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Constant-damage residual ratios of SDOF systems subjected to pulse type ground motions

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ABSTRACT: Residual displacement is an important index to quantify post-earthquake structural performance, as it provides information about the structure reparability and its structural performance during aftershocks. This manuscript presents the results of a statistical study into residual ratio, i.e. the ratio of the residual displacement to the maximum inelastic displacement, for single degree of freedom (SDOF) systems with constant damage performance under 71 near-source pulse type ground motions. The effects of seismic and modeling parameters such as the peak ground acceleration to peak ground velocity ratios (AP/VP), hysteretic model, ultimate ductility capacity and strain hardening ratio on residual ratios are also evaluated. The results indicate that the residual ratios in the whole range of periods are strongly dependent on the damage index, DI, and mean residual ratios increase with the increase of damage index, DI. The findings clarify that the residual ratios are significantly influenced by the AP/VP. Additionally, they show that the hysteretic model of SDOF systems and strain hardening ratio have more obvious effects on the residual ratios than the ultimate ductility capacity.

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1. INTRODUCTION

Most structures designed based on the current seismic design code will encounter residual displacement at the end of earthquake excitation. Residual displacement is very unfavorable due to repairing and renovation problems after occurring earthquake. The consequences of the past ground motions represent the fact that residual displacement plays an important role in seismic performance definition and underhung economic damage due to earthquake. Since structures need to be destroyed due to extra rated residual displacements even though they do not encounter heavily constructive damage [1-3]. Numerous researches were conducted to estimate the residual displacement demand of structures based on the Single-Degree-of-Freedom (SDOF) systems with constant ductility performance [4-8] or the SDOF systems with constant strength performance subjected to earthquake ground motions [9-16]. Mahin and Bertero [6] conducted the first study considering the relationship between residual displacement and maximum inelastic displacement of SDOF systems with elasto-plastic (EP) behavior. It has been noticed that the residual displacements have a high percentage of the maximum inelastic displacements reached. Christopoulos and Pampanin (2004) investigated the influence of hysteretic behavior on the residual displacement spectra of constant-ductility EP SDOF systems subjected to 20 earthquake records [7]. Ruiz-Garcia and Miranda (2005) as well as Ruiz-Garcia and Miranda (2006) conducted a comprehensive statistical study into residual displacement demands of structures located on firm and soft soil site condition. They proposed two equations to estimate residual displacement demands of SDOF systems: residual displacement ratio, C_r, (residual to maximum elastic displacement) and residual ratio,γ , (residual to maximum inelastic displacement) [9,10]. One study into constant ductility residual displacement ratios C_r demonstrated that the significant duration of ground motions had significant influence on C_r [13]. In one recent study, Guerrero et al. (2017) and Ruiz-García and Guerrero (2017) conducted a comprehensive statistical study into residual ratios, γ, of SDOF systems on soft soil sites of Mexico City. The conventional and dual SDOF systems were applied in their study [14, 15]. Moreover, Guerrero et al. (2017) thoroughly evaluated variation of C_r with the lateral strength ratio, ductility, strain hardening ratio, and type of hysteretic response of the primary and secondary parts of dual SDOF oscillators [14].

The record strong motions in near fault areas contain large amplitude and long period pulses in their velocity time history being able to create larger residual displacements [11]. They considered that the Cr of SDOF systems under to pulse type motions were sensitive to post-yield stiffness ratios as well as the ratio of SDOF system period to velocity pulse period of ground motion. More recently, Liossatou and Fardis (2015) as well as Liossatou and Fardis (2016) examined the effect of near-fault ground motions with distinct velocity pulses or fling step displacements on the C_r and the

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γ of constant strength SDOF systems with various hysteretic typical reinforced concrete (RC) structures [17, 18]. Liossatou and Fardis (2015) concluded that a velocity pulse increased maximum inelastic displacements and residual displacements approximately in proportion. The residual displacement measurement is sensitive to force reduction factor R and type of hysteresis model. Increasing C_r leads to increase of R value, particularly for lateral strength ratio, R between 3 and 5. It was also obtained that γ was almost independent on pulse period. One of the more appropriate methods to evaluate structural performance is applying the damage index. These indexes are proper bases for seismic structures performance during an earthquake excitation. The damage indexes are involved in the function of structural ductility, hysteretic energy dissipation, amplitude, time and number of loading cycles. The SDOF systems with constant damage performance are used to evaluate the potential damage of various earthquake ground motions. The constant damage performance is the response of the SDOF system in a certain damage index when a certain earthquake ground motion is applied.

Based on the above discussions, few detailed researches have focused on evaluating the residual displacement demand of SDOF systems subjected to near-fault ground motions. These studies are only limited to the response of SDOF systems with constant-ductility or constant strength performance under to near-fault ground motions. This manuscript studies the constant damage residual ratios of SDOF systems under 71 pulse type ground motions. The modified Park–Ang damage index [19] is selected to estimate the damage performance of structures. Residual ratio is obtained through the response of SDOF systems with 4 levels of damage index and two types of hysteretic behavior (EPP and Takeda) subjected to 71- pulse type records. The effects of A_P/V_P ratio, ultimate ductility capacity, the strain hardening ratios and hysteretic behavior on the residual ratio are studied statistically.

