Influence of Strong Motion Duration on Damage Spectra of Pinch Degrading SDOF System in Earthquake Engineering

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Abstract. Ground motion duration can significantly influence the dynamic response and cumulative damage of structures. To investigate the influence of ground motion duration on structures with pinch degradation behavior, this study used the seismic design spectra as the target spectra, and the spectra matching method to obtain 221 spectral-equivalent ground motion records, and used them as the inputs to calculate the damage spectra of the hysteretic model with pinch-degradation behavior for four different strength reduction coefficients. The results of analyzing the damage spectra show that the structural damage of the pinch hysteresis model increases with the increase of duration, and the influence of ground motion duration on structural damage first increases and then decreases with the increase of period.

Keywords: Ground motion duration, Damage index spectrum, Yield strength reduction factor, Earthquake engineering

1 Introduction

The influence of ground motion amplitude and frequency content on structural damage has been extensively studied. However, the influence of ground motion duration on structural damage has not been sufficiently investigated. To better consider the influence of ground motion duration, a lot of researchers have conducted studies on its influence on the dynamic response of structures. Results have shown differences depending on the choice of damage indicators and structural types. While indicators based on peak response show a low correlation with ground motion duration, those based on cumulative damage exhibit a higher correlation. [1].

In addition, the influence of seismic excitation duration is related to the hysteresis behavior of structures. Relevant studies indicate that structures with greater nonlinearity are more susceptible to the effects of seismic excitation duration [1], such as structures experience both stiffness and strength degradation [2]. However, for pinch

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degradation structures, which exhibit higher degrees of nonlinearity, the relationship between structural damage and seismic excitation duration has not been fully investigated. In addition, most related studies use deterministic duration thresholds to classify seismic excitation into short and long durations. However, the definition of duration thresholds is subjective[2][3], and several definitions are currently in use [4]. Furthermore, the methods used to classify short and long durations result in long-duration groups encompassing a wide range of ground motion durations, resulting in discrete research results that are not conducive to estimating the effects of ground motion duration on structures.

To solve this problem and to analyze the influence of ground motion duration on the structural damage of the pinch hysteresis model, this paper calculates and analyzes the damage spectra for different durations with different yield strength reduction factors.

2 Ground Motion Selection

The 5-95% significant duration ($D_{s5\text{-}95}$) [5] is used as the definition of the measure of ground motion duration, which is widely used in studies of the influences of ground motion duration on structural response.

To investigate the influence of ground motion duration on structural damage, this study selects 221 ground motion records with varying durations from the K-NET ground motion database of Japan. The principles for selecting ground motion are as follows:

(1) Moment magnitude of ground motions greater than 5;

(2) The spectral shape of the ground motion record and the target spectrum should be similar, the target spectrum based on the seismic design spectra in the code for seismic design (GB 50011-2010, the site category is Category II.), and the function to control the spectral shape error is shown in equation (1):

$$\Delta San_{\mathrm{RMS}} = \sqrt{\frac{1}{N_{\mathrm{T}}} \sum_{i=1}^{N_P} \left(\frac{Sa_0(T_i)}{Sa_0} - \frac{Sa_{\mathrm{s}}(T_i)}{Sa_{\mathrm{s}}} \right)^2} \tag{1}$$

Where: ΔSan_{RMS} is the normalized spectral acceleration difference, which is used as a measure of the difference between spectral shapes, N_T is the number of taken period points, $S_{a0}(T_i)$ is the acceleration spectral value of the selected record at period T_i, $S_{as}(T_i)$ is the acceleration spectral value of the target spectrum at period T_i, S_{a0} is the peak of the proposed acceleration spectra of the selected record, and Sas is the peak of the acceleration spectra of the target spectrum.

The distribution of ground motion duration for these records is shown in Figure 1(a). Given that ground motion amplitude and spectral characteristics significantly influence structural damage and dynamic response, this paper utilizes the wavelet transform method [6] for secondary processing and matching of the selected ground motion records. The results post-matching and processing are depicted in Figure 1(b), demonstrating that these records reduce differences in amplitude and spectral characteristics significantly.

