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EVALUATION OF INELASTIC DISPLACEMENT RATIOS OF BILINEAR SDOF SYSTEMS

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ABSTRACT

Estimation of inelastic displacement demand of a structure is an important issue for the evaluation or design of structures. Several methods are used for estimation of inelastic displacement demand. Coefficient method is a reliable and the easiest method for estimation of inelastic displacement of an equivalent single degree of freedom (SDOF) system. Inelastic displacement demand is obtained by multiplying the elastic spectral displacement demand with a coefficient as a ratio between inelastic and elastic displacement demand of a SDOF system (C_R) . This coefficient (C_R) is usually determined for a constant lateral strength. It is important to derive an equation for C_R to estimate a reliable inelastic displacement demand. In this study, nonlinear time history analyses were conducted based on bilinear hysteretic behavior with 160 ground motions and near field effect was not considered. An extensive statistical study was conducted to obtain C_R for different single degree of freedom systems and site classes. The effects of post-yield stiffness and site class on C_R were investigated. Also, proposed equations in the literature were compared to C_R of earthquake data and an evaluation was conducted regarding to the reliability of the proposed equations.
Keywords: Inelastic displacement ratios, displacement demands, nonlinear analysis, post-yield stiffness, site classes.

İKİLİ DOĞRUSAL TSD SİSTEMLERİN YERDEĞİŞTİRME SABİTLERİNİN DEĞERLENDİRİLMESİ

ÖZET

Bir yapının tasarımında veya deprem güvenilirliğinin belirlenmesinde inelastik yerdeğiştirme talebinin elde edilmesi oldukça önemlidir. İnelastik yerdeğiştirme talebinin elde edilmesi için literatürde farklı yöntemler önerilmiştir. Bu yöntemlerden biri olan "Katsayılar Yöntemi", eşdeğer tek serbestlik dereceli (TSD) sistemlerin inelastik yerdeğiştirme taleplerinin elde edilmesinde kullanılan güvenilir ve kolay bir yöntemdir. Bu yöntemde, inelastik yerdeğiştirme talebi, elastik spektral yerdeğiştirmeyi, bir katsayı ile çarparak elde edilir. Bu katsayı (C_R) genellikle sabit yatay dayanım için, inelastik ve elastik spektral yerdeğiştirmelerin oranlarının regresyon analizleri ile elde edilir. İnelastik yerdeğiştirmenin doğru bir şekilde elde edilebilmesi için, C_R denkleminin oluşturulma kısmı önemli bir husustur. Çok sayıda yer hareketi için tek serbestlik dereceli sistemlerin inelastik yerdeğiştirme oranları elde edilmiş; akma sonrası eğim ve zemin sınıflarının inelastik yerdeğiştirme oranı üzerine etkisi incelenmiştir. Ayrıca, literatürde önerilen C_R denklemlerinin sonuçları ile çalışmada kullanılan deprem dataları ile bulunmuş C_R'ler karşılaştırılarak, önerilen denklemlerin güvenilirlikleri de araştırılmıştır.
Anahtar Sözcükler: İnelastik yerdeğiştirme sabiti, yerdeğiştirme talebi, doğrusal olmayan analiz, akma sonrası rijitliği, zemin sınıfı.

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1. INTRODUCTION

Severe earthquakes cause large lateral displacements on structures and structural or nonstructural elements can be damaged because of those large deformations. Thus, estimation of inelastic lateral displacement is an important issue for the design of a new structure or the seismic evaluation and rehabilitation of an existing structure. Although using nonlinear time history analyses for the estimation of inelastic displacement of a structure is a reliable method, it is still not practical for the engineering practice. Some simplified and reliable methods were developed by various researchers and seismic design codes for the engineering practice. Two of them are the capacity spectrum method developed originally by Freeman [1] and adopted by ATC-40 [2], and the displacement coefficient method developed by Seneviratna and Krawinkler [3] and used by FEMA 356 [4]. In these methods, the global inelastic displacement demand is estimated from the response of an equivalent single degree of freedom (SDOF) system and it is based on a nonlinear static pushover analysis of the structure. In the displacement coefficient method, inelastic displacement (S_{di}) demand of a building is obtained by multiplying the elastic spectral displacement (S_{de}) with several modification factors derived from SDOF analysis.

$$S_{di} = C_0C_1C_2C_3S_{de} \tag{1}$$

C_0 is a modification factor relating spectral displacement of an equivalent SDOF system to the roof displacement of the multi degree of freedom (MDOF) system, C_1 (inelastic displacement ratio) is a modification factor relating expected maximum inelastic displacements to displacements calculated for linear elastic response, C_2 is a factor that takes the degradation effects into consideration and C_3 is a factor that takes increased displacement due to dynamic P-Δ effect into account [4].

