of structures. The amplitude, frequency spectrum and duration have been studied widely by the researchers and engineers over the world. Especially the study of amplitude and frequency spectrum has been carried out a lot and used in seismic design codes in many countries. However, the study and research results on the duration of strong ground motion has seldom been applied in the seismic design codes. The past earthquake events show that the duration of strong ground motion has great influence on the seismic response of structures [1-2]. Some researchers point out the duration has little influence on the seismic maximum displacement of the structure [3-4]. Some researchers find that the duration has no influence on the maximum deformation of the structure when the elastic perfectly-plastic constitutive model is adopted in structure analysis, but it has great influence on the cumulative damage of the structure [5-9]. Unfortunately, most of the studies do not eliminate the effects of different recording frequency characteristics on the structural response when considering the duration influence. In 2016, Chandramohan et al. use spectrally equivalent method, which can eliminate the effects of amplitude and frequency content between different ground motion records, to analyze the influence the duration on structural seismic response, and only a five-story steel frame structure is analyzed for an example. The proposed spectrally equivalent method provides a new idea for duration study [10]. Based on the above analysis, this paper uses the spectral matching method proposed by Chandramohan et al. to study the single-degree-of-freedom (SDOF) structures with different periods.

There are three problems need to be solved in the study of influence of ground motion duration on seismic response of structures: (1) selecting a certain number of long-duration strong ground motions; (2) eliminating the effects of frequency content and amplitude; (3) selecting effective duration index to consider the duration. There are many kinds of definitions of strong ground motion duration. In this paper, the significant duration $D_{s5\text{-}75}$ is used as the metric of ground motion duration, and 114 long-duration ground motion records are selected from the NGA-West 2 database [11], China Seismological Network and Japan K-Net and Kik-net [12]. By matching response spectrum method, the effects of frequency content and amplitude are eliminated, and 114 short-duration ground motion records are matched and obtained from NGA-West 2 database. By using the 114 pairs of long and short duration strong ground motions, the SDOF structural model is established by using the OpenSees software [13], and four strength reduction factors are selected to calculate the equal strength ductility spectra, and the ductility demand ratio spectra are obtained by statistical analysis. At last, the influence of strong ground motion duration on displacement ductility demand of structure with different period are analyzed and studied, and some important conclusions are obtained.

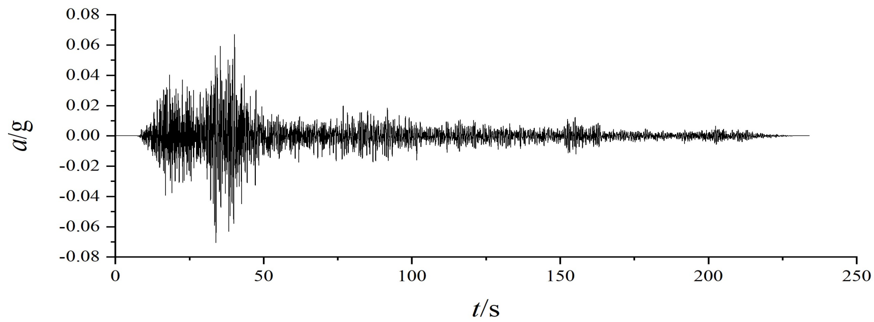
2. Selection of strong ground motions

The duration metrics must be determined before selecting strong ground motions. In general, the duration index of strong ground motion includes bracketed duration (D_b), uniform duration (D_u), significant duration (D_s) and the duration related to the Arias intensity (I_A), cumulative absolute speed (CAV) and normalized strength index I_D. In fact, when the amplitude (i.e., Peak Ground Acceleration) of strong ground motion is adjusted, the bracketed duration (D_b), uniform duration (D_u), the duration related to the Arias intensity (I_A) and cumulative absolute velocity (CAV) will be changed accordingly. That is to say, the duration, which is not dependent on the amplitude adjustment, should be used and analyzed to characterize the different strong ground motions.

