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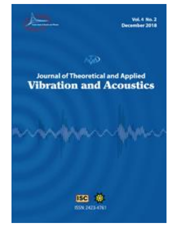

Influences of temporal evolution of ground motion frequency content on developed dynamic ratcheting in SDOF systems

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A B S T R A C T

Dynamic Ratcheting (DR) is a nonlinear dynamic phenomenon occurring in hysteretic damping systems. It means the structural plastic deformation increases asymmetrically in successive cycles under an earthquake excitation. Although it is generally recognized that DR is closely related to the frequency contents of an earthquake excitation applied to the structure, no targeted analysis has been conducted on the influence of time- varying frequency content on occurrence and development of DR. This manuscript aims to analyze the influence of time evolution of DR-inducing ground motion frequency content on developed DR phenomenon in the Single Degree-Of-Freedom (SDOF) system with the Elastic-Perfectly-Plastic (EPP) hysteretic behavior. To survey the influence of time evolution of ground motion frequency content on the developed DR: In the first step, the three DR-inducing ground motion records were selected as excitations input of EPP SDOF systems. In the second step, time-varying frequency of ground motions were changed by shifting their frequency content forward or backward in time using wavelet transform to produce altered versions records. In the final step, the displacement responses of EPP SDOF systems under selected records and their altered versions were compared. By analyzing the displacement response of EPP SDOF systems excited by selected ground motions and their altered versions, it can be found that the time-varying frequency content considerably influences the developed DR behavior in SDOF systems. In the selection of records for dynamic analysis of structures, time-varying frequency content could be further considered as an important characteristic variable for ground motion records.

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1. Introduction

The ground motion is a random variation process with non-stationary intensity and frequency-content characteristics. The effect variation of ground motion frequency content on the variation of the structural response is significant with time. Several investigations have been performed in the study of the time-varying effect of the ground motion frequency content on the structural response. Yeh and Wen[1] examined the effect of the time-varying frequency-intensity content of ground motion on the inelastic response of SDOF systems and a frame structure. The obtained results are demonstrative of this fact that its effect is significant, especially when the predominant frequencies of earthquake excitation are close to the fundamental period of the structure. Conte *et al*. [2] demonstrated that the time-frequency energy distribution of earthquake excitation has significant effects on the nonlinear displacement response of SDOF systems. Consequently, several methods considering spectral non-stationary in earthquake input were proposed, such as Fourier transform [3], Hilbert transform[4], and wavelet transforms[5, 6]. Cao and Friswell [7] examined the implication of the energy concentration of earthquake excitation on the nonlinear response of RC structures. A six-story reinforced concrete moment-resisting frame structure with a natural period of 1.02 seconds was subjected to six ground motion excitations. They employed Wavelet Transform (WT) to characterize the energy content of earthquake excitation in the time and the frequency domains. It was shown that the concentration of energy throughout the duration of earthquake excitation was critical to the response of structures, especially the concentration in time. Li *et al*.[8] investigated the stochastic effects of the time-varying frequency content in the ground motions on the response of the linear elastic models of structural systems. It was found that the time-varying frequency content in earthquake excitation can have significant effects on the stochastic properties of system response. Yaghmaei-Sabegh [9, 10] used wavelet transform to represent the energy input of earthquake ground motions in time and frequency domains and found the amount of input energy and its corresponding frequency contents have a great influence on the level of damage. It indicates that the energy distribution of ground motion has a significant influence on the structural response.
Dynamic Ratcheting (DR) phenomenon was demonstrated for the response of the nonlinear SDOF system with Elastic-Perfectly-Plastic (EPP) hysteretic behavior under earthquake excitation[11]. In hysteretic damping systems, DR is a nonlinear dynamic behavior in which plastic deformation increases asymmetrically in successive cycles.[12-14]. Previous research [12, 13] indicated that DR phenomenon can be observed only when the frequencies of an excitation are in integer ratios (i.e., commensurable) and the product of the terms comprising the ratio is an even number. The nonlinear time history analysis was used alongside Fourier Transform and the spectrogram analysis for DR behavior identification during earthquake excitations. The obtained results of the study clearly demonstrated that the DR-inducing frequencies (active frequencies) play an important role in the induced DR behavior in EPP SDOF systems under earthquake excitation [14]. Recently, a new method was suggested for the identification of active frequencies of DR-inducing ground excitation using WT. The identification method was based on reduced dimensionality and filtered frequency content of DR-inducing ground motion[15].

As it is mentioned, in several previous researches, identification of DR-inducing frequencies and dependency of DR on these frequencies were evaluated. However, the effect of the temporal evolution of DR-inducing frequencies on the developed DR behavior in EPP SDOF systems has not been well addressed; therefore, it is necessary to clarify the influence of the time-varying frequency content of DR-inducing ground motions on the developed DR behavior in SDOF systems. For this purpose, three DR-inducing ground motions were decomposed to several components, using discrete wavelet transform. Then, by shifting the frequency content of these wavelet components to forward or backward in time, altered versions records were produced. Finally, seismic displacement response of EPP SDOF systems under the main records and their altered versions were investigated.

2. Scope

The contents of this paper are arranged as follows: Section 3 presents our used structural model. In Section 4, three DR-inducing ground motion records are selected as the earthquake input of structures. Section 5 presents a brief introduction to the wavelet transform. Section 6 describes the time-shift technique. Section 7 discusses the time-shift technique is applied on the selected records, and Section 8 presents some conclusions.