2. MEASURES OF RESIDUAL DISPLACEMENTS

The most extensive study of residual displacements to date seems to be the study conducted by Ruiz-Garcia and Miranda [9-10]. They proposed two equations to estimate residual displacement demands of SDOF systems: a) A direct method using residual displacement ratios, Cr, allowing estimation of residual displacement demands of SDOF systems with constant strength performance from maximum elastic displacement; and b) An indirect method taken as the ratio of residual displacement to the maximum inelastic displacement of a SDOF system with constant strength performance, γ, subjected to earthquake excitation. Liossatou and Fardis (2016) showed that the residual ratio, γ , was a suitable middling step to predict residual displacement demand [18]. In this paper, the residual ratio,γ , is presented as the ratio of residual displacement to the maximum inelastic displacement of a SDOF system with constant damage performance for the certain damage index level:

$$\gamma_{DI} = \left| \frac{x_r}{x_m} \right| \tag{1}$$

Where x_r denotes the residual displacement and x_m is the maximum inelastic displacement of SDOF system to a specified damage level *DI* for a given ductility capacity μ_u. The parameter DI, modified Park–Ang damage index coefficient [19] is selected to assess the damage of structures. It is defined as:

$$DI = \frac{\mu_m - 1}{\mu_u - 1} + \beta \frac{E_h}{F_y \mu_u x_y} \tag{2}$$

Considering DI as the damage index, μ_m is ductility factor when the structure reaches the maximum elastic-plastic deformation under earthquake ground motion, μ_u is the ductility capacity when the structure fails under monotonic loading , F_y is yield strength, x_y is yield displacement , E_h is cumulative hysteretic energy dissipation under earthquake ground motion, β is a positive dimensionless parameter to scale the effect of hysteretic energy dissipation on the final damage of structure. Obtained by a regression curve from about 260 experimental results, the coefficient ranged between about –0.3 to + 1.2, with a median of about 0.15, was reported by Park and Ang [20]. Referring to the investigations [21, 22], (i.e. β=0.15) is used in this manuscript. In this investigation, constant damage residual ratios, γ_{DI} , are computed for inelastic SDOF systems with a set of 30 fundamental periods of vibration between 0.1 and 3.0 s with an interval of 0.1 s and damping ratio is defined ξ=0.05. Four damage indices *DI* = 0.1, 0.3, 0.5 and 0.8 are selected to consider the different damage performance. The value ranges of damage index are minor damage, moderate damage, severe damage and collapsed Respectively. Referring to the investigations s [22, 23], to consider structures with various ultimate ductility capacity three levels of ultimate ductility capacities, μ_u had been used in this study (μ_u = 6, 10 and 14). Fig.1 describes the major steps to calculate γ_{DI} for the pulse type ground motion.

3. PULSE-LIKE GROUND MOTIONS DATA

At the first time, Baker (2007) proposed a quantitative classification procedure of pulse-like ground motions, and 91 ground motions with large-velocity pulses in the fault-normal component of records were selected from the ground motions in the Next Generation Attenuation (NGA) project ground motion library [24]. In this study, 71 pulse type ground motions are selected from those proposed by Baker (2007).

4. STRUCTURAL MODEL

Two different hysteretic models are used in this paper a) bilinear; b) Takeda. The bilinear hysteresis model is used in this study to represent structures without stiffness and strength degradation; therefore, its response serves as a baseline. Only three parameters are needed to characterize bilinear model, the initial stiffness (k), yielding strength (F_y) and strain-hardening ratio (α). The Takeda model [25] is used in this study to describe the behavior of reinforced concrete structures. Fig. 2. displays typical loop shapes generated by these hysteretic models. This paper examines residual

