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The effects of ground motion duration and pinching-degrading behavior on seismic response of SDOF systems

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ABSTRACT

This study tries to highlight the importance of considering the influence of pinching-degrading in cyclic behavior to show the destructive effects of the duration on ductility (μ_m) and hysteretic energy dissipation (E_N) demands for single degree of freedom systems. At first, the effect of duration should be isolated from other ground motion characteristics. At the second step, the aforementioned parameters are calculated for five models, which have periods between 0.05 and 3.0 s and four strength reduction factors for 47 records with long and short durations. The analysis of the results of non-linear response history shows that in pinching-degrading models with short periods, the duration effect not only has a significant influence on the median of E_N but also has substantial effect on μ_m. Moreover, these models are more dangerous under long-duration. Two predictive models are proposed to quantify the effect of duration and finally, they are integrated into Park–Ang damage index to determine the required ductility capacity.

1. Introduction

The most important characteristics of earthquake motions that are really effective on response of the structures are source mechanism, propagation path of waves, local site conditions, frequency content, amplitude and duration [1–4]. These factors are reflections of some special characteristics of earthquake, which are caused by shaking [5]. For instance, amplitude, which is one of the effective parameters on the damage of the structure, represents peak ground acceleration, peak ground velocity and peak ground displacement. This subject is like the frequency content, which can be determined by Fourier spectrum of ground motions. When the dominant frequency gets a value, which is near to the natural frequency of the structure, the probability of structural damage will increase due to amplification phenomenon. This phenomenon often happens in the ground motions with larger amplitude. These two factors (amplitude and frequency content) are applied by means of the idealized seismic design spectrum or response spectrum of used ground motion records to determine seismic demands of structures. The Ground Motion Duration (GMD) is another characteristic that researchers have recently studied its effects on response and damage of the structure [6–8], and its importance has become clear to engineering society. In the following, some of these effects are briefly discussed.

Owing to the significance of GMD on the seismic response of structures, many attempts have been done to evaluate GMD effects on seismic response of structures and considering the importance of this parameter in the evaluation of damage in structures [9,10]. It was found that GMD might be affected in the energy dissipation in structures [11]. The results caused to the conclusion that GMD did not have an important influence on displacement and ductility demand. Hancock and Bommer [12] and Houser [13] concluded that a positive correlation between strong motion duration and structural damage could be seen when damage measures regarding to cumulative energy were employed. Some researchers considered only the peak of structural deformations (e.g., [14,15]), and they commonly found negligible or no correlations between duration and damage. Most of the other investigations [10,16,17] found that duration influenced cumulative damage indices. Some other investigations [18–21] also confirmed the results, which were found, by Houser [13]. Hou and Qu [22] expressed that GMD effects had insignificant impacts on the ductility and hysteretic energy dissipation demands. They had also attempted to isolate the effects of GMD from the other characteristics, such as spectral amplitude and spectral shape. For this aim, they used the spectral equivalent sets for analysis the history response of SDOF systems with Elastic-Perfectly Plastic (EPP) in their cyclic behavior. In order to correctly present the response of structures, a realistic hysteric behavior model should be employed. When the response is beyond the elastic range, Strength and Stiffness Degrading (SSD), which have been studied

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only in some papers, can be seen [23–26]. The influence of GMD on the collapse capacities of a steel frame and a reinforced concrete bridge pier was studied by Raghunandan et al. [17] and Chandramohan et al. [27]. They concluded that the most effective parameter to characterize ground motion duration for structural analysis was significant duration. They also expressed that based on sensitivity analysis, structures with high deformation capacities and rapid rates of cyclic deterioration were very sensitive to duration. The mentioned points and also the results of some other investigations conducted in the recent decades indicated to the necessity of considering the effects of duration on the structural damage and response. On account of the lack of settlement in results of different researches (e.g., [28]), current seismic instructions and regulations such as the alternative performances based on evaluation methodologies (e.g., FEMA [29] and PEER [30]) have not considered the effects of GMD as an effective characteristic explicitly and directly. In this connection, the following results can be mentioned.

Firstly, the past studies did not consider the cyclic deterioration of strength and stiffness in numerical analysis of structures and damage indices. Since the energy releasing from an earthquake in a structure is depended on GMD, considering SSD effects in cyclic behavior which caused the analytical models become sensitive to the number of cycles of motion and shaking due to strong ground motion duration [31]. Secondly, most of the previous researches studied structural responses under the mild nonlinear conditions, and the effects of GMD on structural collapse was considered only in few numbers of studies (e.g., [26]). Finally, some of the different measurement criteria used for describing the duration characteristic were not efficient. This matter was proved by the experiences from studied structures [32]. Moreover, the disagreements for difficulties in isolating the effects of duration from other characteristics like amplitude and frequency content still exits [31,33], e.g., some studies indicates that the response of spectral amplitude and spectral shape can considerably affect the results of different damage levels. However, isolating the effects of duration from other characteristics is not an easy task [32,34].