Several researchers developed equations of C_1 for the estimation of inelastic displacement demand of a structure. The first suggestion for relating elastic and inelastic displacements was proposed by Veletsos and Newmark [5]. They analyzed SDOF systems using three earthquake records and used elastic-perfectly plastic model to represent the global behaviour of the structure. They concluded that elastic and inelastic displacements are equal for long periods and also inelastic displacement is higher than the elastic one for short periods.

Shimazaki and Sozen [6] investigated the inelastic displacement ratio (the ratio of inelastic displacement to elastic displacement) of SDOF systems for 5 different hysteretic models using only El Centro earthquake record. They concluded that inelastic displacement is approximately equal to elastic displacement regardless of hysteresis model confirming the equal displacement rule for a period longer than the characteristic period which is defined as the transition period between the constant acceleration and constant velocity region of the response spectrum. For a period shorter than the characteristic period, they concluded that inelastic displacement is higher than the elastic displacement.

Miranda [7], [8], [9] proposed equations of inelastic displacement ratio for elastic-perfectly plastic SDOF systems using 124 ground motions recorded on different soil types. Miranda [10] proposed inelastic displacement ratio plots for different soil conditions, earthquake magnitude and epicentre distance using 264 earthquake records and suggested an equation for the inelastic displacement ratio for constant ductility based on elastic-perfectly plastic behaviour.

Miranda and Ruiz-Garcia [11] investigated inelastic displacement ratios for constant ductility and known lateral strength using 216 earthquake records assuming an elastic-perfectly plastic behaviour. They concluded that the value of displacement ratio with known lateral strength is higher than the value for the constant ductility.

Ruiz-Garcia and Miranda [12] conducted a study to investigate the effects of soil conditions, post-yield stiffness, earthquake magnitude and distance to the rupture and proposed an equation of displacement ratio with known lateral strength for different soil conditions.

Nassar and Krawinkler [13] proposed an equation of the displacement ratio for different post-yield stiffness.

Aydinoglu and Kacmaz [14] proposed an equation for displacement ratio using 146 ground motion records with elastic-perfectly plastic behaviour. However, they did not consider the effects of soil conditions and post-yield stiffness.

Chopra and Chintanapakdee [15] proposed equations of inelastic displacement ratio for constant lateral strength and constant ductility using 140 ground motion records with the bilinear hysteretic behaviour assumption and the equation of the inelastic displacement ratio were determined based on earthquake magnitude and epicentre distance.

In this study, inelastic displacement demands of SDOF systems with constant lateral strength were computed considering six different strength reduction factors (the ratio between lateral strength required to maintain the system elastic and yielding strength, R = 1.5, 2, 3, 4, 5, 6) and using 160 earthquake acceleration records based on bilinear hysteretic behaviour. The considered damping ratio is 5%. The period of considered SDOF systems varies between 0.1 and 3 s (T = 0.1:0.02:0.2; 0.22:0.03:1; 1.1:0.1:3) and post-yield stiffness ratios are α_s = 0%, 3%, 5%. Inelastic displacement ratios (C_R) were determined by dividing each inelastic displacement demand to corresponding elastic displacement demand and a statistical study was carried out to investigate the effects of soil conditions and post-yield stiffness on the inelastic displacement ratio of SDOF systems with constant lateral strength. Yielding point of the bilinear hysteretic model needs to be stated for the application of nonlinear time history analysis. There are two ways to determine the yielding point of hysteretic behaviour, such as using constant strength reduction factor or constant ductility. Detailed information about considering constant lateral strength reduction factor and constant ductility can be seen in the study of Ruiz-Garcia and Miranda [12]. Also, Ruiz-Garcia and Miranda [12] concluded that the inelastic displacement ratio determined based on the constant ductility underestimates the expected value of the maximum displacement of a system. Hence, inelastic displacement ratios for constant lateral strength reduction factor are particularly useful for the evaluation of existing structures. Furthermore, the effectiveness of the equations proposed by other researchers was investigated.

