The effect of duration of strong ground motion on the ductility demand of SDOF structure

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Abstract. As one of the basic parameters of strong ground motion, the duration of strong ground motion has not been considered in the seismic design codes over the world. To study the ground motion duration on the effects of the SDOF structure ductility demand, the $D_{5.75}$ is chosen as the duration index, and the ductility demand ratio spectrum under long and short ground motion is calculated, then the effect of duration on structural ductility demand under different strength reduction factor is analyzed. The results show that the ductility demand of the structure under long duration ground motion is significantly greater than that under the short duration ground motion. For most periods, the ductility demand of long-duration ground motion is 1.3 times that of short-duration ground motion, and the maximum is 2.5 times. It is suggested that the effect of duration should be considered when the time history analysis of structure is carried out.

1. Introduction

Frequency, amplitude and duration, as the three basic elements of ground motion, have been studied widely by the researchers over the world. Among them, the study of spectrum and amplitude has been carried out a lot and used in seismic design codes in many countries. However, the research on the duration of ground motion has seldom been applied in the codes. The past earthquake events show that the duration of ground motion has a great effect on the response of structures [1-2]. Some researchers found that when the maximum deformation of the structure is used as the demand index, the duration has little effect on the maximum deformation of the structure [3-4]. Some found that when the elastic perfectly-plastic constitutive model is adopted, the duration has no effect on the maximum deformation of the structure, but it has a great effect on the cumulative damage index of the structure [5-9]. These studies fail to eliminate the effect of different recording frequency characteristics on the structural response when considering the duration effect. In 2016, Chandramohan et al. first used spectrally equivalent method, which can eliminate the effect of amplitude and frequency content between different ground motion records, but only a five-story steel frame structure was studied. The proposed spectrally equivalent method provides a new idea for duration research [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 to be solved in the study of ground motion duration: (1) selecting a certain number of long duration ground motion records; (2) eliminating the effect of frequency content and amplitude; (3) selecting effective duration index. In this paper, the duration $D_{5.75}$ is used as the metric of ground motion duration, and 114 long-duration ground motion records are selected from the NGA-West 2 database, China Seismological Network and Japan K-Net and Kik-net. By matching
response spectrum, the effect of frequency content and amplitude is eliminated, and 114 short-duration ground motion records are obtained from NGA-West 2 database.

By using 114 pairs of long and short duration ground motion records, the SDOF structure model was established by OpenSees. Four strength reduction factors were selected to calculate the equal strength ductility spectrum, and the ductility demand ratio spectrum was obtained by statistical analysis. The results show that the ductility requirement of the structure under long duration ground motion is significantly greater than that under short ground motion. In this paper, the effect of ground motion duration on ductility demand of structure with different period was studied, and some important conclusions were obtained.

2. Selection of ground motion records

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 standardized strength index \( I_D \). However, when the amplitude of ground motion records is adjusted, the bracketed duration \( D_b \), uniform duration \( D_u \), Arias intensity \( I_A \) and cumulative absolute velocity \( CAV \) will change accordingly.

Chandramohan et al. studied the merits and demerits of different duration metrics for studying the effect of duration on structures. The results show that the significant duration \( D_{s5-75} \) is a more appropriate duration metric for selecting strong ground motions to evaluate the performance of structures. \( D_{s5-75} \) is not affected by the adjustment of amplitude and has a good correlation with the structural response. Therefore, the significant duration \( D_{s5-75} \) was chosen as the duration metric in this paper. Figure 1.(a) shows the time history of ground motion acceleration recorded at the CIGO station of the 2002 Denali earthquake, and Figure 1.(b) shows the standard Arias intensity cumulative curve of the record. The \( D_{s5-75} \) of the record in Figure 1.(a) is 27.67s. The longitudinal coordinate of Figure 1.(b) is the standard Arias intensity, and the calculation equation is as follows:

\[
I_A = \frac{\int_0^t a(t)^2 dt}{\int_0^t a(t)^2 dt}
\]

In equation (1), \( a(t) \) is the acceleration time history of ground motion, and \( t_0 \) is the total time recorded.

At present, there is no definite threshold between long duration and short duration of ground motion. Chandramohan et al. have made statistical analysis on \( D_{s5-75} \) of existing ground motion records. It was found that when the threshold is 25s, the duration effect can be observed in the study and a sufficient number of long duration ground motion records can be selected. In this paper, long duration and short duration ground motions are divided according to this criterion. Four conditions are used to select long duration ground motions: (1) Richter magnitude greater than 7.0; (2) significant duration \( D_{s5-75} > 25s \); (3) peak ground acceleration PGA>0.1g; (4) peak ground velocity PGV>10cm/s.