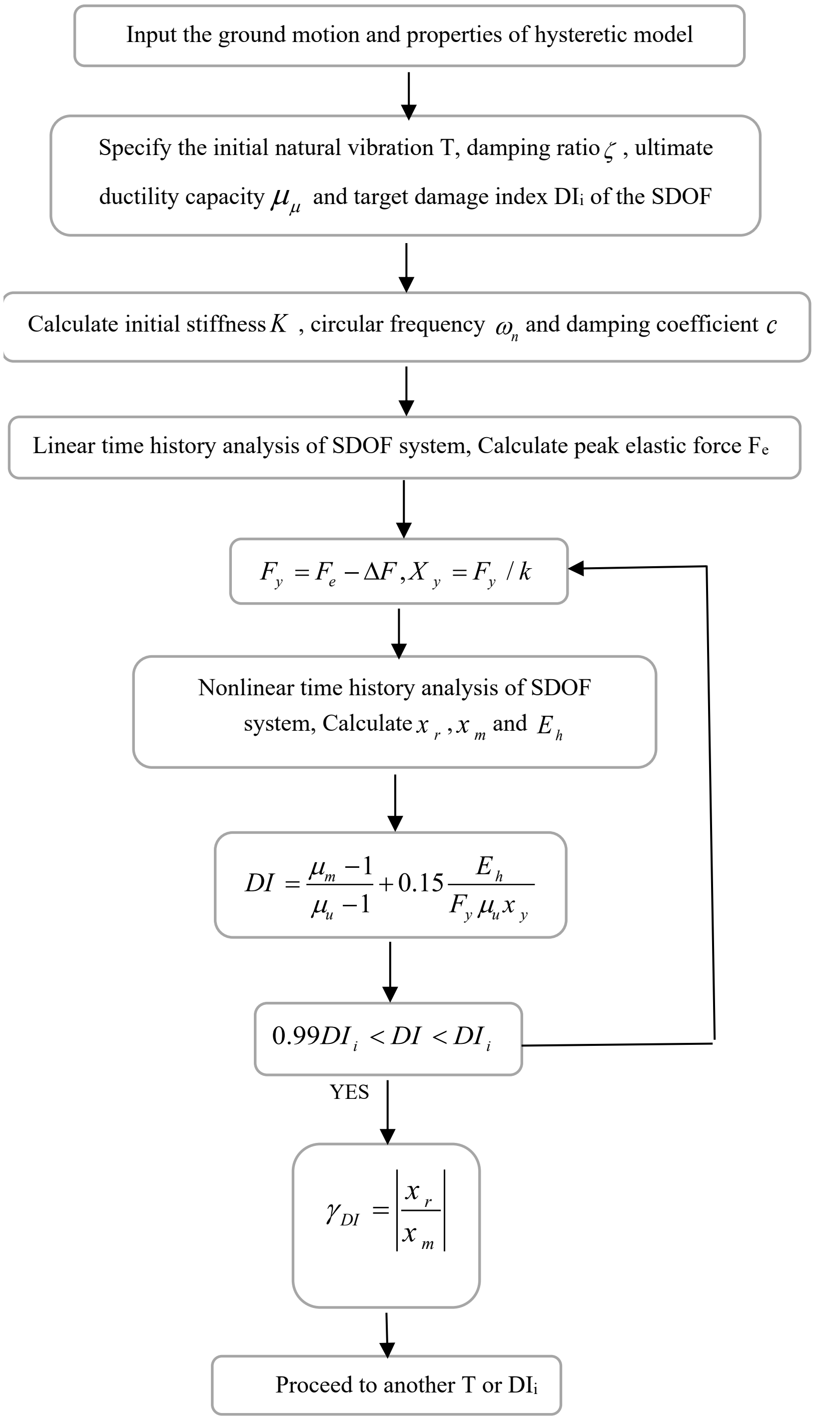

Fig. 1. Detail of analysis procedure to calculate the residual ratio, γ_{DI}.

displacement ratios of constant damage SDOF systems with linear hardening under pulse like ground motions. The equation of motion of these systems is given by

$$m\ddot{u} + c\dot{u} + ku = -m\ddot{u}_g \tag{3}$$

Where m is the mass, u the relative displacement, c the viscous damping coefficient, k the stiffness, $\ddot{u}_g$ the acceleration of the ground motion and upper dots stand for time derivatives. The peak force response of a linear elastic system can be denoted by f_e, while the yield strength of a nonlinear elasto-plastic system can be denoted by f_y. Strain hardening takes place after yielding initiates. For a defined inelastic stiffness, i.e. the slope $k_p = \alpha k_i$ of the second branch of the skeleton force–displacement relationship (see Fig. 2), the post-yield stiffness ratio, α, can be defined as:

$$\alpha = \frac{k_p}{k_i} \tag{4}$$

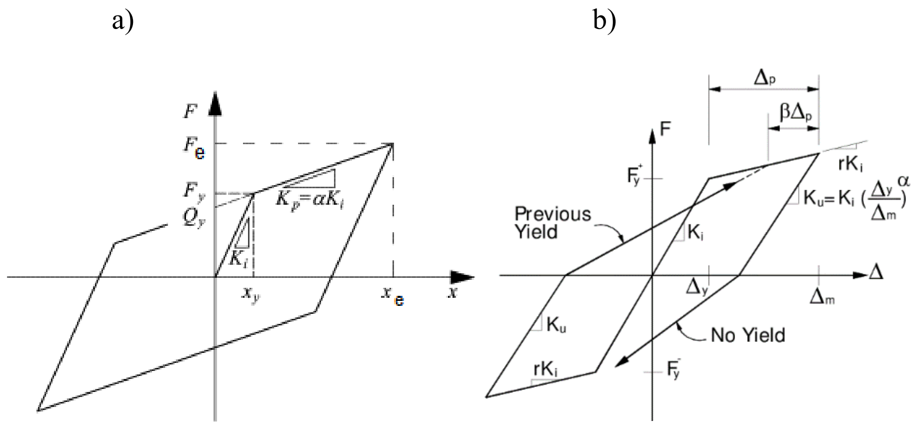

Fig. 2. Hysteretic models considered in this study: (a) bilinear behavior; (b) Takeda behavior

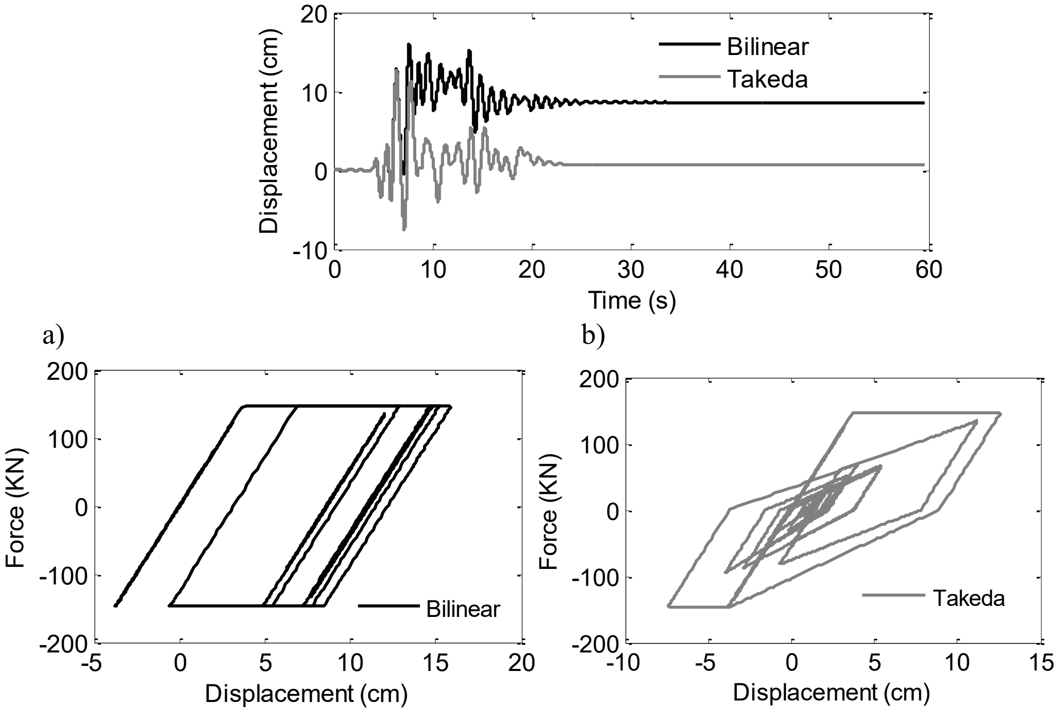

Fig. 3. Displacement time history and SDOF system hysteretic response with T = 1s and damage index DI=0.5 to the Los Gatos-Lexington Dam record (Loma Prieta1989) for the two models (a) EPP system (b)Takeda system.