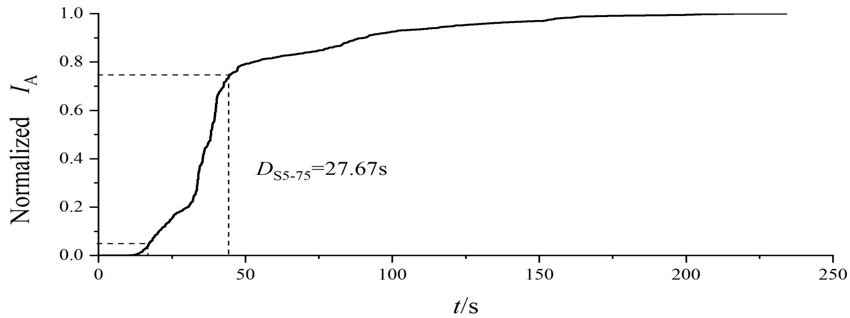
In 2016, Chandramohan et al. studied the merits and demerits of different duration metrics for studying the influence of duration on seismic response of structure [10]. Their results show that the significant duration $D_{s5\text{-}75}$ is a more appropriate duration metric for selecting strong ground motions to evaluate the performance of structures. Moreover, $D_{s5\text{-}75}$ is not affected by the adjustment of amplitude and has a good correlation with the structural seismic response. Therefore, the significant duration $D_{s5\text{-}75}$ is chosen as the duration metric parameter in this paper. The definition is illustrated by using the strong ground motion recorded at the CIGO station in the 2002 Denali earthquake. The calculation of the $D_{s5\text{-}75}$ is shown in Fig. 1, in which Fig. 1(a) shows the time history of the acceleration and Fig. 1(b) shows the normalized Arias intensity cumulative curve of the record. The normalized Arias intensity is calculated by using Eq. (1).

$$I_{\mathrm{A}} = \frac{\int_o^t a(t)^2\,dt}{\int_o^{t_0} a(t)^2 dt} \tag{1}$$

In Eq. (1), $a(t)$ and t_0 are the acceleration time history and the total time of one strong ground motion. Then the $D_{s5\text{-}75}$ of the strong ground motion can be determined from the normalized Arias intensity as shown in in Fig. 1(b), and the result of the $D_{s5\text{-}75}$ for this strong ground motion is 27.67s.



(a) The acceleration time history



(b) The significant duration $D_{s5\text{-}75}$

Fig 1. The acceleration time history and significant duration $D_{s5\text{-}75}$ of the strong ground motion recorded at CIGO station in the 2002 Denali earthquake

At present, there is no definite threshold between long-duration and short-duration of strong ground motion. Chandramohan et al. have made statistical analysis on $D_{s5\text{-}75}$ of existing strong ground motions. It is found that 25s is the proper threshold for distinguish long and short duration strong ground motions. In this paper, the 25s is used as the criterion to define the long-duration and short-duration strong ground motions. Moreover, four additional conditions are considered to select long-duration ground motions: (1) Richter magnitude M>7.0; (2) significant duration $D_{s5\text{-}75}$>25s; (3) peak ground acceleration PGA>0.1g; (4) peak ground velocity PGV>10cm/s. These conditions can ensure that the selected strong ground motions have engineering significance. According to the above conditions, 114 long-duration strong ground motions are selected from NGA-West 2 database of the United States [11], China Seismological Network, K-net and Kik-net of Japan [12]. Then according to the 114 long-duration ground motions, 114 short-duration records with $D_{s5\text{-}75}$ less than 25s are obtained from NGA-West 2 database by spectrally equivalent method. The detailed process of spectrally equivalent method and selection of strong ground motions is summarized as followed.

(1) The first step is to calculate the acceleration response spectrum of a long-duration ground motion record. The period ranges from 0.05s to 6.0s, and the interval time is 0.05s, and 120 spectral ordinates of response spectrum L_1, L_2, L_3, ⋯, L_{120} are obtained.

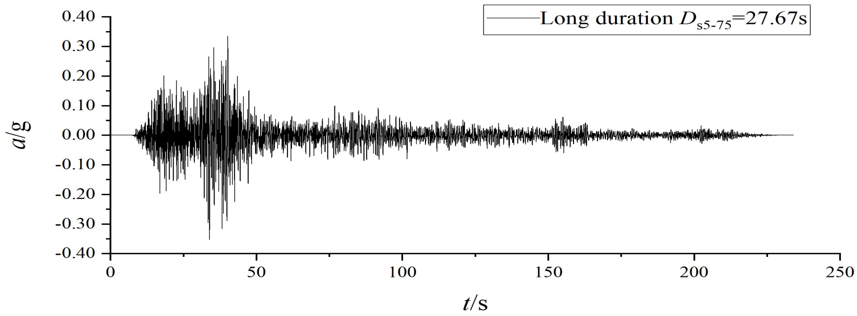
(2) Then the acceleration response spectrum of each record in the NGA-West 2 database are calculated by using the same period points, and 120 corresponding spectral ordinates of response spectrum S_1, S_2, S_3, ⋯, S_{120} are obtained.

(3) Then the Eq. (2) is used to calculate the sum of residual squares (*SSE*) of 120 pair of spectral ordinates in response spectra of long and short duration ground motion records. To avoid obtaining low intensity ground motion records due to excessive scaling, the scaling factor k is limited to a constant less than 5. The minimum residual square sum of ground motion records is selected, and a set of long-duration and short-duration ground motion records pairs are obtained finally.