3. Structural model

Previous semi-analytical and numerical studies demonstrated that elasto-perfectly-plastic (EPP) model can develop DR. in this study, SDOF system with EPP hysteretic behavior and the viscously damped force–deformation relationship is used to investigate the structural response under DR-inducing ground motions excitations. The hysteretic SDOF system is generalized as a function of two variables, the initial fundamental period T and the yield displacement uy. Model an EPP SDOF system with a yield displacement of 10 cm, an initial damping ratio ξ= 5%, and a mass of 1 kg. The increase in the ductility demand of SDOF system is considered to be the effect of DR behavior (i.e. possessing displacement ductility greater than 3).

4. Earthquake excitations

In this study, three earthquake records we selected that exhibit DR behavior as excitations. DR-inducing ground motion records and characterizes SDOF hysteretic damping systems that experience significant DR behavior under these records that are listed in Table 1. Each ground motion was scaled by dividing into its Peak Ground Acceleration (PGA). Figure 1 shows DR behavior in SDOF EPP models induced by these ground excitations. The displacement ductility time history of the SDOF systems shows that the occurrence of DR is confirmed.

Table 1: DR-inducing ground motion records and period of SDOF hysteretic damping systems that experience significant DR behavior.

Earthquake(year)	Magnitude	PGA (g)	Ductility factor	DR duration(sec)	period of SDOF (s)
Ardakul (1997)	Mw 7.1	0.37	6.0	20	0.7
Chin Hills (2008)	Mw 5.4	0.71	4.0	20	1
Kojur-Firoozabad(2004)	Mw 6.4	0.237	4.0	18	0.75

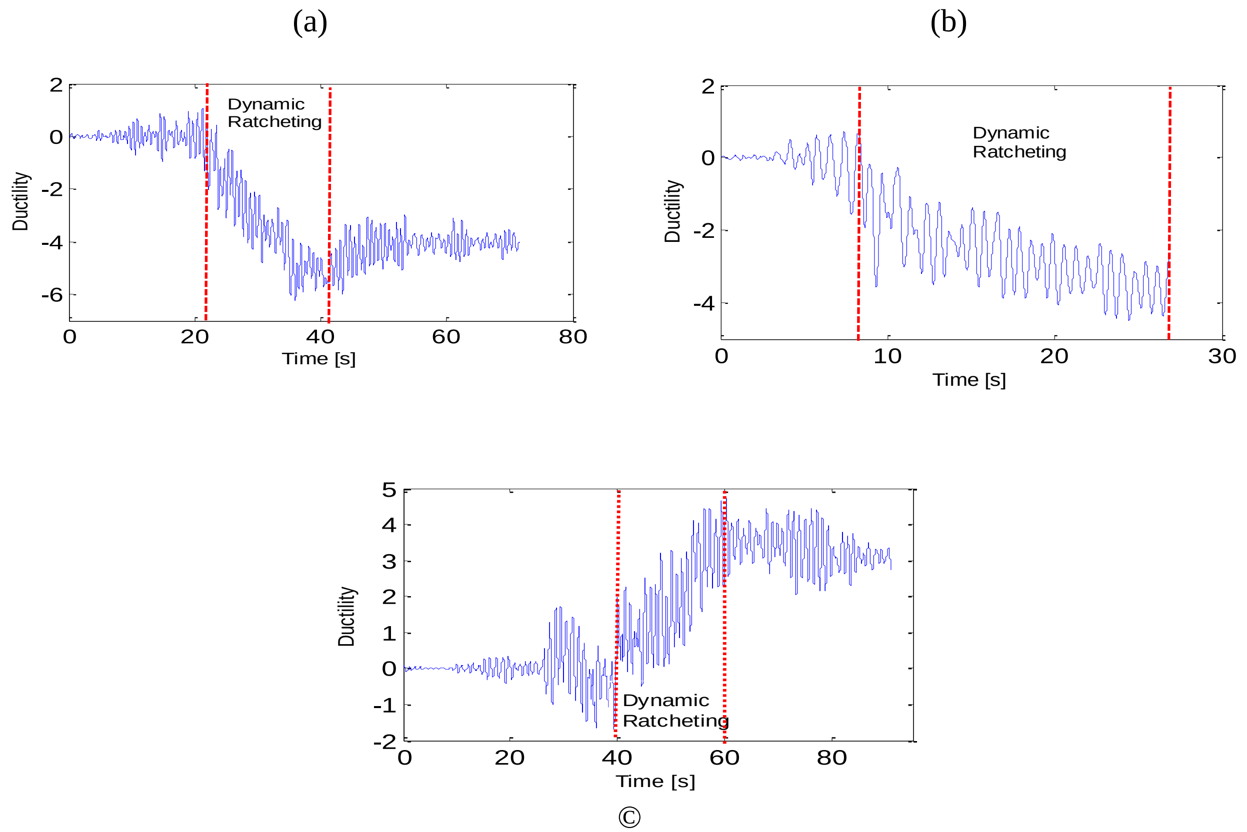


Fig. 1. Dynamic Ratcheting under ground motion (PGA: 1.0 g, U_y: 10 cm): (a) Ardakul Earthquake (5/10/1997) recorded at at Birjand station, (b) Kojur-Firoozabad Earthquake (5/28/2004, 10:42 UTC) recorded at Farashband (c) Chino Hills, CA Earthquake (7/29/2008, 18:42 UTC) recorded at a fire station in Mecca.