In this study, γ_{DI} values are computed using the response of SDOF systems with typical viscous damping ratios of 5%. For sample, Fig. 3 shows the displacement time history and hysteretic response of SDOF system with (T=1 s) and (DI=0.5) subjected to the Los Gatos-Lexington Dam record earthquake (Loma Prieta,1989). It is noted that an accurate evaluation of residual displacement cannot be obtained through simple reading of the last value of displacement unless a few seconds of trailing zeros-acceleration are manually added at the end of each record.

5. EVALUATION OF MEAN RESIDUAL RATIOS

In the past studies, the residual ratio displacement has been introduced as the most important parameter in evaluating the capacity of damaged structures for tolerance of future predictive earthquakes and strong aftershocks. Therefore, a majority of researchers agrees that approximation of residual displacement ratios can play an important role in structural performance evaluation. This study presents an evaluation of residual ratio, γ_{DI} for SDOF systems with constant damage performance subjected pulse type ground motions. This study is significant since the results can be used to evaluate residual displacement demand of structures with constant damage performance subjected to pulse type ground motions. A total of 87,480 residual ratios, γ_{DI} of the SDOF system are computed for two hysteretic models, 30 fundamental periods, 4 levels

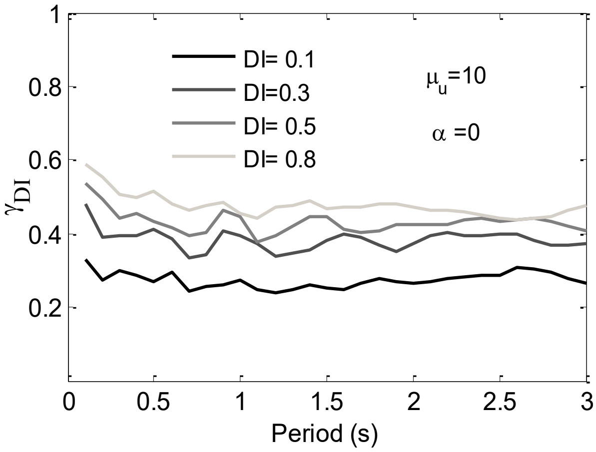

Fig. 4. The mean residual ratios γ_{DI} of EPP SDOF system for four given damages index values *DI* for 71 pulse type ground motions.

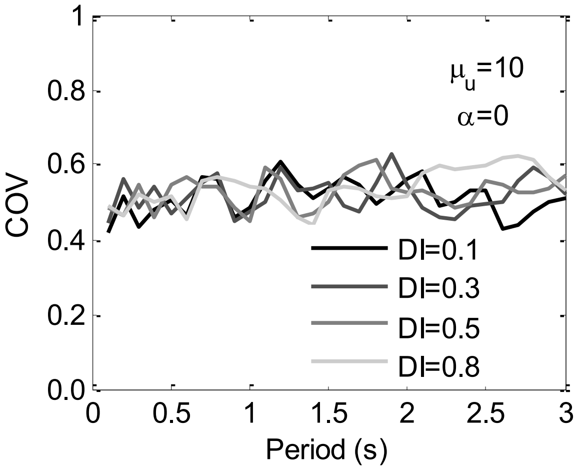

Fig.5. COVs of the residual ratio γ_{DI} of EPP SDOF system for four given damages index values *DI* for 71 pulse type ground motions.

of damage index, 3 levels of ultimate ductility capacities and 3 levels of the strain hardening ratios when subjected to 71 pulse type ground motions. Fig. 4 presents the mean residual ratio, γ_{DI} of Elastic-Perfectly-Plastic (EPP) SDOF system with μ_u = 10 for all pulse type ground motions. For the periods smaller than 0.4 s, the mean γ_{DI} has strong dependence on the period and decreases as the period increases. When the period is >1.0 s, the mean γ_{DI} region has weaker dependence on the period. The results in Fig. 4 indicate that residual ratio, γ_{DI} in the whole period region is strongly dependent on the damage index, DI and mean γ_{DI} increases with the increase of damage index values. The significant and considerable point about residual ratio, γ_{DI} is that only few differences appear when the value of damage index changes from DI=0.3 to DI= 0.5, but differences are more pronounced when going from DI = 0.1 to DI=0.3. Fig. 5 presents the COVs of γ_{DI} for EPP SDOF system and 71 pulse type ground motions. In the whole period region, variations of period do not lead to create significant changes in COVs; therefore, they are almost period independent.

6. EFFECTS OF A_p/V_p RATIO

The structural damage has a direct relationship with important parameters of the ground motion such as frequency content, significant duration, and amplitude. The peak ground velocity (V_p) and peak ground acceleration (A_p) are important parameters for near-field area having significant effect on the structural response [26-29]. The best indicator of ground motion frequency content is the A_p/V_p ratio [30]. Recently, there has been a renovated interest in the effects of A_p/V_p ratio on the variation of inelastic displacement ratio and several studies [31, 32] demonstrated that Ap/Vp parameter could have considerable influence on the inelastic displacement ratio of structures. In this section, according to Ref. [31], the selected pulse type ground motions are fallen into three categories based on the Ap/Vp ratios, that is, low Ap/Vp ratios (A_p/V_p < 5 Hz), intermediate A_p/V_p ratios (5 Hz < A_p/V_p < 8 Hz), and high A_p/V_p ratios (A_p/V_p > 8 Hz). Fig. 6 shows the ratios of mean residual ratio, γ_{DI} in each A_p/V_p ratio range to the mean γ_{DI} of 71 pulse type ground motions for EPP system with μ_u = 10 and four given damage index values (*DI*= 0.1, 0.3,