2. GROUND MOTION RECORDS

A total of 160 earthquake acceleration time histories, two horizontal components at each station, with magnitudes ranging from 6.5 to 7.5 were used in this study. The earthquake acceleration time histories were divided into four groups as site classes A, B, C, D according to USGS [16] classification. There are different limitations on the fault distance defined in the literature to describe the near fault effect. In this study, the minimum considered fault distance is 50 km so that the near fault effect can be minimized. All selected ground motions are given in Table 1.

Table 1. Earthquake Records (PEER-NGA) [17]

Number	*NGA#	Event	Station	Mag.	Soil Class
1	59	San Fernando	Cedar Springs, Allen Ranch	6.61	A
2	788	Loma Prieta	Piedmont Jr High	6.93	A
3	789	Loma Prieta	Point Bonita	6.93	A
4	795	Loma Prieta	SF - Pacific Heights	6.93	A
5	797	Loma Prieta	SF - Rincon Hill	6.93	A
6	804	Loma Prieta	So. San Francisco, Sierra Pt.	6.93	A
7	925	Big Bear-01	Rancho Cucamonga - Deer Can	6.46	A
8	943	Northridge-01	Anacapa Island	6.69	A
9	946	Northridge-01	Antelope Buttes	6.69	A
10	1033	Northridge-01	Littlerock - Brainard Can	6.69	A
11	1041	Northridge-01	Mt Wilson - CIT Seis Sta	6.69	A
12	1060	Northridge-01	Rancho Cucamonga - Deer Can	6.69	A
13	1074	Northridge-01	Sandberg - Bald Mtn	6.69	A
14	1096	Northridge-01	Wrightwood - Jackson Flat	6.69	A

15	1518	Chi-Chi, Taiwan	TCU085	7.62	A
16	2633	Chi-Chi, Taiwan-03	TCU085	6.2	A
17	2687	Chi-Chi, Taiwan-03	TTN042	6.2	A
18	2805	Chi-Chi, Taiwan-04	KAU003	6.2	A
19	2929	Chi-Chi, Taiwan-04	TTN042	6.2	A
20	2996	Chi-Chi, Taiwan-05	HWA003	6.2	A
21	56	San Fernando	Carbon Canyon Dam	6.61	B
22	58	San Fernando	Cedar Springs Pumphouse	6.61	B
23	63	San Fernando	Fairmont Dam	6.61	B
24	83	San Fernando	Puddingstone Dam (Abutment)	6.61	B
25	86	San Fernando	San Onofre - So Cal Edison	6.61	B
26	89	San Fernando	Tehachapi Pump	6.61	B
27	91	San Fernando	Upland - San Antonio Dam	6.61	B
28	94	San Fernando	Wrightwood - 6074 Park Dr	6.61	B
29	121	Friuli, Italy-01	Barcis	6.5	B
30	124	Friuli, Italy-01	Feltre	6.5	B
31	323	Coalinga-01	Parkfield - Cholame 12W	6.36	B
32	325	Coalinga-01	Parkfield - Cholame 2E	6.36	B
33	327	Coalinga-01	Parkfield - Cholame 3E	6.36	B
34	330	Coalinga-01	Parkfield - Cholame 4W	6.36	B
35	1154	Kocaeli, Turkey	Bursa Sivil	7.51	B
36	1159	Kocaeli, Turkey	Eregli	7.51	B
37	1162	Kocaeli, Turkey	Goynuk	7.51	B
38	1163	Kocaeli, Turkey	Hava Alani	7.51	B
39	1164	Kocaeli, Turkey	Istanbul	7.51	B
40	1172	Kocaeli, Turkey	Tekirdag	7.51	B
41	52	San Fernando	Anza Post Office	6.61	C
42	54	San Fernando	Borrego Springs Fire Sta	6.61	C
43	62	San Fernando	Colton - So Cal Edison	6.61	C
44	66	San Fernando	Hemet Fire Station	6.61	C
45	85	San Fernando	San Juan Capistrano	6.61	C
46	122	Friuli, Italy-01	Codroipo	6.5	C
47	123	Friuli, Italy-01	Conegliano	6.5	C
48	166	Imperial Valley-06	Coachella Canal #4	6.53	C
49	188	Imperial Valley-06	Plaster City	6.53	C
50	186	Imperial Valley-06	Niland Fire Station	6.53	C
51	268	Victoria, Mexico	SAHOP Casa Flores	6.33	C
52	324	Coalinga-01	Parkfield - Cholame 1E	6.36	C
53	326	Coalinga-01	Parkfield - Cholame 2WA	6.36	C
54	328	Coalinga-01	Parkfield - Cholame 3W	6.36	C
55	329	Coalinga-01	Parkfield - Cholame 4AW	6.36	C
56	331	Coalinga-01	Parkfield - Cholame 5W	6.36	C
57	1149	Kocaeli, Turkey	Atakoy	7.51	C
58	1153	Kocaeli, Turkey	Botas	7.51	C
59	1157	Kocaeli, Turkey	Cekmece	7.51	C
60	1160	Kocaeli, Turkey	Fatih	7.51	C
61	452	Morgan Hill	Foster City - APEEL 1	6.19	D
62	732	Loma Prieta	APEEL 2 - Redwood City	6.93	D
63	759	Loma Prieta	Foster City - APEEL 1	6.93	D
64	760	Loma Prieta	Foster City - Menhaden Court	6.93	D
65	780	Loma Prieta	Larkspur Ferry Terminal (FF)	6.93	D
66	808	Loma Prieta	Treasure Island	6.93	D
67	962	Northridge-01	Carson-Water St	6.69	D
68	1147	Kocaeli, Turkey	Ambarli	7.51	D
69	1229	Chi-Chi, Taiwan	CHY078	7.62	D
70	1357	Chi-Chi, Taiwan	KAU011	7.62	D
71	1599	Duzce, Turkey	Ambarli	7.14	D
72	2493	Chi-Chi, Taiwan-03	CHY078	6.2	D