5. Wavelet transform

Wavelet transform is used as one of the powerful tools in engineering for studying the ground motions in time and frequency domain [16-18]. The continuous wavelet transform of a signal is defined as follows

$$W_{\psi}(a,b)=\int_{-\infty}^{+\infty}S(t)\psi^{*}\left(\frac{t-b}{a}\right)dt \tag{1}$$

where $W_{\psi}(a,b)$ is the wavelet coefficient, a and b are the scale and translation factor. For analysis of the ground motion, discrete wavelet transform (DWT) is usually attained. DWT is obtained by dyadic values of a and b:

$$a=2^{-j}\ ,\ b=2^{-j}\times k \tag{2}$$

where k and j are integers. The decomposition of the ground motion using DWT is expressed as

$$S(t)=\sum_{j=1}^{n}d_{j}(t)+a_{n}(t) \tag{3}$$

where n is the total number of decomposition levels, and (d_j) the detail components, (a_n) approximate components of the original signal (S). Decomposed procedure can be extended up to a level in which there is no noticeable information remaining in approximate component. At level n, having truncating decomposition, the original signal is able to be reconstructed via the inverse discrete wavelet transform from the details only as follow:

$$S(t) = \sum_{j=1}^{n} d_j(t) \tag{4}$$

where n is the total number of decomposition levels. In this study the basis function of order10 (db10) Daubechies mother wavelet is used for the seismic performance analyses and is orthogonal and there is relatively a small frequency overlapping between adjacent levels[19-21] .

6. Methodology

In previous research, analyses of various DOF systems under different combinations of sinusoidal and earthquake excitations showed the persistence of active frequencies dependence of DR. Additionally, DR depends on characteristics of earthquake excitations. Three main characteristics of earthquake excitations are frequency content, excitation amplitudes, and duration of excitation[22]. The ground motion frequency content is used not only to describe the energy of earthquake record but also to estimate or judge the magnitude of the structural response.

The time-shift technique is a powerful approach to redistribute the energy of a ground motion record in the time utilizing wavelet transform presented by Cao and Friswell [7]. They used this technique to determine the significant effect of the energy concentration of ground acceleration in time on the nonlinear response of reinforced concrete structures. The main purpose of this study is to determine the contribution of time-varying frequency content of DR-inducing earthquake record on DR developing in EPP SDOF model. In this study, the time shift technique is implemented to analyze time-varying frequency content of ground motion. The procedure of this method is summarized as follows:

1. The ground motion is decomposed into component signals with limited frequency band using discrete wavelet transforms (DWT).
2. The nonlinear displacement response of EPP SDOF system under each wavelet component is computed using response history analyses.
3. The contribution of each wavelet component is determined from the total displacement response of EPP SDOF system.
4. Selection of dominant components with the important contribution in development of DR.
5. The time-frequency content of the dominant components is altered by shifting their frequency content in time.
6. The altered record is produced by the superposition of these altered and original components.

7. The displacement ductility time history of EPP SDOF systems under selected records and their altered versions are compared.

The time shift technique does not have a law and is somewhat arbitrary. This technique ensures that the total energy of ground excitation remains unchanged. As the present work is based on wavelet decomposition and the reconstruction of ground excitation, a brief review of WT used in the paper is provided in the next section.

7. Influence of the time evolution of frequency content in selected ground motions on developed DR behavior

7.1 The Chin Hills earthquake record

The registered earthquake record at fire station in Mecca during the 2008 Chino Hills earthquake is selected to illustrate this procedure. Figure 2 presents the displacement ductility time history of EPP SDOF model (with T = 1 sec, u_y = 10 cm) based on the excitation caused by the Chino Hills earthquake, where the displacement ductility is increased by 4 times. The analysis starts with the decomposition procedure of the record using the wavelet analysis in nine components to monitor their evolution in time and frequency. Each component covers a specified frequency content of ground motion. The obtained result of the wavelet analysis and the nonlinear dynamic time history indicate that the frequency ranges of the sixth component (1.56–3.12 Hz band) and the seventh component (0.8–1.56 Hz band) have significant energy, and heavily affect the displacement response of the SDOF system. In fact, the displacement response is dominated by the aforementioned dominant components (the sixth and the seventh components). In a study, it was shown that DR-inducing frequencies exist in the frequency range of dominant wavelet components[15]. Therefore, the frequency bands of these components cover DR-inducing frequencies of ground motion. The time–frequency content of the sixth component is altered to investigate the effect of the time-varying frequency intensity content on developed DR behavior in EPP SDOF models. Figure 2(a) shows the acceleration time history of the original sixth component. The strong motion in the sixth component is concentrated in the middle portions of the record (between 30 and 48 seconds) from the beginning of the record as was the case for the original record. The acceleration of the sixth component in the time window-1 (between 30 and 48 seconds) is moved forward by 12 seconds along the time axis and the acceleration of sixth component in time window-2 (between 60 and 78 seconds) is moved backward by 12 seconds along the time axis to keep the allocation of energy in the frequencies unchanged. Figure 2(b) shows the acceleration time history of the altered the sixth component. The altered record (altered-1) is reconstructed using Equation 4.