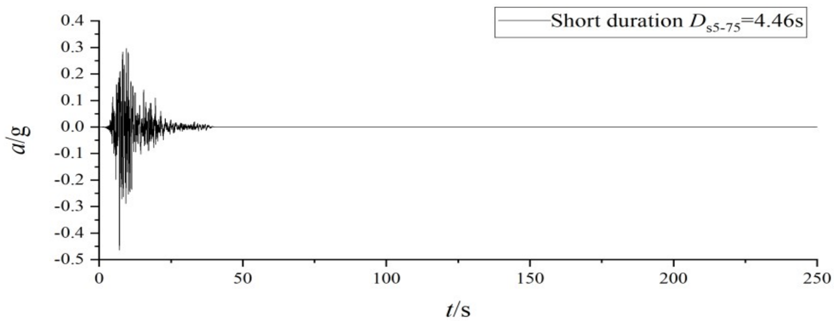
$$SSE = \sum_{i=1}^{120} (L_i - kS_i)^2 \tag{2}$$

(4) Finally, by repeating the above procedure, a total of 114 short-duration ground motion records matching the response spectrum of long-duration ground motion records are obtained.

Here, an example of a pair of long and short duration strong ground motion is compared as shown in Fig. 2. In the example, the whole duration of long-duration ground motion record is about 240s as shown in Fig. 2(a), and the its $D_{s5\text{-}75}$ is 27.67s after calculated by using Eq. (1). However, the whole duration of corresponding short-duration ground motion record is less than 50s as shown in Fig. 2(b) with $D_{s5\text{-}75}$=4.46s calculated by using Eq. (1). After the amplitude modification for both ground motion records, the acceleration response spectra with damping ratio 0.05 of both records are calculated as shown in Fig. 3, from which it can be seen that the spectra are almost same. Therefore, it can be considered that difference between the two strong ground motions only exists in the duration.



(a) Acceleration time history of long-duration strong ground motion



(b) Acceleration time history of short-duration strong ground motion

Fig.2 Comparison of a pair of long and short duration ground motions

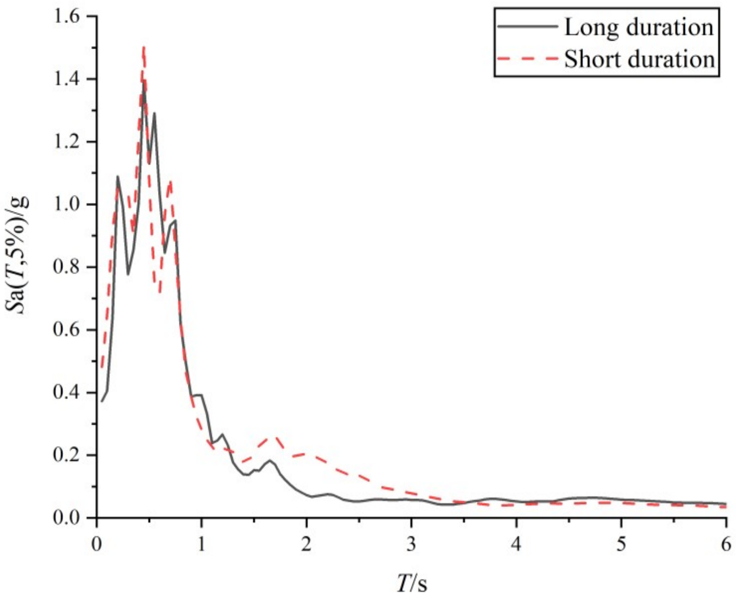


Fig. 3 Comparison of response spectra of long and short duration ground motions

3. Ductility demand analysis of SDOF structure

According to the nonlinear analysis theory of structure in earthquake engineering [14], the yield strength reduction factor R_y of an elastic-plastic SDOF system can be defined by using the following Eq. (3).

$$R_y = \frac{f_0}{f_y} = \frac{u_0}{u_y} \tag{3}$$

In Eq. (3), the parameters f_0 and μ_0 are the maximum values of restoring force and deformation in the corresponding linear elastic system, and f_y and u_y are the yield force and yield displacement respectively of an elastic-plastic SDOF system with a selected hysteretic model [14].

Then, the ductility demand μ (ductility factor) of an elastic-plastic SDOF system can be defined by using the following Eq. (4).

$$\mu = \frac{u_m}{u_y} \tag{4}$$

In Eq. (4), u_m and u_y are the maximum displacement and yield displacement respectively for an elastic-plastic SDOF system induced by a given strong ground motion.

Assuming that the strength reduction coefficient R_y is a certain value, the ductility demand μ of an SDOF structure can be obtained by non-linear time history analysis. For a series of SDOFs with different periods, the equal strength ductility demand spectrum can be obtained for a given strength reduction coefficient R_y. By setting different R_y values, a series of equal strength ductility curves with different strength reduction factors can be obtained. In this paper, the nonlinear analysis of SDOF structure is performed by using the OpenSees software [13], which is a widely used software framework for simulating the seismic response of structure subjected to earthquakes.