According to the above conditions, 114 long-duration horizontal ground motion were selected from NGA-West 2 database of the United States, China Seismological Network, K-net and Kik-net of Japan. According to the 114 long-duration ground motion records selected above, 114 short duration records
with $D_{5,75}$ less than 25s were obtained from GA database by spectrally equivalent method. The detailed process of spectrally equivalent method is as follows:

The first step is to calculate the pseudo-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 $L_1, L_2, L_3,..., L_{120}$, with mean $\bar{L}$. Then the pseudo-acceleration response spectrum of each record in the NGA-West 2 database are calculated by using the same periodic points, and 120 corresponding spectral ordinates of response spectra, $S_1, S_2, S_3,..., S_{120}$ with mean $\bar{S}$ are obtained.

Then equation (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, by repeating the procedure, a total of 114 short duration ground motion records matching the response spectrum of long duration ground motion records were obtained.

As shown in Figure 2.(a), the duration of long duration ground motion records is 240s ($D_{5,75}=27.67s$), and the duration of corresponding short-duration ground motion records is less than 50s ($D_{5,75}=4.46s$). After the amplitude modification of ground motion records, the pseudo-acceleration response spectra of the two records are almost same. Therefore, it can be considered that difference between the two ground motion records only exist in duration.

![Figure 2. Time histories and pseudo-acceleration response spectra of long and short duration ground motions](image)

(a) time histories of long and short duration ground motions  
(b) pseudo-acceleration response spectrum of long and short duration ground motions

3. **Ductility demand analysis of SDOF structure**

The yield strength reduction factor $R_y$ of elastic-plastic systems is defined as:

$$R_y = \frac{f_0}{f_y} = \frac{\mu_0}{\mu_y}$$

In the equation (3), $f_0$ and $u_0$ are the maximum values of restoring force and deformation in the corresponding linear elastic system.
Ductility demand of elastic-plastic systems $\mu$ is defined as:

$$\mu = \frac{\mu_m}{\mu_y}$$  \hspace{1cm} (4)

The maximum deformation and yield deformation of elastic-plastic system induced by ground motion are $\mu_m$ and $\mu_y$ in the formula.

Assuming that the strength reduction coefficient $R_y$ is a certain value, the ductility demand $\mu$ of the structure at different periods can be obtained by non-linear time history analysis. A curve with the strength reduction coefficient $R_y$ is a fixed value, the abscissa is period, and the ordinate is ductility demand of the structure can be drawn, which is called equal strength ductility spectrum. By setting different $R_y$ values, a series of equal strength ductility curves with different strength reduction factors can be obtained. During the calculation, the hysteretic material in OpenSees was used to describe the constitutive relationship of the SDOF structure.

In order to quantitatively study the effect of ground motion duration on the ductility demand of structure, the ductility demand $\mu_{L/D}$ of structure subjected to long duration ground motion is standardized based on the ductility demand $\mu_{S/D}$ of structure subjected to corresponding short duration ground motion, and the ductility demand ratio $\mu_{L/D}/\mu_{S/D}$ is obtained. Then the average value of 114 pairs of ground motions is calculated. Finally, the ductility demand ratio spectrum is obtained. The result is shown in Figure 3.

As can be seen from Figure 3, for all periods (except for very few short period), the ratio $\mu_{L/D}/\mu_{S/D}$ is greater than 1. When $R_y = 2$, $\mu_{L/D}/\mu_{S/D}$ increases with the increase of the period $T$. The maximum value of $\mu_{L/D}/\mu_{S/D}$ reaches 2.5 at about $T=1.0s$, and $\mu_{L/D}/\mu_{S/D}$ decreases to about 1.3 with the increase of the period $T$. Among the whole period, most of $\mu_{L/D}/\mu_{S/D}$ are greater than 1.3. When $R_y = 4$, $\mu_{L/D}/\mu_{S/D}$ increases with the increase of the natural vibration period $T$. The maximum value of $\mu_{L/D}/\mu_{S/D}$ is 2.0 when $T=1.5s$. In the period range of 1.5s to 6.0s, $\mu_{L/D}/\mu_{S/D}$ change around 1.7 with the increase of the period $T$. Among the whole period, most of $\mu_{L/D}/\mu_{S/D}$ 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, $\mu_{L/D}/\mu_{S/D}$ change around 1.6 with the increase of the period $T$, and then increases to about 1.7 with the increase of period $T$. Among the whole period, most of $\mu_{L/D}/\mu_{S/D}$ are greater than 1.5. In the period range of 0-3.0s, $\mu_{L/D}/\mu_{S/D}$ at $R_y = 2$ is larger than that at $R_y = 4, 6$ and 8.

4. Conclusion
In this paper, 114 pairs of long and short duration ground motion records were used to analyze the effect of ground motion duration on structural ductility demand. The main conclusions are summarized as follows:

(1) Ground motion duration has a great effect 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) In the short period, the structure with larger yield strength ($R_y=2$) is significantly affected by duration, while in the long period, the structure with smaller yield strength ($R_y=4, 6, 8$) is significantly affected by duration.

(3) The duration should be considered carefully in structural seismic design and input record selection in time history analysis.

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