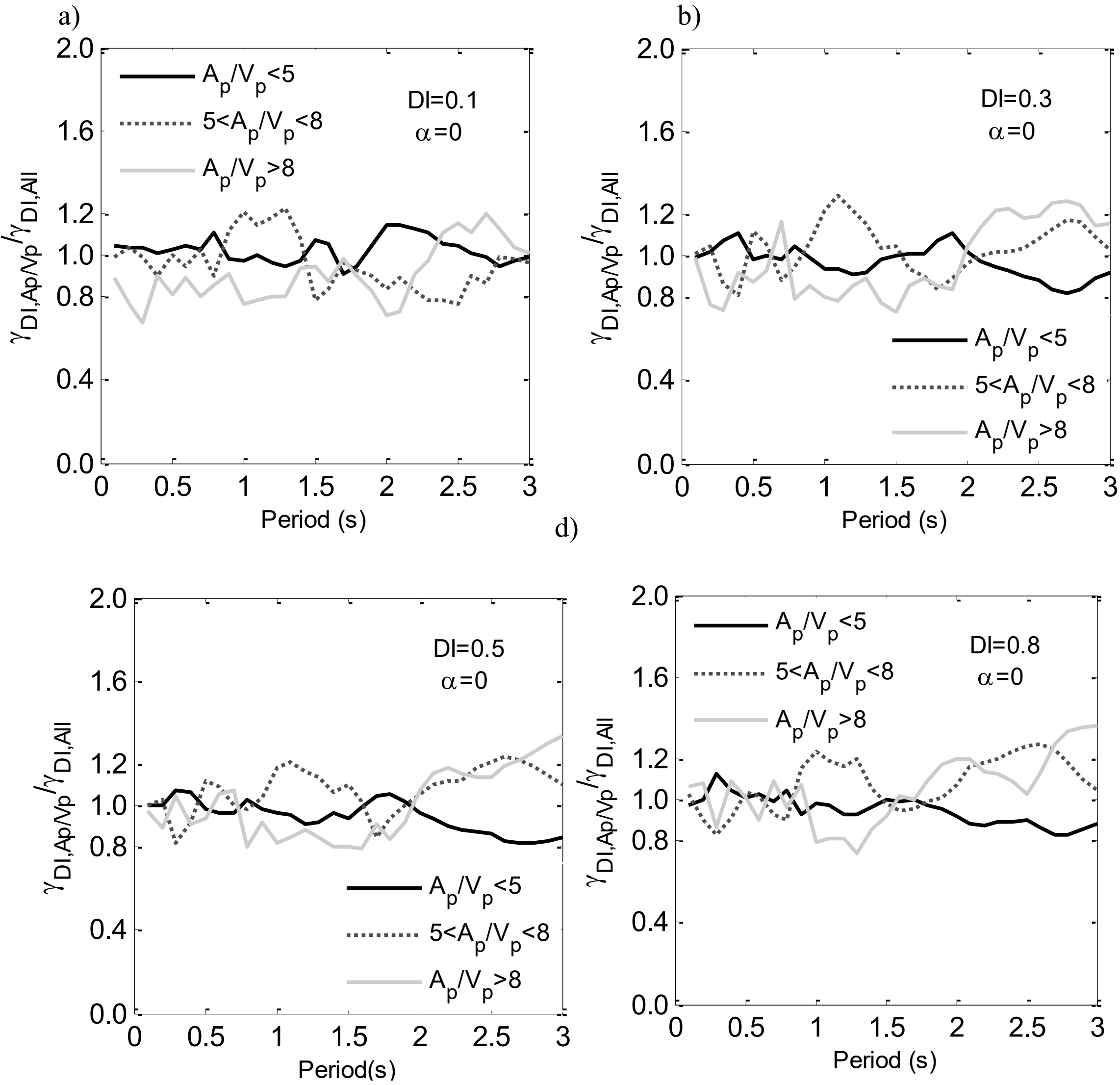

Fig. 6. The ratios of residual ratios, γ_{DI} in each A_p/V_p ratio range to the mean residual ratios, γ_{DI} of 71 near-fault pulse type ground motions of EPP system when μ_u = 10 and four different damage index values: (a) *DI*= 0.1; (b) *DI* = 0.3; (c) *DI* = 0.5; (d) *DI* = 0.8.

0.5, 0.8). As Fig. 6 shows, the differences among the residual ratios ($\gamma_{DI,\ Ap/Vp}/\gamma_{DI,All}$) for the different A_p/V_p ratio ranges in Fig. 6d are larger than those in Fig. 6a. This phenomenon means that the influence of A_p/V_p ratios on the residual ratio, γ_{DI} is more obvious when the damage index values increase. Results show that in high damage index values (e.g. DI = 0.5 and 0.8), the residual ratios, γ_{DI} have high sensitivity to changes of of A_p/V_p ratios in a long period region. In addition, variation of A_p/V_p ratios are more effective than the variation of damage index values on the residual ratios, γ_{DI}.

7. EFFECT OF ULTIMATE DUCTILITY CAPACITY

To study ultimate ductility capacity influence on residual ratios γ_{DI}, two levels (6 and 14) of ultimate ductility capacities are selected to compare the effect. For the convenience of comparison, the ratio between the γ_{DI} spectra of EPP SDOF system with different ultimate ductility capacity and the γ_{DI} spectra of EPP SDOF system with μ_u = 10 are calculated in each damage index, DI, and the results are shown in Fig. 7. In Fig. 7, it can be noticed that the mean ratios of γ_{DI} do not depend on period of vibration for all damage index, DI values. It can also be observed that the mean residual ratios ($\gamma_{DI}\ \mu_u$=6/ $\gamma_{DI}\ \mu_u$=10) in Fig. 7a are smaller than 1.0 within the range of [0.7 1], while the mean residual ratios ($\gamma_{DI}\ \mu_u$=14/ $\gamma_{DI}\ \mu_u$=10) in Fig. 7b are greater than 1.0 and they are within the interval [1 1.2]. From the figures, it can be seen that the effect ultimate ductility capacity is moderate. It should be noted that the mean residual ratios in Fig. 7a increase with the increase of damage index, DI, while the mean residual ratios in Fig. 7b decrease by increase of damage index, DI. This phenomenon means that the residual ratios, γ_{DI} increase as the ultimate ductility capacity increases. However, the influence of ultimate ductility capacity on the γ_{DI} is beyond 25%, when the damage index is small (e.g. DI = 0.1).