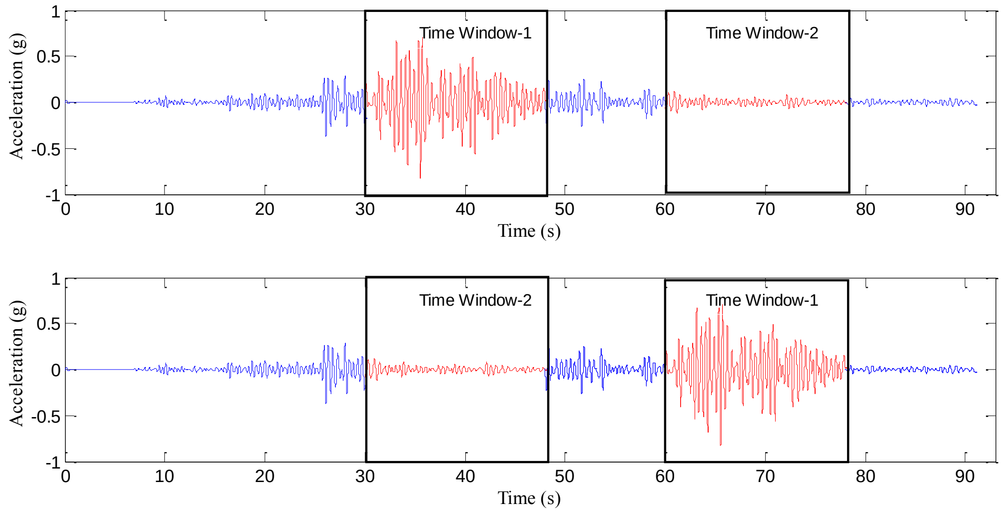
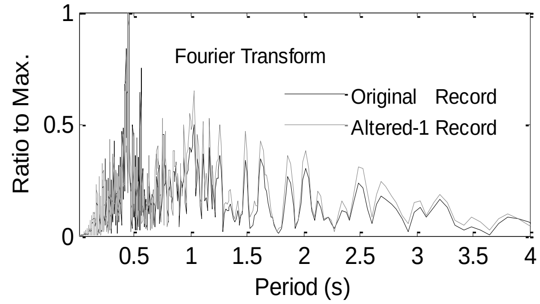
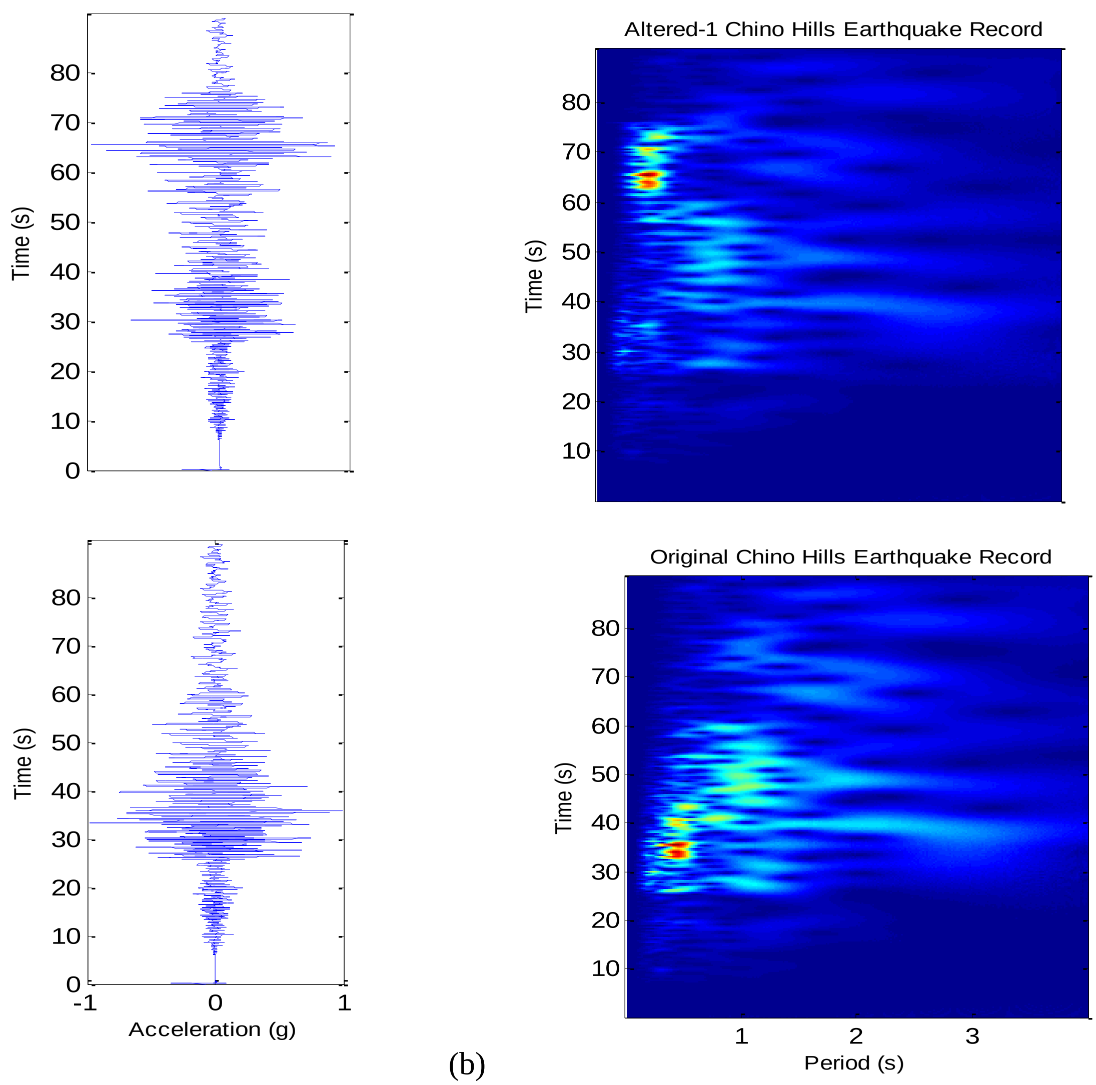


Fig.2 Acceleration time history (a) Original sixth component wavelet (b) Altered sixth component wavelet.