3 Computation of Damage Spectra

In performing the damage spectrum calculation, the pinching (PH) model was chosen as the hysteresis model for the SDOF system. To characterize the PH model properly, the M1 model from the literature [3] was simulated using the hysteretic material in OpenSees software. Its parameters are selected as shown in Table 1, and its hysteretic curve is shown in Fig. 1(c).

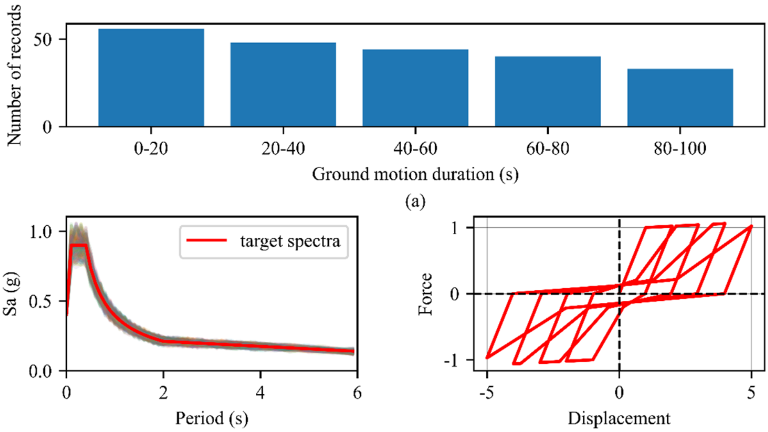
Table 1. Hysteresis model parameters

Pinching factor		D_2(Damage due to energy)	β(Degradation factor for unloading stiffness)
δ	F		
0.7	0.2	0.25	0

The constant-strength spectra [7] are used to calculate and analyze the influence of ground motion duration on the structural damage spectra. The constant-strength spectra are a kind of structural inelastic response spectra, and the seismic response of the structure under different yield strengths is obtained by controlling the yield strength reduction factor, which is defined as shown in Equation (2):

$$R = \frac{F_e}{F_y} \tag{2}$$

Where F_e represents the strength demand of a single-degree-of-freedom system to maintain the elastic response underground motion, and F_y represents the yield strength of a single-degree-of-freedom system. To study the influence of ground motion duration on structural damage under different yield strengths, a total of four different yield strength reduction coefficients, R=2, 3, 4, and 5, are selected for analysis in this paper.



(a)

(b)

(c)

Fig. 1. (a) Ground motion duration distribution, (b) acceleration response spectrum and target spectra, (c) hysteresis curve

The Park-Ang damage index is used here as a damage indicator for analysis. For the single-degree-of-freedom system, the Park-Ang damage index, DI is defined as shown in Equation (3):

$$DI = \frac{\mu - 1}{\mu_{\mathrm{u}} - 1} + \beta \frac{E_H}{F_y \mu_{\mathrm{u}} x_y} \tag{3}$$

Where μ is the ductility demand, μ_u is the corresponding ultimate ductility capacity of the structure under monotonic loading, this paper takes 10 [8], E_H is the hysteretic energy dissipation demands of the structure, x_y is the yield displacement, β is the dimensionless parameter to measure the influence of the structural hysteretic energy dissipation on the structural damage, this paper takes β to be 0.15 [8]. For the different periods of the single-degree-of-freedom system, respectively, after the computation of the damage index spectrum can be obtained.

4 Analysis of Damage Spectra

To quantitatively analyze the influence of ground motion duration on damage spectra under various yield reduction factors, this paper computes the damage spectra using 221 ground motion records as inputs. Four different yield strength reduction factors are considered. The ground motion duration is divided into five groups with intervals of 20 seconds, and each group is evaluated in terms of average damage and duration. The results are presented in Figure 2.

Observing Figure 2(a)(b)(c)(d), it is evident that the structural damage index increases with ground motion duration and decreases with the structural natural period, regardless of the yield strength reduction factor, and the damage spectra spectral values of the different ground motion durations tend to be the same after T>2s, which indicates that ground motion durations have a higher influence on the PH model with periods less than 2s. Furthermore, comparing the four plots of Figure 2(a)(b)(c)(d), it is apparent that the structural damage index increases with the yield strength reduction factor increases.