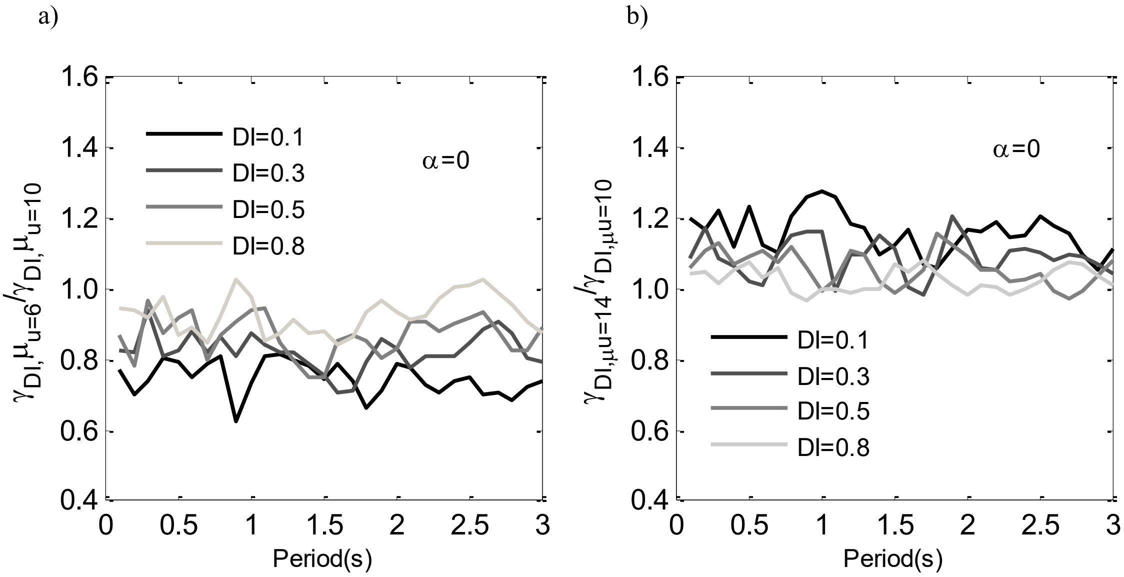

Fig.7. The mean ratios of residual ratios, γ_{DI} of EPP systems with ultimate ductility capacity μ_u=10 to the residual ratios, γ_{DI} of EPP systems with ultimate ductility capacities (a) μ_u=6; (b) μ_u=14 to under 71 near-fault pulse type ground motions, for four given damage index, DI values.

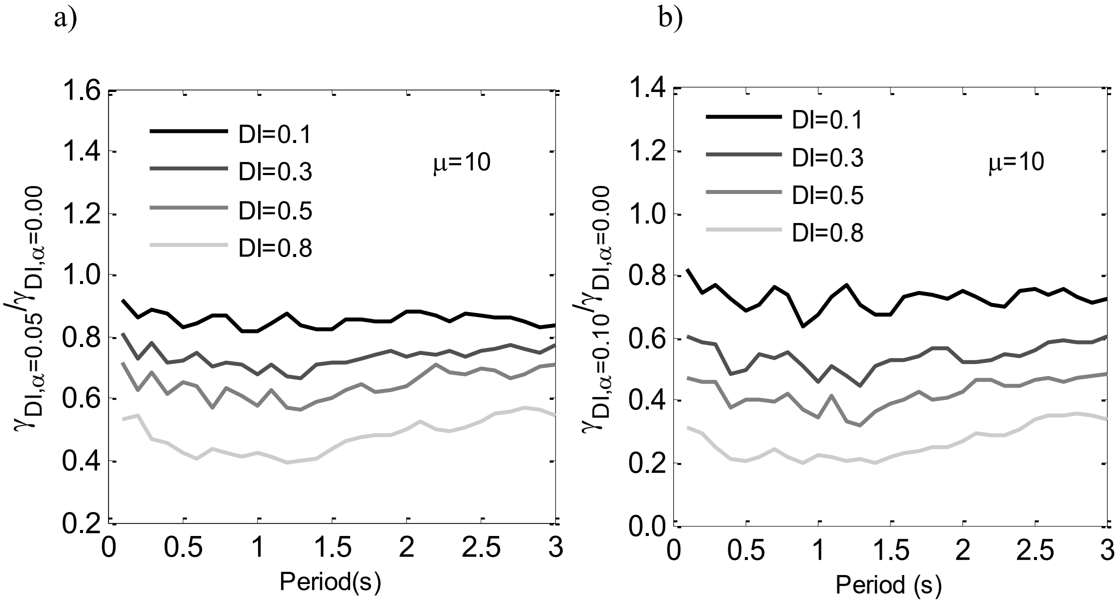

Fig. 8.The mean ratios of residual ratios, γ_{DI} of EP systems with strain hardening ratio to the residual ratios, γ_{DI} of EPP systems under 71 pulse type ground motions, for four given damage index values *DI* for different strain hardening ratios: (a) α = 0.05; (b) α = 0.1.