The Figure 3(a) shows the Fourier transform of both original and altered-1 records. The energy distribution in the frequency for the Altered-1 record is almost the same as that of the original record it is hard to distinguish the difference between them. This technique ensures that the total energy of ground excitation remains unchanged. In this article, WT is used to obtain the time–frequency map of the ground motions. Figure 3(b) and Figure 3(c) show the acceleration time history, and the wavelet map of the Chino Hills record and its altered version. The analysis of these two wavelet maps shows that the significant energy of the Chino Hills ground motion is concentrated in the initial portions of the record (between 30 and 48 seconds from the beginning of the record). Furthermore, this analysis explains how the shifts to the late portions of the altered record (between 60 and 78 seconds) occurs. The bulk of energy in the original record as well as the altered version exists at periods around 0.45 sec and this bulk energy is concentrated over a short period of time (approximately less than 4 seconds). The quantification of the effect of time-varying frequency content on developed DR behavior is investigated by comparing the ductility time history caused due to original and altered ground motions. Figure 4 shows the displacement ductility time history of SDOF system (T = 1sec, uy = 10cm) when excited by the altered-1 record; a significant signature of DR in displacement ductility reveals that it is greater than that of the original ground excitation. Nevertheless, the bulk of energy in the shift in time for the altered-1 version, the time occurrence of DR behavior as well as the DR duration in displacement ductility time history response of SDOF system under the altered record are almost the same as those under the original record. It is concluded that the large energy content in the ground motion does not contribute much to DR behavior. It is also evident that the two ground motion records with the same energy have different effects on the structural response.



(a)



(b)

Fig.3 Comparison between (a)) Fourier Transform of the recorded and altered version, and (b) their acceleration time-histories and wavelet map in the case of Chino Hills earthquake recorded at the fire station in Mecca.

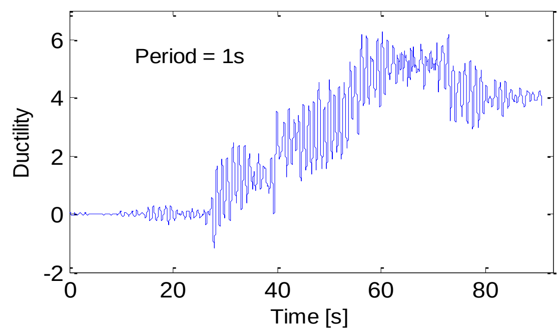


Fig.4 Ductility history of SDOF system with (T=1sec) from time history analysis under altered version (altered-1) of Chino Hills record.

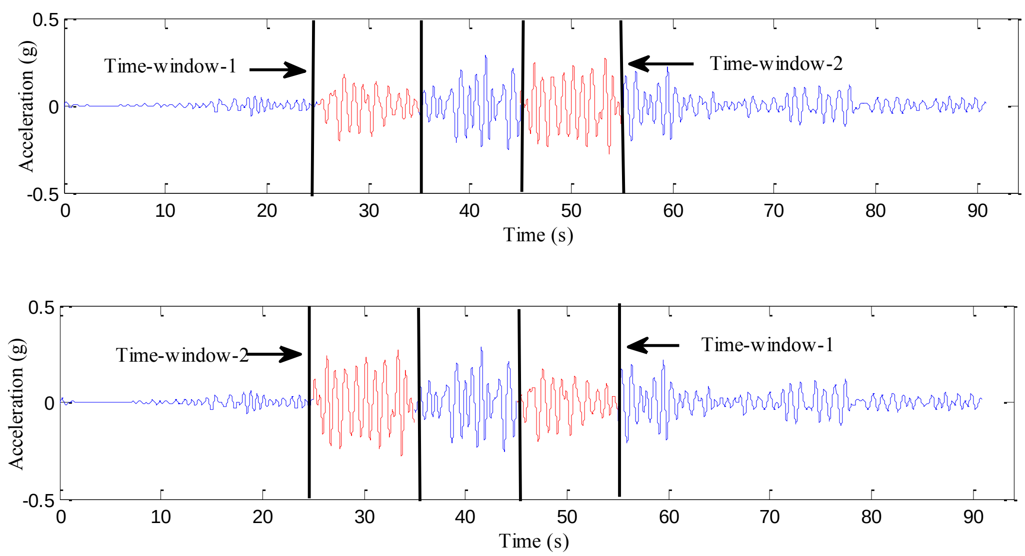
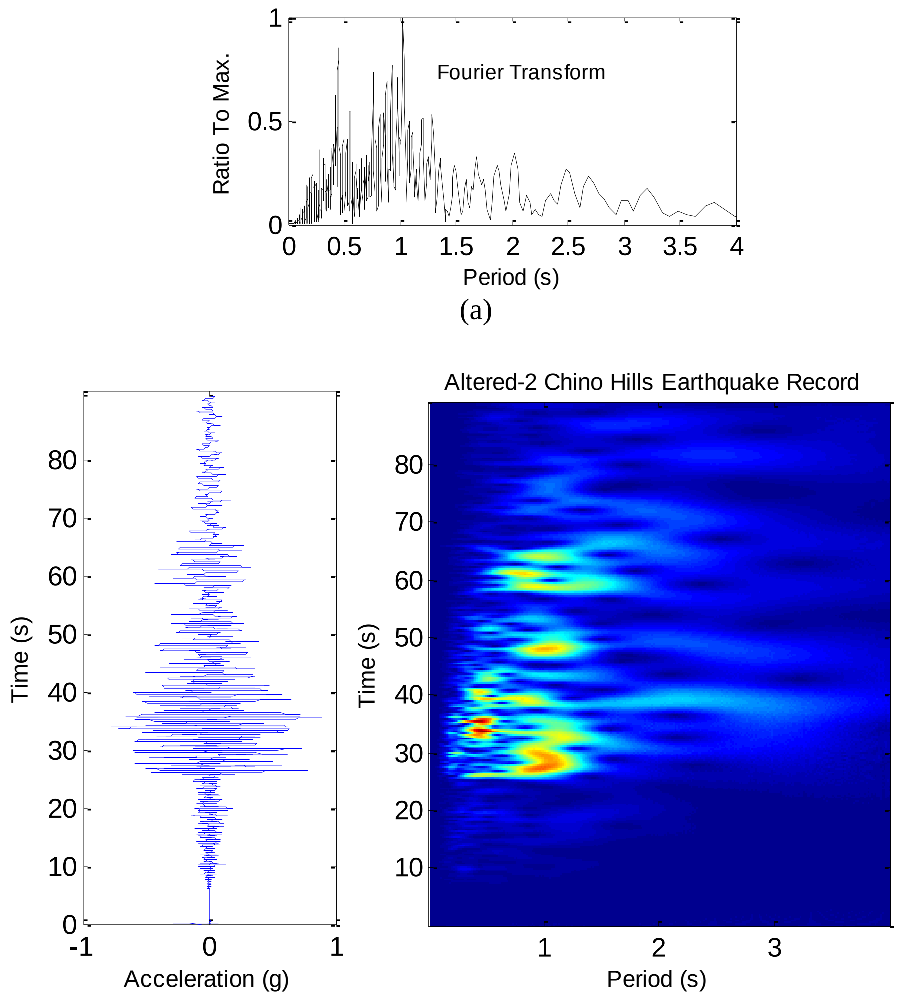


