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Correlations between Spectral Parameters of Earthquakes and Damage Intensity in Different RC Frames

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Abstract

In recent decades many researchers have studied on the damage assessment of structures after a seismic event. To assess the damage of structures under an earthquake, it is so important to study the correlations between earthquake parameters and damages of the structures. A lot of seismic parameters have been defined by researchers to characterize an earthquake. Spectral parameters of an earthquake convey a variety of information about ground motion, so they can properly characterize an earthquake. Also a lot of damage indices were proposed by researchers to quantify the damage of the structures or to rank their vulnerability relative to each other. Park-Ang index is one of the best indices to describe the damage of a structure. In this paper, the correlations between spectral parameters of earthquakes and Park-Ang indices are studied. Three RC frames with different height are analyzed under far-fault earthquake records

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by nonlinear dynamic analyses. The correlations between spectral parameters and Park-Ang indices of the frames are calculated. The results show that in all the frames most of spectral parameters have strong correlations with damage intensity. In order to estimate the damage potential of an earthquake, some spectral parameters which have high correlations with damage intensity can be proper indices. Housner intensity, acceleration spectrum intensity and velocity spectrum intensity are shown to have strong correlations with damage intensity. In this paper, a new spectral parameter which has high correlation with damage intensity is achieved.

Keywords: Spectral parameters, Damage intensity, Park-Ang index, Correlation coefficient

Introduction

Many researchers have studied on the damage assessment of structures under an earthquake. Alongside theses researches, some researches have studied on the correlations between seismic parameters and damages of structures. The aim of the present research is to find the appropriate seismic parameters to predict the damage potential of an earthquake. To characterize a seismic event a lot of parameters have been proposed. No single seismic parameter can be an ideal index of damage lonely. The correlation of some seismic parameters with actual damage has shown a complicated multi-parameter subject of research [1]. Massumi and Gholami [2] studied four reinforced concrete frames with short to medium range periods, using a set of 85 earthquake ground motions and analyzied the

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damage results, using principal components analysis. Their results indicate that frequency-dependent parameters can better predict damage criteria in comparison to time-dependent parameters. Elenas *et al.* showed that spectral acceleration and energy parameters have the most correlation with damage [3], [4]. Danciu concluded that peak ground velocity, Arias intensity, and also spectral intensity have the most correlation with damage [5]. Alvanitopoulos *et al.* studied on correlation between damage indices and ground motion parameters and proposed two seismic parameters: the maximum amplitude (AHHT_max) and the mean amplitude (AHHT_mean). Emphasis of their work has been placed on the use of the Hilbert–Huang transform (HHT) [6]. Nanos did a study on the importance of seismic parameters selection for the vulnerability assessment of mid-rise reinforced concrete structures. He found that energy parameters of earthquakes and Arias intensity have high correlation with damage intensity of earthquakes [7]. Chen and Wei studied on correlation between ground motion parameters and lining damage indices for mountain tunnels. They concluded that Overall lining damage indices were found to be highly correlated to the velocity-related seismic parameters but not so well correlated to spectra-related parameters [8].

The correlation of spectral parameters with damage intensity is studied in this paper. Spectral parameters are extracted from far-fault records which are applied to three RC frames. The damage intensity of the frames is measured by Park-Ang index. The best single spectral parameters are defined to describe the damage intensity. Finally, a new combined parameter which has the most correlation with damage index is proposed.

Spectral parameters

Spectral parameters are based on the spectral characteristics of a seismic recording. They incorporate both peak ground motion characteristics and frequency content. A number of spectral parameters are proposed by researchers. In this paper four spectral parameters which are widely used by researchers are studied.

1. Housner Intensity (HI)

The response spectrum intensity was first proposed as an indicator by Housner [9]. It describes the area under pseudo velocity response spectrum between periods of 0.1 and 2.5 seconds, as follows:

$$HI=\int_{0.1}^{2.5} PSV(\xi,T)dT \qquad (1)$$

where *PSV* is pseudo-velocity at natural period *T*. Since many structures have fundamental periods of 0.1 and 2.5 seconds, the response spectrum in this period range can provide information about damage potential of a seismic event for these structures. The HI parameter can be calculated for any structural damping ratio.

2. Acceleration Spectrum Intensity (ASI)

Acceleration Spectrum Intensity is the area under acceleration response spectrum between periods of 0.1 and 0.5 seconds. It was first introduced by Von Thun *et al.* for concrete dams [10], as concrete

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dams generally have fundamental periods less than 0.5 seconds. It is defined as:

$$ASI=\int_{0.1}^{0.5} S_a(\xi=0.05,T)dT \qquad (2)$$

where S_a is acceleration for a damping coefficient of 5% and natural period T.