73	2561	Chi-Chi, Taiwan-03	ILA044	6.2	D
74	2718	Chi-Chi, Taiwan-04	CHY054	6.2	D
75	2736	Chi-Chi, Taiwan-04	CHY076	6.2	D
76	2737	Chi-Chi, Taiwan-04	CHY078	6.2	D
77	2818	Chi-Chi, Taiwan-04	KAU045	6.2	D
78	2958	Chi-Chi, Taiwan-05	CHY054	6.2	D
79	2975	Chi-Chi, Taiwan-05	CHY076	6.2	D
80	2976	Chi-Chi, Taiwan-05	CHY078	6.2	D

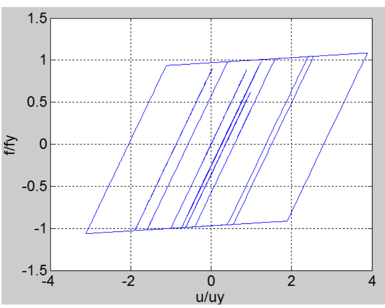
*NGA (Next Generation Attenuation): The ID numbers of the acceleration time histories in the PEER NGA database which is an updated and extension to the PEER Strong Motion Database

3. ANALYSIS

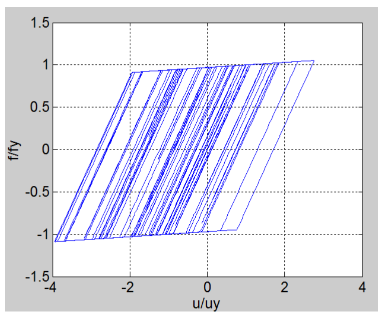
The inelastic displacement ratio (C_R) is defined as the ratio of the maximum lateral inelastic displacement demand (S_{di}) to the maximum lateral elastic displacement demand (S_{de}) on a structure with the same mass and initial stiffness. It is expressed as follows:

$$C_R = \frac{S_{di}}{S_{de}} \tag{2}$$

In this study, inelastic displacement ratios of SDOF systems were computed for a constant lateral strength considering six different strength reduction factors (R = 1.5, 2, 3, 4, 5, 6) and using 160 earthquake acceleration records. The considered damping ratio is 5%. The period of considered SDOF systems varies between 0.1 and 3 s (T = 0.1:0.02:0.2; 0.22:0.03:1; 1.1:0.1:3). Nonlinear time history analyses were conducted to determine inelastic displacement ratios and Newmark-Beta method was used in the solution of the equation of motion [18]. A bilinear hysteretic behaviour was assumed as global hysteretic behaviour of the system. The assumed post-yield stiffness ratios (α_s) are 0% (elastic-perfectly plastic), 3% and 5%, respectively. 152640 time history analyses were conducted in determination of inelastic displacement ratios for 160 earthquake acceleration records, six strength reduction factors, 53 period of vibrations and three post-yield stiffness ratios. Nonlinear time history analysis was coded as an in-house program via MATLAB [19] for SDOF systems. In Figure 1, samples of bilinear hysteretic cycling can be seen. Vertical axis of Figure 1 is f/f_y (f: lateral strength, f_y: lateral yielding strength) and horizontal axis of Figure 1 is u/u_y (u: lateral displacement, u_y: lateral yielding displacement).



a) Loma Prieta Earthquake Point Bonita record



b) Chi-Chi Taiwan Earthquake CHY054 record

Figure 1. Bilinear hysteretic cycle (T = 1.0 sec; R_y = 4; α_s = 0.03)

4. INELASTIC DISPLACEMENT RATIOS

Inelastic displacement ratios were computed via nonlinear time history analysis for each ground motion record. Mean inelastic displacement ratios for a constant lateral strength of all site classes were given in Figure 2. In Figure 2, C_R increases while strength reduction factor increases in the short period region. Inelastic displacement ratios are nearly equal to 1 for the periods longer than 0.7s confirming the equal displacement rule. For the short period region (almost T<0.7s.), inelastic displacement demand is higher than the elastic displacement demand and it is clear from the figure that the period region where the equal displacement rule is valid changes according to post-yield stiffness ratio. The period, equal displacement rule becomes valid is longer for elastic-perfectly plastic system (α_s = 0%).

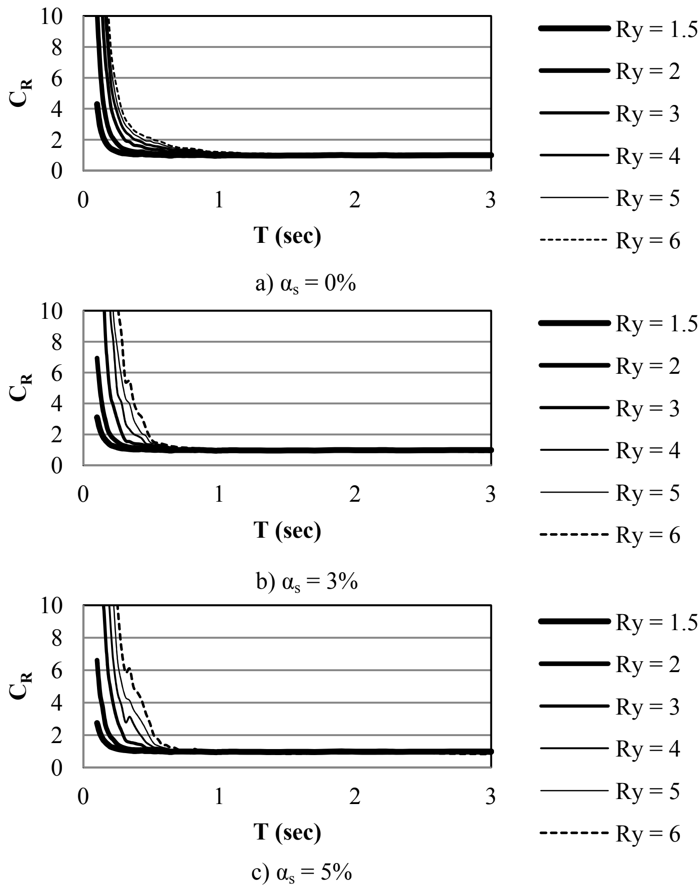
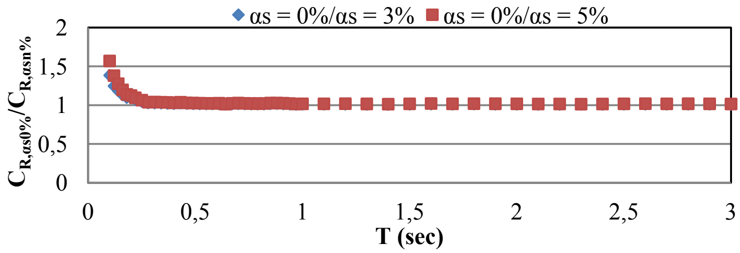