Fig.5 Acceleration time history (a) Original seventh component wavelet (b) Altered seventh component wavelet.

By comparing and considering the difference between the Chino Hills and altered-1 records in developed DR behavior, a second altered record is produced. Now, the seventh component of the original ground motion in the time window around of the strong motion is moved backward by 12 seconds to produce the altered-2 record. Figures 5(a, b) show the original and altered-2 version of acceleration time history of seventh component. Figure 6 shows that the altered-2 record has some of the bulk of the energy at a period of about 1second and this has a significant amplitude for a long period of time. The strong burst of energy of this altered version is concentrated in time with a wide band of periods. Figure 7 shows the displacement ductility time history of SDOF systems with periods (T = 0.9, 1, and 1.15 sec) under the altered-2 record. It can be see that the ductility time history response of SDOF system with the period T = 1 sec is smaller than the original response, and this altered version does not lead to creating DR behavior. Another interesting point is that SDOF systems with periods of 0.9 and 1.15 sec under the altered-2 record experienced significant DR behavior. In addition, in SDOF systems with periods of 0.9 and 1.15 sec, the duration of DR behavior is longer than the original record. It is concluded that the creation of difference between the displacement ductility time history due to the Chino Hills ground motion and its altered version is a result of the change of the temporal localization of DR-inducing frequencies in the altered version records. In other words, the developed and the magnitude of DR behavior in SDOF system depends on the temporal localization of DR-inducing frequencies.



(b)

Fig.6 Time-varying frequency content investigation procedure (altered version of Chino Hills earthquake (altered-2)): (a) Fourier Transform of the altered version, and (b) acceleration and wavelet map of altered record.

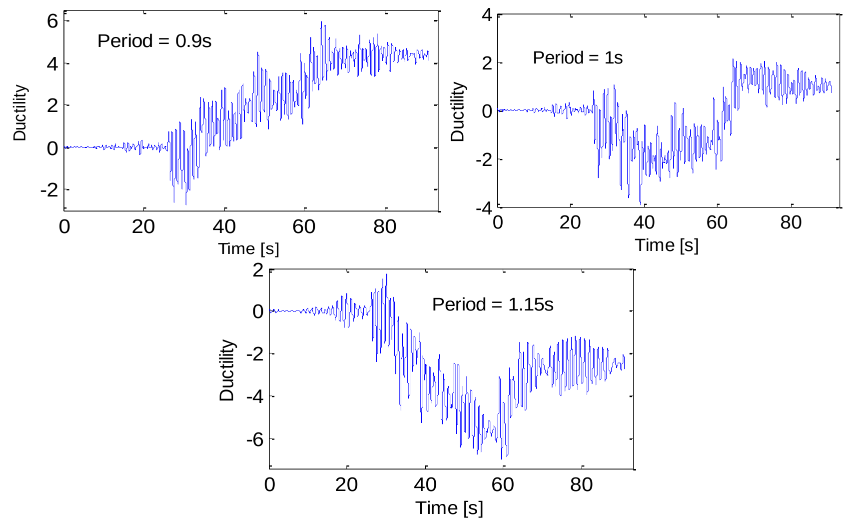
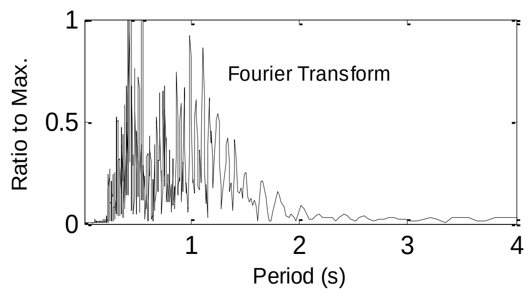
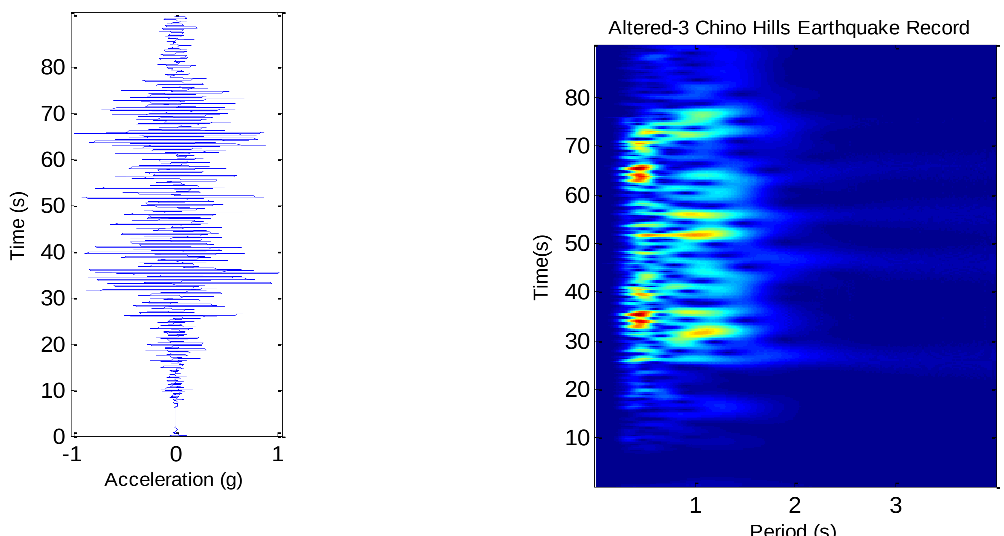