To study the influence of ground motion duration on structural damage in more depth, this paper computes the ratio of the structural damage index under each ground motion duration group to the index of the group with the shortest duration ($D_{s5\text{-}95}$=0~20s). This ratio, denoted as Ratio(DI) and defined in Equation (4):

$$Ratio(DI) = \frac{DI}{DI_{\mathrm{shortest}}} \tag{4}$$

Where $DI_{shortest}$ is the structural damage index for the shortest duration group ($D_{s5\text{-}95}$=0~20s).

The damage spectra at each yield strength reduction factor are illustrated in Figure 2(e)(f)(g)(h). The influence of the ground motion duration on the damage spectra shows a tendency to increase and then decrease with the increase of the period, according to the calculation. The Ratio(DI) value decreases monotonically with the period after the period is greater than 0.4s, and the slope of the decrease can reach -0.4 at R=2. Comparing Figure 2(e)(f)(g)(h), it becomes evident that the Ratio(DI) decreases with an increase in the yield strength reduction factor. This observation demonstrates that the influence of the yield strength reduction factor (R) on the damage spectra is not independent of the influence of ground motion duration on the damage spectra for the PH model.

5 Regression Analysis

Based on the above analysis, it can be inferred that the association between ground motion duration and damage index spectra can be influenced by the yield strength reduction factor (R). To facilitate the prediction of damage spectra for the PH hysteresis model based on ground motion duration, this study separately conducted regression analyses on the damage spectrum under various yield strength reduction coefficients. Consequently, a prediction formula was proposed, as shown in Equation (5):

$$DI = \left(\frac{a}{T^b} + c\right)\cdot\left(d\cdot T + e + f\cdot D_s\right) \tag{5}$$

(5) Where a, b, c, d, e, and f are the parameters to be fitted and D_s is $D_{s5\text{-}95}$.

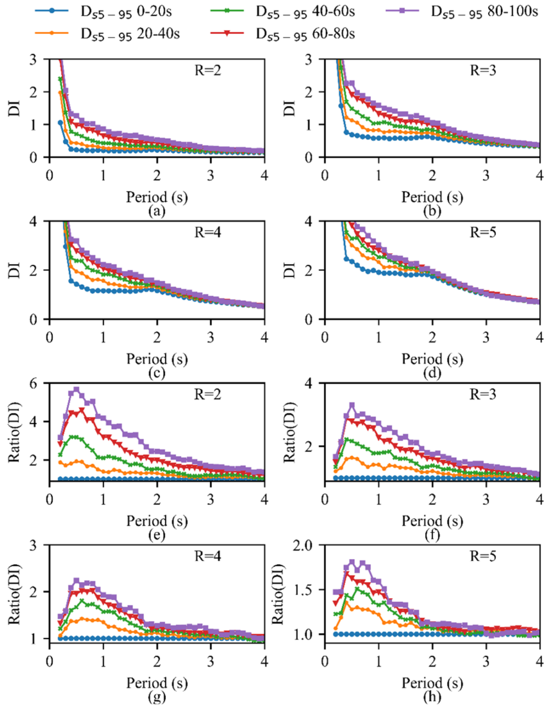


Fig. 2. Damage spectra and damage ratio spectra

The values of the fitted parameters and the goodness-of-fit values are shown in Table 2, and the comparison of the regression values with the actual values is shown in Figure 3. A phenomenon consistent with the previous paper can be observed by looking at the fitting parameters in Table 2: the influence of ground motion duration on the damage spectrum of the PH model gradually decreases with the increase of the yield strength reduction factor, and for the same period, the influence of R=5 ground motion duration is reduced by 80% compared to that of R=2. In addition, to verify the predictive capability of the formula, 20 additional ground motions are selected from the Pacific Earthquake Engineering Research Center (PEER) and the damage spectra are calculated in this paper. The ground motion information is shown in Table 3, and its comparison with the predicted damage spectra is shown in Figure 3. It can be concluded that the prediction formula has a good prediction influence on the damage spectra of the PH hysteresis model.