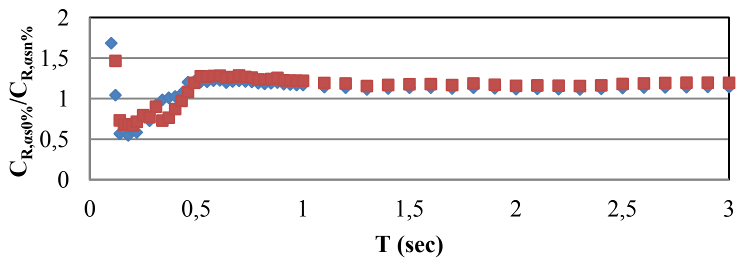
Figure 2. Mean inelastic displacement ratios (C_R) for bilinear hysteretic model

5. EFFECT OF POST-YIELD STIFFNESS

Figure 3 shows the ratio of C_R for α_S =0%, 3% and 5%. The plots are given only for R_y = 1.5 and 4 because of the space limitation. An elastic-perfectly plastic system represents a higher C_R than the C_R of considered bilinear systems on short periods and α_S does not affect the C_R on long periods for R_y =1.5 and 2. C_R is significantly affected by α_S for periods which are shorter than 0.5 sec. Elastic-perfectly plastic systems represent lower values of C_R than the C_R value of α_S =3% and 5% on short periods for R_y =3, 4, 5, 6. Although, elastic-perfectly plastic systems represent higher C_R than the C_R value of α_S =3% and 5% for R_y = 3, 4, 5, 6 on long periods, this difference can be neglected. Thus, post-yield stiffness ratio must be considered in the determination of C_R, especially for short periods (T<0.50 sec).



a) $R_y = 1.5$



b) $R_y = 4$

Figure 3. The ratio of C_R values which are determined by considering α_S = 0%, 3% and 5%

6. EFFECT OF SOIL CONDITIONS

Soil condition does not have a considerable effect on C_R for long periods; however, it considerably affects C_R for shorter periods. The limit period that the effect of soil condition on C_R becomes significant mainly depends on the strength reduction factor. Furthermore, that limit period increases with increasing R_y. On the short period region, the mean of C_R of all ground motions is higher than the mean of C_R of ground motions recorded on site classes A and B, while it is lower than the mean of C_R of ground motions recorded on site classes C and D. As a result, site classes must be considered in the determination of C_R. Figure 4 shows the ratio of mean of C_R of all ground motions to the mean of C_R of each site class.