In order to analyze the influence of the strong ground motion duration on the ductility demand of structure quantitatively, the ductility demand $\mu_{L\text{-}D}$ of structure subjected to long-duration ground motion is normalized based on the ductility demand $\mu_{S\text{-}D}$ of structure subjected to corresponding short-duration ground motion, and the ductility demand ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ is defined and obtained. Then the average value of 114 pairs of ground motions is calculated. Finally, the ductility demand ratio spectra are obtained and analyzed. The results are shown in Fig. 4. In this paper, the strength reduction coefficient R_y are assigned with the values 2, 4, 6 and 8.

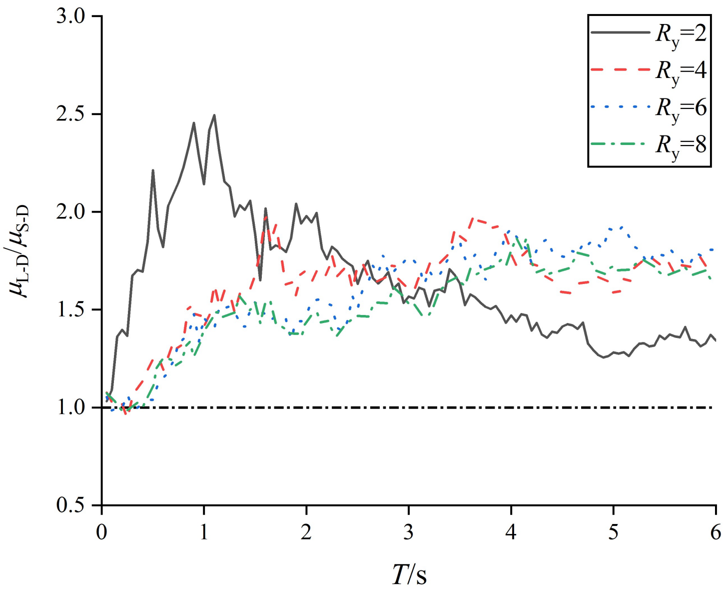


Fig. 4 Ductility demand ratio spectra

It can be seen clearly from the Fig. 4, for all periods (except for very short period), the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ is greater than 1.0. When $R_y = 2$, the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ increases with the increasing of the period T. The maximum value of the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ reaches 2.5 at about T=1.0s, and the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ decreases to about 1.3 with the increasing of the period T. Among the whole period, most of $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ are greater than 1.3. When R_y=4, the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ increases with the increasing of the period T. The maximum value of $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ is 2.0 when the period T=1.5s. In the period range of 1.5s to 6.0s, the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ changes around 1.7 with the increasing of the period T. Among the whole period, most of the ratios $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ are greater than 1.5. The spectrum curve of R_y=6 is almost same as that of R_y=8. In the period range of 0-1.5s, the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ increases to about 1.6 with the increasing of the period T, and then increases to about 1.7 with the increasing of period T. Among the whole period, most of the ratios $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ are greater than 1.5.

Moreover, in the period range of 0~3.0s, the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ of R_y = 2 is larger than those of R_y= 4, 6 and 8. While in the period range of 3.0~6.0s, the ratio $\mu_{L\text{-}D}/\mu_{S\text{-}D}$ of R_y = 2 is smaller than those of R_y= 4, 6 and 8. It means that the influence of strong ground motion duration on the seismic response of structure is related to the structural period, as well as the nonlinear hysteretic model.

4. Conclusion

In this paper, 114 pairs of long and short duration ground motion records are used to analyze the influence of ground motion duration on structural ductility demand. The main primary conclusions are summarized as followed:

(1) Ground motion duration has great influence on the ductility demand of structure. For most cases, the ductility demand of long-duration ground motion can reach 1.3 times of that of short-duration ground motion, and the maximum reaches 2.5 times.

(2) For the SDOFs with shorter periods, the structure with larger yield strength (R_y=2) is significantly influenced by duration, while for the SDOFs with longer period, the structure with smaller yield strength (R_y =4, 6, 8) is significantly influenced by duration.

(3) The influence of strong ground motion duration on the seismic response of structure is related to the structural natural period and nonlinear response characteristics. Anyway, the duration of strong ground

motion should be considered carefully and adequately in the structural seismic design and time history analysis of structures for structural evaluation.

In this paper, the influences of strong ground motion duration on structural displacement ductility demand are analyzed only by using the SDOF structural systems, and influences of duration on displacement ductility demand and seismic response for MDOF (multi-degree-of-freedom) systems and different type of structures will be studied in future.

5. Acknowledgements

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