Fig.7 ductility history of SDOF systems with (T=0.9, 1 and 1.15 sec) from time history analysis under altered version (altered-2) of Chino Hills record.



(a)



(b)

Fig.8 Time-varying frequency content investigation procedure (altered version of Chino Hills earthquake (Altered-3)): (a) Fourier Transform of the altered version, and (b) acceleration and wavelet map of altered record

For producing the third altered record, the sixth and the seventh component are moved backward by 12 seconds. The altered-3 record shown in Figure 8 has a high energy at several periods, which have high peaks for a long period of time. The ductility time history of the Altered-3 record in Figure 9 indicates that in SDOF system with the period T = 1sec, potential DR was expected. A maximum effect of DR is seen in Figure 8 for the altered-3 record at SDOF system with a period of T = 1.25 sec, where the displacement ductility is increased by 10 times. After moving the sixth and the seventh components, the time occurrence of DR behavior in the displacement ductility time history of SDOF system with period T = 1.25 sec under the altered-3 record is almost the same as that under the original record. DR duration is longer than that of the original record. Also, it can be seen from Figure 9 that DR phenomenon occurs within 30–70 sec, which is consistent with the time-frequency energy distribution in Figure 8 (b). This phenomenon is due to the fact that the time-varying frequency content in DR-inducingground motion record has a significant effect on developed DR behavior. magnitude DR behavior depends on the temporal localization of DR-inducing frequencies and the dynamic properties of SDOF system. Significant effects of DR behavior are observed for the altered versions with energy concentrated in a narrow period band, but spread out in time (altered-3 record).

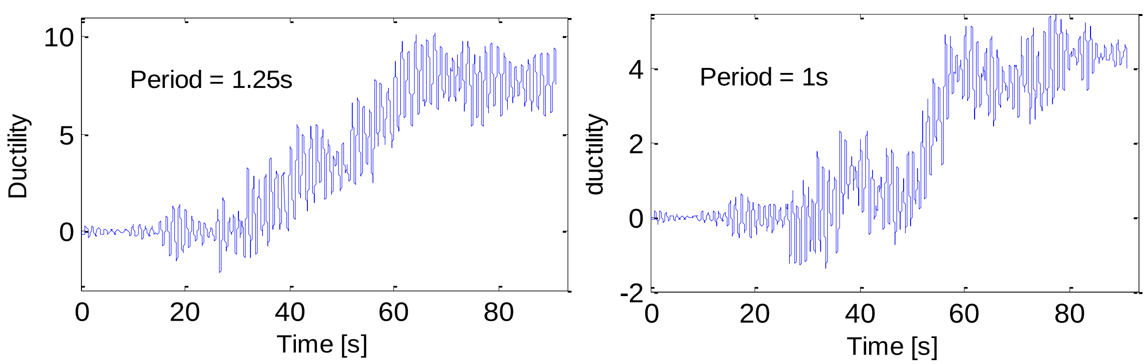


Fig.9 ductility history of SDOF systems with (T=1and 1.25 sec) from time history analysis under altered version (Altered-3) of Chino Hills record.

7.2. The Ardakul earthquake

For Ardakul earthquake excitation at Birjand station, the fifth, the sixth, and the seventh components have a maximum effect on the structural response. The altered versions of Ardakul record are obtained by moving these three components. Two altered records are produced for the Ardakul record. Numerical analyses showed that all the altered version records did not caused DR. Figure 10 shows the displacement ductility history of SDOF systems with period (T = 0.7 sec), under altered versions of the Ardakul earthquake record. Figure 10 depicts two cases where DR occurs under the altered versions of the Ardakul record. The amplitude of DR induced by altered records are larger than that of the original record. It is worth noting that DR occurs in

SDOF systems with same period (T = 0.7 sec). However, it is explained that the temporal localization of DR-inducing frequencies during excitation and the temporal localization of active frequencies have a close relationship with the occurrence and developed of DR behavior.