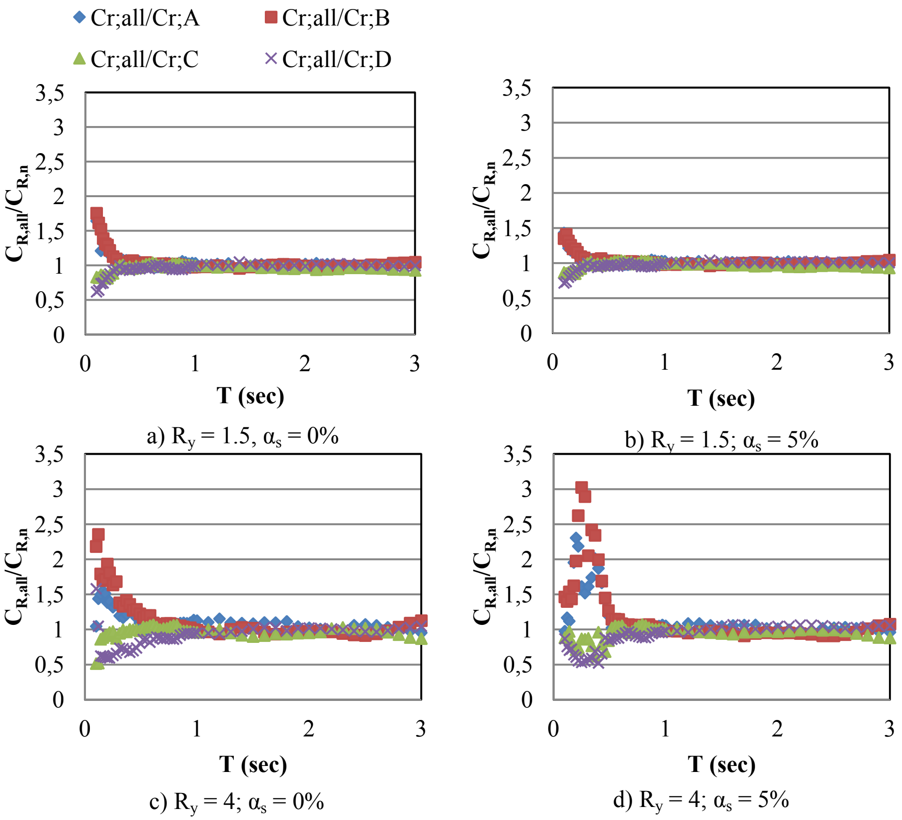


Figure 4. Ratio of C_R values determined by mean of all site classes to each group of site class

7. PROPOSED EQUATIONS OF C_R

Ruiz-Garcia and Miranda [12] proposed Eq (3). T_s is the characteristic period and the values of a, b and c vary according to site class.

$$C_R = 1 + \left[\frac{1}{a\left(\frac{T}{T_s}\right)^b} - \frac{1}{c}\right](R-1) \tag{3}$$

Vidic et al. [20] proposed the equations given in Eq (4) and Eq (5):

$$C_R = \left\{1 + \left[0.74(R-1)\frac{T_0}{T}\right]^{1.053}\right\}/R \qquad (T<T_0) \tag{4}$$

$$C_R = \{1 + [0.74(R-1)]^{1.053}\}/R \qquad (T>T_0) \tag{5}$$

T_0 is the characteristic period which is based on the target ductility and the transition period between the constant acceleration to constant velocity region of response spectrum and T_0 is assumed as 0.60 sec in this study [14]

Aydinoglu and Kaçmaz [14] proposed Eq (6) for C_R:

$$C_R = 1 + \frac{(R-1)^{0.5}}{300} + \frac{1}{10T^2}\left(-20\frac{T^{0.5}}{R^2}\right) \tag{6}$$

Chopra and Chintanapakdee [15] proposed an equation for C_R as:

$$C_R = 1 + \left[(L_R - 1)^{-1} + \left(\frac{a}{R_y^b} + c\right)\left(\frac{T_n}{T_c}\right)^d\right]^{-1} \tag{7}$$

$$L_R = \frac{1}{R_y}\left(1 + \frac{R_y - 1}{\alpha}\right) \tag{8}$$

T_n is the period of the system and T_c is the transition period between the constant acceleration to constant velocity region of response spectrum and T_c is assumed as 0.60 sec [14]. The equation proposed by Nassar and Krawinkler [13] is given in Eq (9)

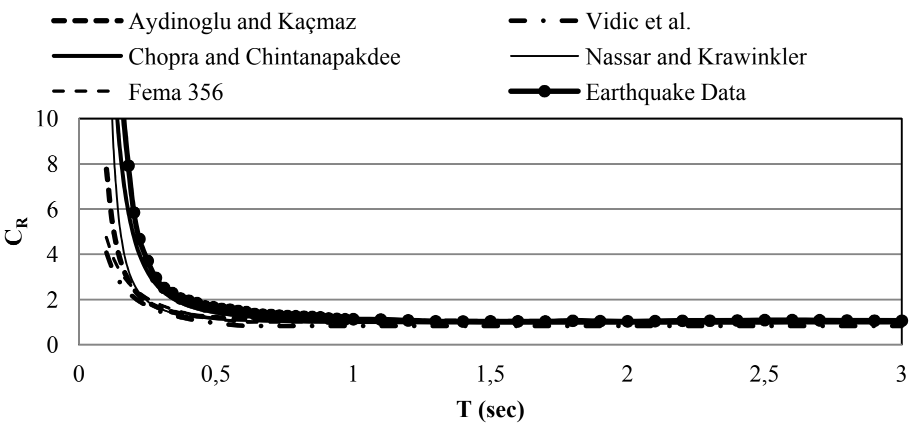
$$C_R = \frac{1}{R}\left[1 + \frac{R^c - 1}{c}\right] \tag{9}$$