The aim of this study is to highlight the importance of considering the effects of pinching-degrading in cyclic behavior of structures to show the destructive effects of the GMD on ductility and hysteretic energy dissipation demands. The results of a parametric study to quantify the effects of GMD on a non-linear SDOF systems that is able to consider EPP and different levels of pinching-degrading effects in its cyclic behavior are discussed in this paper. In this research, SDOF systems are expanded to include five hysteretic models. To isolate the duration effects from the other ground motion characteristic effects, at first, spectral equivalent sets of earthquakes with short and long durations are generated. Then, two parameters of ductility and hysteretic energy dissipation demands of the structure are obtained from Non-Linear Response History Analysis (NLRHA) to study the effects of GMD on the response of the structure. After that, the new regression equations are presented to quantify the effects of cyclic behavior of EPP and pinching-degrading and the effects of GMD for the mentioned parameters under two suites, which are short-duration and long-duration motions compatible with a specific target spectrum. The regression equations are used for showing the effects of ductility and dissipation of hysteretic energy demands on required ductility capacity to avoid structural failures in models that pinching-degrading effects are considered. For this purpose, they are integrated into Park–Ang damage index [35] to determine the required ductility capacity. Finally, ductility capacity in different levels of damage is calculated.

2. Measure of GMD

It should be mentioned that the total recording time of an accelerogram is not a scientific measurement criterion of GMD since the total length of the accelerogram may be different. In fact, this item depends on the recording device, and only a part of strong ground motion record may cause nonlinear behavior and finally structural damage. Therefore, before analyzing the effects of duration on the response of the structure, it is necessary to choose a suitable metric to determine the quantity of duration in the accelerogram. More than 30 different definitions of GMD have been presented to measure the duration, which are applicable for different purposes [31,36]. The following definitions are used extensively to classify the ground motions based on the duration character and hazard quantification.

2.1. Bracketed duration method

This method is considered as the simplest definition of duration. In this definition, the time interval between the first and the last time, which ground motion acceleration becomes more than a specific value, is introduced as duration [37,38]. Page et al. [39] considered the acceleration threshold as 5%g to determine the earthquake duration. In this definition, the record shape in the ground motion time intervals is not considered at all. Thus, it is possible that two completely different earthquakes with the same acceleration threshold have equal duration.

2.2. Uniform duration method

This definition considers the general characteristics of an earthquake record. In this definition, duration is the summation of time intervals that acceleration becomes more than a specific value [40]. In 1973, Bolt [38] presented this definition by two threshold values of 5% g and 10% g.

2.3. Significant duration method

The Significant Duration Method (SDM) calculates based on the integral of the ground acceleration square. As seen in Eq. (1), this definition presents a time interval, which includes 90% or 70% of the total energy. (5–95% or 5–75% are common used ranges for the accumulated energy). Trifunac and Brady [41] determined duration based on the difference between maximum and minimum of time (t), which satisfied the Eq. (1):

$$0.05 \le \frac{\frac{\pi}{2g}\int_0^t a^2 dt}{\int_0^{T_{\max}} a^2 dt} \le 0.95 \tag{1}$$

The Arias Intensity (IA) is obtained from Eq. (2):

$$I_A = \frac{\pi}{2g}\int_0^{T_{\max}} a^2 dt \tag{2}$$

where a(t), $T_{\max}$ and g defines ground acceleration time-history, length of earthquake record and ground acceleration respectively [42].

2.4. Effective duration method

The concept of effective duration method is similar to the concept of significant duration method, and the only difference between them is the use of Cumulative Absolute Velocity (CAV) instead of total arias intensity [31]. CAV can be calculated as follows [43]:

$$CAV = \int_0^{T_{\max}} a^2 dt \tag{3}$$

In order to study the liquefaction potential of soil deposits, CAV and IA have been used by geotechnical engineers [42,43]. The noticeable point is that even for one earthquake record, four predefined methods of measuring the earthquake duration may not have the same results. Fig. 1 shows two recorded ground motions with equal PGAs and different durations. Fig. 1(a) and (b) show the time history of the ground motion with short and long-duration of load reversals, respectively. However, as it can be obtained from Fig. 1(c) and (d), in the ground motion with long-duration, energy accumulates over longer time period comparing to the ground motions with short duration. The analysis and