8. EFFECT OF STRAIN HARDENING RATIO

Several investigations have demonstrated that strain hardening ratio is an important parameter with significant effect on amplitude of residual displacement demands of structures. To quantitatively study effect of strain hardening ratio (ratio of the post-yield stiffness to the initial stiffness) on the γ_{DI}, the ratios of γ_{DI} of EP SDOF systems with two values (5% and 10%) of strain hardening ratios to the γ_{DI} of EPP SDOF systems are computed for μ_u = 10, and each damage index DI. Fig. 8 illustrates the mean ratios of γ_{DI} of EP SDOF systems with two different strain hardening ratios (α= 0.05 and 0.1) to the γ_{DI} of EPP SDOF systems. It can be observed that the mean residual ratios are less than 1.0, indicating that the residual ratios, γ_{DI} decrease as the strain hardening ratio α increases. As Fig. 8 shows, in the whole range of periods, the dependency of residual ratios, γ_{DI} to the damage index values DI is highly intensive, and with the increase in the damage index values, these ratios will decrease. According to Fig. 8, these ratios are not dependent on the period of vibration. It is found that strain hardening can reduce the γ_{DI} relative to

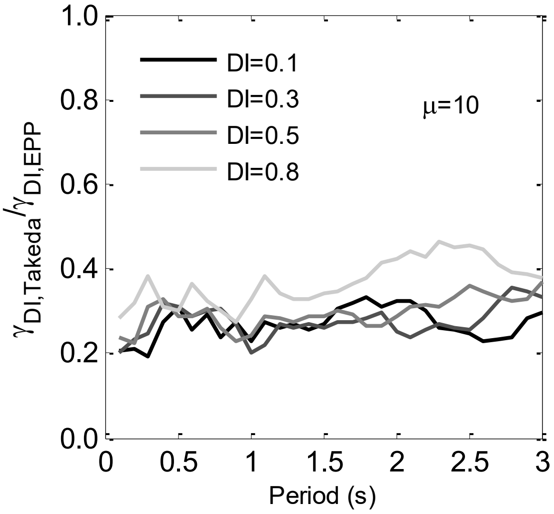

Fig. 9. The mean of residual ratios γ_{DI} of Takeda systems to the mean of residual ratios γ_{DI} of EPP systems for μ_u=10 and 71 near-fault pulse type ground motions.

EPP SDOF systems. Therefore, strain hardening ratio has significant effects on residual ratios, $\gamma_{DI.}$

9. EFFECT OF HYSTERESIS BEHAVIOR

To evaluate influence of type of hysteretic behavior on residual ratio, γ_{DI}, the residual ratio γ_{DI} of SDOF system with the Takeda hysteretic behavior is evaluated and normalized using mean residual ratios γ_{DI} of SDOF system with the EPP hysteretic behavior for each pulse type ground motion and each damage value *DI*. Fig. 9 shows mean residual ratios against the fundamental period in terms of the ratios of the residual ratios, γ_{DI} for the SDOF systems with Takeda behavior, to the residual ratios, γ_{DI} of SDOF systems with EPP behavior for μ_u= 10 and the five levels of damage index (DI = 0.1, 0.3, 0.5, and 0.8) under the 71 pulse type ground motions. As Fig. 9 shows, the mean ratios of γ_{DI} increase with increase of DI in whole period range, and it also increase with the increase of fundamental period in the long period range. The results revealed that the structures with Takeda hysteretic behavior would lead to smaller γ_{DI} than structure with the EPP hysteretic behavior. The residual ratios, γ_{DI} for Takeda hysteresis are approximately 30% of corresponding EPP models.

10. CONCLUSIONS

In previous studies, residual displacement ratio has been introduced as the most important parameter in evaluating the capacity of damaged structures for tolerance of future predictive earthquakes and strong aftershocks. Therefore, most researchers agree that approximation of residual displacement ratios plays a crucial role in structural performance evaluation. In this study, the constant damage residual ratios, γ_{DI} demands from SDOF systems with constant damage performance subjected to pulse type ground motions were statistically evaluated. To evaluate residual ratios, γ_{DI}, the extended number of SDOF systems (from 0.1 to 3 Sec.) was considered for two hysteretic models, three ultimate ductility capacities and four damage index levels subjected to 71 pulse type ground motions. The influence of A_p/V_p, hysteretic model, ultimate ductility capacity and strain hardening ratio on residual ratios was statistically studied. The main results obtained are classified as follows:

1. In the whole range of periods, residual ratios, γ_{DI} are strongly dependent on the damage index, DI and mean γ_{DI} increases with the increase of damage index, DI. The residual ratio, γ_{DI} and COV were almost period independent. The COVs are not sensitive to the damage index values DI and period.
2. A_p/V_p has more obvious effects on the residual ratios, γ_{DI} in the long period region than in the short period region. Furthermore, variation of A_p/V_p ratios is more effective than the variation of damage index values on the residual ratios, γ_{DI}.
3. The effects of the ultimate ductility capacity on the residual ratios, γ_{DI} were moderate, being within 25% for most period regions.
4. The results indicate that the effects of strain hardening ratio on residual ratios, γ_{DI} are significant in the whole period region, and the effect of this parameter on the residual ratio, γ_{DI} is valid dependently of the damage index values; for higher damage index values, the influence of the strain hardening ratio becomes more obvious.
5. It is demonstrated that residual ratios, γ_{DI} for Takeda hysteresis are approximately 30% of the corresponding EPP models.