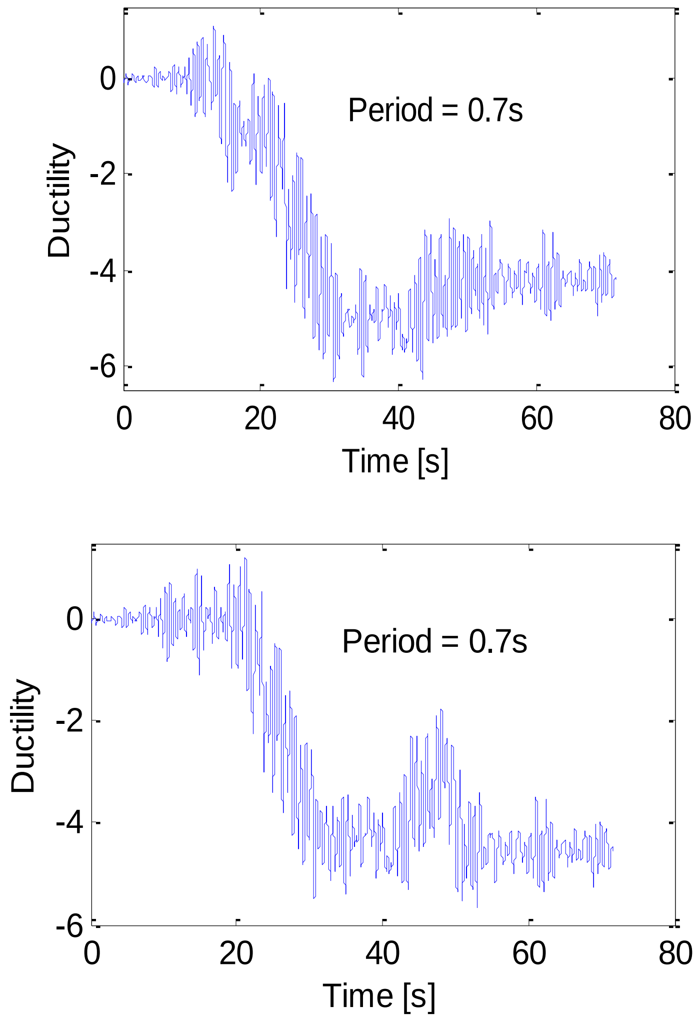


Fig.10 ductility history of SDOF system with (T=0.7 sec) from time history analysis under altered versions of Ardakul record.

7.3. Kojur-Firoozabad record

For Kojur-Firoozabad earthquake excitation at Farashband station, the sixth and the seventh wavelet components have considerable energy from the original record and also have a maximum effect on the structural response. The altered version of Kojur-Firoozabad record are obtained by moving these two components. The displacement response of EPP SDOF systems under the altered version of Kojur-Firoozabad record is Analyzed. Figure 11 shows the displacement ductility history of SDOF system with period T = 0.75 sec, under altered version of Kojur-Firoozabad record. It is known from Figure 11 that DR does not occur. In conclusion, EPP SDOF system shows a very significant DR behavior under Kojur-Firoozabad earthquake excitation but EPP SDOF system does not show DR behavior under altered version of Kojur-Firoozabad record. This indicates that the occurrence of structural dynamic ratcheting is closely to temporal localization of DR-inducing frequencies of ground motion.

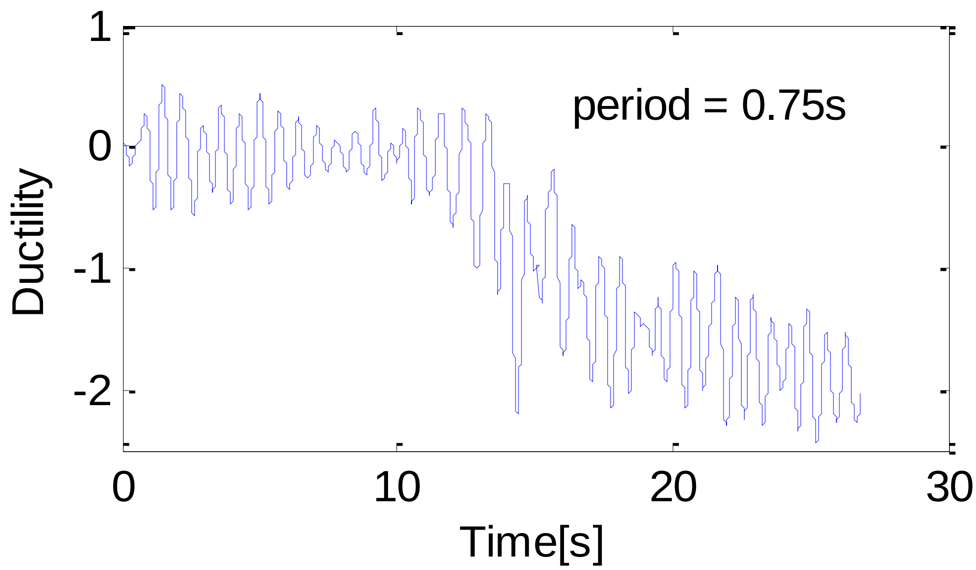


Fig.11 ductility history of SDOF system with (T=0.75 sec) from time history analysis under altered version of Kojur- Firoozabad

8. Conclusions

DR phenomenon increases the plastic deformation of SDOF hysteretic damping system in successive cycles. Although it is generally recognized that DR is closely related to the frequency contents of an earthquake excitation applied to the structure, no targeted analysis has been conducted on the influence of time- varying frequency content on occurrence and development of DR. To achieve this purpose, in this manuscript, the time-shift technique is utilized. The time-shift technique is a powerful approach to change the original record into an altered record in which the total energy of ground excitation remains unchanged. The three ground motion records exhibiting DR behavior were selected as the excitations. The important conclusions of this study are summarized as follows:

1. The wavelet transform can help the analyst decide which earthquake records may be more appropriate for the analyses of a given structure, and help to interpret the results of a nonlinear dynamic analysis.
2. Results of the nonlinear analyses of EPP SDOF systems under original records and their altered versions indicate that, in addition to frequency content, the time-varying

frequency content of DR-inducing ground motion can have significant effects on developed DR behavior. In fact, the magnitude of DR behavior in SDOF systems depends on the temporal localization of active frequency and the dynamic properties of SDOF system.

3. The temporal evolution of ground motion frequency content could be further considered as a characteristic variable for earthquake ground motion, which has a significant effect on the structural response, especially in the nonlinear range.
4. By evaluating the time-varying frequency content of the earthquake ground motions with the wavelet transform, it is possible to anticipate which earthquake ground motion would cause more damage to a structure.

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