$$c = \frac{T^a}{1+T^a} + \frac{b}{T} \tag{10}$$

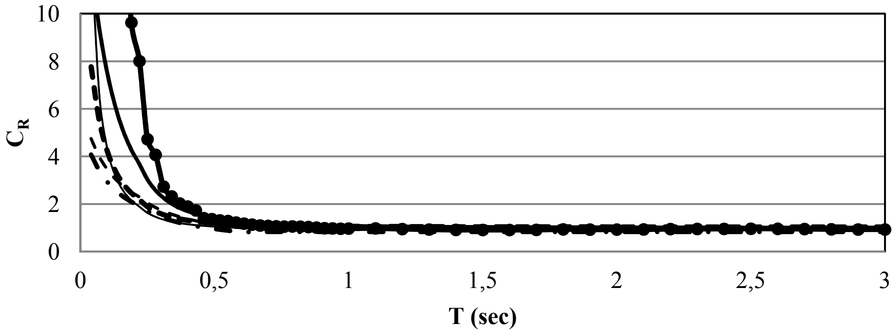
a and b are the constants related to post-yield stiffness. However, the values of a and b were given only for α_S = 0%, 2% and 10%. Because of that α_S = 2% values were used in comparison of C_R for α_S = 3% and α_S = 5%. After all, all other equations were proposed for α_S = 0% except Chopra and Chintanapakdee's [15] proposal.

FEMA 356 [4] and FEMA 440 [21] also proposed equations for C_R. Comparisons of C_R obtained for the ground motion database used in this study and the proposed equations are given in Figure 5.

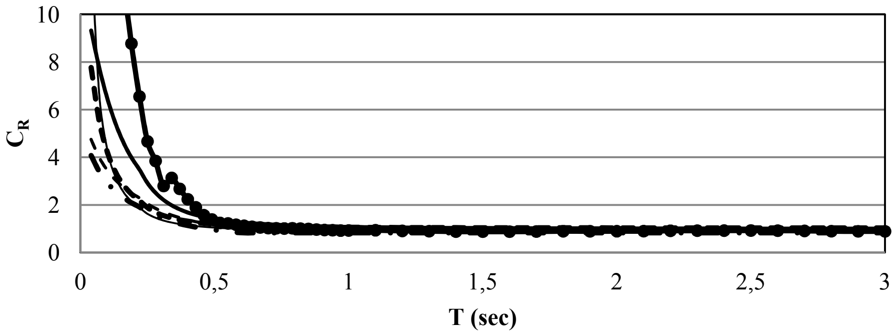
It can be seen from Figure 5 that all the proposed equations of C_R for α_S = 0% give lower values than the values determined by using earthquake data except Chopra and Chintanapakdee's [15] proposal. For α_S = 3% and α_S = 5%, all the equations give lower C_R values than the values determined by using earthquake data.



a) R_y = 4; α_s = 0%



b) $R_y = 4$; $\alpha_s = 3\%$



c) $R_y = 4$; $\alpha_s = 5\%$

Figure 5. Comparison of C_R between real data and proposed equations

8. CONCLUSIONS

In this study, inelastic displacement ratio of SDOF systems were investigated for a constant lateral strength considering six different strength reduction factors (R = 1.5, 2, 3, 4, 5, 6), using 160 earthquake acceleration records, with a damping ratio of 5%. The period of the considered SDOF systems varies between 0.1 and 3 s (T = 0.1:0.02:0.2; 0.22:0.03:1; 1.1:0.1:3). Nonlinear time history analyses were conducted to determine the inelastic displacement ratios and Newmark-Beta method was used in the solution of equation of motion [18]. A bilinear hysteretic behaviour was assumed as global hysteretic behaviour of the considered SDOF systems. The assumed post-yield stiffness ratios (α_s) are 0% (elastic-perfectly plastic), 3% and 5%, respectively. 152640 time history analyses were conducted in determination of inelastic displacement.

It is observed that the post-yield stiffness ratio and site classes have considerable effect on C_R and must be considered in the determination of C_R, especially for the short period region. The limit period at which effects of post-yield stiffness and site classes on C_R becomes significant changes according to R_y. These limit periods increase as R_y increases.

Chopra and Chintanapakdee [15] proposed the most conservative equation for C_R. Also they proposed the equation based on post-yield stiffness and site classes. All other proposed equations of C_R give lower values than the values determined by using earthquake data.

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