REFERENCES

[1] E. DiPasquale, A. Cakmak, Detection of seismic structural damage using parameter-based global damage indices, Probabilistic Engineering Mechanics, 5(2) (1990) 60-65

[2] A. Ghobarah, H. Abou-Elfath, A. Biddah, Response-based damage assessment of structures, Earthquake engineering & structural dynamics, 28(1) (1999) 79-104

[3] H.S. KIM, Y.S. CHUN, Structural damage assessment of building structures using dynamic experimental data, The Structural Design of Tall and Special Buildings, 13(1) (2004) 1-8

[4] G.A. MacRae, K. Kawashima, Post-earthquake residual displacements of bilinear oscillators, Earthquake engineering & structural dynamics, 26(7) (1997) 701-716

[5] K. Kawashima, G.A. MacRae, J.-i. Hoshikuma, K. Nagaya, Residual displacement response spectrum, Journal of Structural Engineering, 124(5) (1998) 523-530

[6] S.A. Mahin, V.V. Bertero, An evaluation of inelastic seismic design spectra, Journal of the Structural Division, 107(9) (1981) 1777-1795

[7] C. Christopoulos, S. Pampanin, Towards performance-based design of MDOF structures with explicit consideration of residual deformations, (2004)

[8] G.D. Hatzigeorgiou, G.A. Papagiannopoulos, D.E. Beskos, Evaluation of maximum seismic displacements of SDOF systems from their residual deformation, Engineering structures, 33(12) (2011) 3422-3431

[9] J. Ruiz-Garcia, E. Miranda, Perfomance-based assessment of existing structures accounting for residual displacements, Stanford university Stanford, CA, 2004

[10] J. Ruiz-García, E. Miranda, Residual displacement ratios for assessment of existing structures, Earthquake engineering & structural dynamics, 35(3) (2006) 315-336

[11] Q. Fu, C. Menun, Residual displacement caused by fault-normal near-

field ground motions, in: the 8th US national conference on earthquake engineering, San Francisco, California, 2006.

[12] T. Huff, Estimating Residual Seismic Displacements for Bilinear Oscillators, Practice Periodical on Structural Design and Construction, 21(2) (2016) 04016003.

[13] B. Ghanbari, A. Akhaveissy, An empirical equation to predict the mean residual displacement ratios in constant ductility SDOF systems under strong motion records in Iran, ASIAN JOURNAL OF CIVIL ENGINEERING (BHRC), 18(3) (2017) 473-484.

[14] H. Guerrero, J. Ruiz-García, T. Ji, Residual displacement demands of conventional and dual oscillators subjected to earthquake ground motions characteristic of the soft soils of Mexico City, Soil Dynamics and Earthquake Engineering, 98 (2017) 206-221.

[15] J. Ruiz-García, H. Guerrero, Estimation of residual displacement ratios for simple structures built on soft-soil sites, Soil Dynamics and Earthquake Engineering, 100 (2017) 555-558.

[16] W. Pu, M. Wu, Ductility demands and residual displacements of pinching hysteretic timber structures subjected to seismic sequences, Soil Dynamics and Earthquake Engineering, 114 (2018) 392-403.

[17] E. Liossatou, M.N. Fardis, Near-fault effects on residual displacements of RC structures, Earthquake Engineering & Structural Dynamics, 45(9) (2016) 1391-1409.

[18] S.K. Kunnath, A.M. Reinhorn, R. Lobo, IDARC Version 3.0: A program for the inelastic damage analysis of reinforced concrete structures, National Center for Earthquake Engineering Research Buffalo, NY, 1992.

[19] Y.-J. Park, A.H.-S. Ang, Mechanistic seismic damage model for reinforced concrete, Journal of structural engineering, 111(4) (1985) 722-739.

[20] M. Azadvar, H. Hajkazemi, A. Karamoddin, structural damage control with interval type-2 fuzzy logic controller, AUT Journal of Civil Engineering, 2(2) (2018) 125-134.

[21] C.-H. Zhai, W.-P. Wen, S. Li, Z. Chen, Z. Chang, L.-L. Xie, The damage investigation of inelastic SDOF structure under the mainshock–aftershock sequence-type ground motions, Soil Dynamics and Earthquake Engineering, 59 (2014) 30-41.

[22] W.-P. Wen, C.-H. Zhai, S. Li, Z. Chang, L.-L. Xie, Constant damage inelastic displacement ratios for the near-fault pulse-like ground motions, Engineering structures, 59 (2014) 599-607.

[23] J.W. Baker, Quantitative classification of near-fault ground motions using wavelet analysis, Bulletin of the Seismological Society of America, 97(5) (2007) 1486-1501.

[24] T. Takeda, M.A. Sozen, N.N. Nielsen, Reinforced concrete response to simulated earthquakes, Journal of the structural division, 96(12) (1970) 2557-2573.

[25] S. Yaghmaei-Sabegh, Application of wavelet transforms on characterization of inelastic displacement ratio spectra for pulse-like ground motions, Journal of Earthquake Engineering, 16(4) (2012) 561-578.

[26] B. Ghanbari, A.H. Akhaveissy, Effects of pulse-like ground motions parameters on inter-story drift spectra of multi-story buildings, International Journal of Structural Engineering, 8(1) (2017) 60-73.

[27] J. Kiani, S. Pezeshk, Sensitivity analysis of the seismic demands of RC moment resisting frames to different aspects of ground motions, Earthquake engineering & structural dynamics, 46(15) (2017) 2739-2755.

[28] Asakereh, M. Tajabadipour, Analysis of Local Site Effects on Seismic Ground Response under Various Earthquakes, AUT Journal of Civil Engineering, 2(2) (2018) 227-240.

[29] C. Durucan, M. Dicleli, AP/VP specific inelastic displacement ratio for seismic response estimation of structures, Earthquake Engineering & Structural Dynamics, 44(7) (2015) 1075-1097.

[30] T. Liu, Q. Zhang, AP/VP specific equivalent viscous damping model for base-isolated buildings characterized by SDOF systems, Engineering Structures, 111 (2016) 36-47.

[31] T. Liu, Q. Zhang, AP/VP specific equivalent viscous damping model for base-isolated buildings characterized by SDOF systems, Engineering Structures, 111 (2016) 36-47.

[32] S. Yaghmaei-Sabegh, S. Safari, K.A. Ghayouri, Estimation of inelastic displacement ratio for base-isolated structures, Earthquake Engineering & Structural Dynamics, 47(3) (2018) 634-659.

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