Table 2. Parameters and goodness of fit values

R	*a*	*b*	*c*	*d*	*e*	f	Goodness of fit
2	0.059	1.456	0.113	-0.473	1.708	0.030	0.983
3	0.110	1.567	0.378	-0.439	1.854	0.016	0.990
4	0.221	1.606	0.966	-0.295	1.285	0.009	0.992
5	0.258	1.668	1.447	-0.326	1.421	0.006	0.988

Table 3. Characteristics of selected ground motions

Earthquake	Number of records	$D_{s5\text{-}95}$ range(s)	M
1995 Kobe Japan	2	56.4~60.1	6.9
1999 Chi-Chi China	5	16.9~32.8	7.62
1979 Imperial Valley-06 The United States	2	25.6~25.9	6.53
1999 Hector Mine The United States	1	26.7	7.13
2004 Niigata Japan	2	9.4~73.5	6.63
2008 Iwate Japan	3	25.2~39.7	6.9
2010 El Mayor-Cucapah The United States	4	24.7~65.8	7.2
Darfield New Zealand	1	27.9	7.0

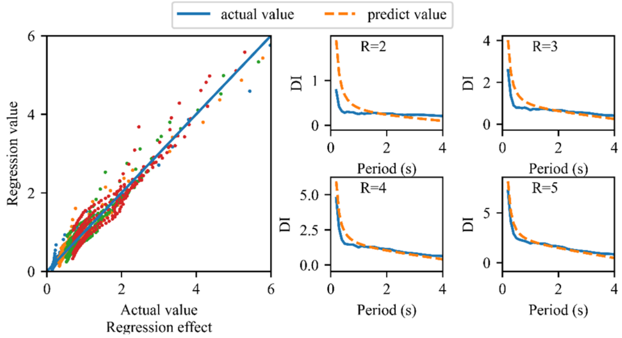


Fig. 3. Regression results and comparison of actual and predicted values

6 Conclusion

In this paper, the effect of ground motion duration on the structural damage of the PH model is investigated using 221 spectrally equivalent ground motion records with different durations as inputs, and the conclusions are as follows:

(1) The damage spectrum of the PH hysteresis model increases with ground motion duration and decreases with the natural period of the structure, and from the spectral shape, the influence of ground motion duration is significantly higher for structures with a natural period of less than 2 s. In addition, the influence of ground motion duration on the damage spectra increases with increasing periods for periods less than 0.4 s and decreases with increasing periods for periods greater than 0.4 s. At R=2, the slope of its decrease with period can reach -0.4.

(2) As the yield strength reduction factor increases, the damage spectrum of the PH model also increases, but the influence of ground motion duration on the damage spectrum decreases, and for the same period, the influence of ground motion duration on the damage spectrum is reduced by 80% at R=5 compared to R=2.

It is worth noting that the conclusions of this paper are based on code design spectra under specific sites, and for ground motion recordings under other site types, the prediction model obtained in this paper may be difficult to achieve good prediction results.

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Reference

1. Otárola K, Gentile R, Sousa L and Galasso C (2023) Influence of ground-motion duration on nonlinear structural performance: Part I: spectrally equivalent records and inelastic single-degree-of-freedom systems. J. Earthquake Spectra, 39(2): 829-859.
2. Chandramohan R, Baker J W and Deierlein G G (2016) Quantifying the influence of ground motion duration on structural collapse capacity using spectrally equivalent records. J. Earthquake Spectra, 32(2): 927-950.
3. Molazadeh M and Saffari H (2018) The influences of ground motion duration and pinching-degrading behavior on seismic response of SDOF systems. J. Soil Dynamics and Earthquake Engineering, 114: 333-347.
4. Wang C, Hao H, Zhang S and Wang G (2020) Influence of ground motion duration on responses of concrete gravity dams. J. Journal of Earthquake Engineering, 24(7): 1156-1180.
5. Otárola K, Gentile R, Sousa L and Galasso C (2023) Accounting for earthquake - induced ground - motion duration in building - portfolio loss assessment. J. Earthquake Engineering & Structural Dynamics, 52(4): 887-909.
6. Al Atik L and Abrahamson N (2010) An improved method for nonstationary spectral matching. J. Earthquake Spectra, 26(3): 601-617.

7. Hao J, Wu G and Wu Z (2013) A study on constant-relative-strength residual deformation ratio spectrum of SDOF system. J. China Civil Engineering Journal, 2013, 46(10): 82-88. (in Chinese)
8. Park Y and Ang A H‐S (1985) Mechanistic seismic damage model for reinforced concrete. J. Journal of Structural Engineering, 111(4): 722-739.