3. Velocity Spectrum Intensity (VSI)

Velocity Spectrum Intensity is the response spectrum intensity for a damping coefficient of 5%. It was first proposed by Von Thun *et al.* for earth and rock fill dams [10], which generally have fundamental periods between 0.6 and 2.0 seconds.

$$VSI=\int_{0.1}^{2.5} S_v(\xi=0.05,T)dT \qquad (3)$$

where S_v is velocity for a damping coefficient of 5% and natural period T.

4. Predominant Period (T_p)

The predominant period is the period at which the maximum spectral acceleration occurs in an acceleration response spectrum calculated for a damping coefficient of 5%. Motions with the same different frequency contents can have the same predominant period. This may lead to errors in estimation of frequency content.

Damage index (Park-Ang)

A lot of damage indices were proposed by researchers to quantify the damage of the structures or to rank their vulnerability relative to each other. Park-Ang Index is one of the most widely used damage indices [11]. Park-Ang Index incorporates deformation and hysteretic energy absorption. It is defined as:

$$D = \frac{d_m}{d_f} + \beta \frac{\int_{E=E_I}^{E=E_M} dE}{F_y d_f} \quad (4)$$

Where the integral represents the accumulation of hysteretic energy absorbed. d_m is the maximum displacement and d_f is the final displacement. β is a strength degradation parameter. For well reinforced concrete, the value of β is 0.1 [11]. F_y is the yield strength of the structure.

Structural modeling and analysis

Three 2D RC frames were modeled by using a computer program IDARC. To confirm the results of the program a ten story frame was modeled based on shaking table tests. The comparison of the analytical and experimental results shows the verification of the IDARC results. The analysis results were also compared with two other computer programs: (i) SARCF-III and (ii) DRAIN-2D. IDARC showed peak differences ranging between 3% to 10% of experimentally observed values.

The comparison of the analytical and experimental results in terms of (i) peak accelerations is shown in Figure 1; and (ii) peak displacements is shown in Figure 2. The maximum displacements reported in Cecen (1979) are based on one-half the double amplitudes, while the IDARC values are absolute peak. The results are presented in Figure 3.

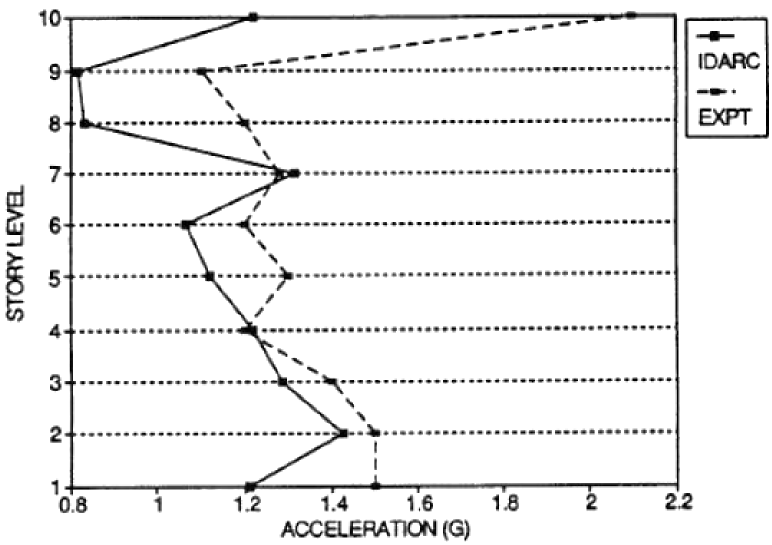

Figure 1. Computed versus observed peak acceleration response

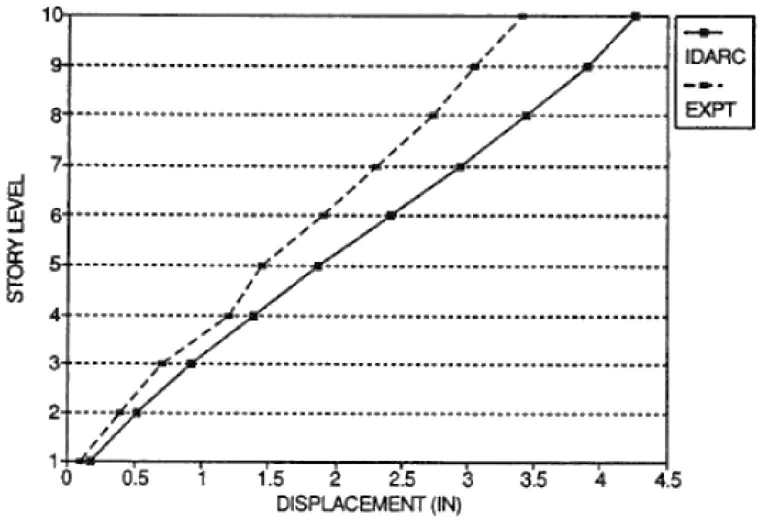

Figure 2. Computed versus observed peak displacement response

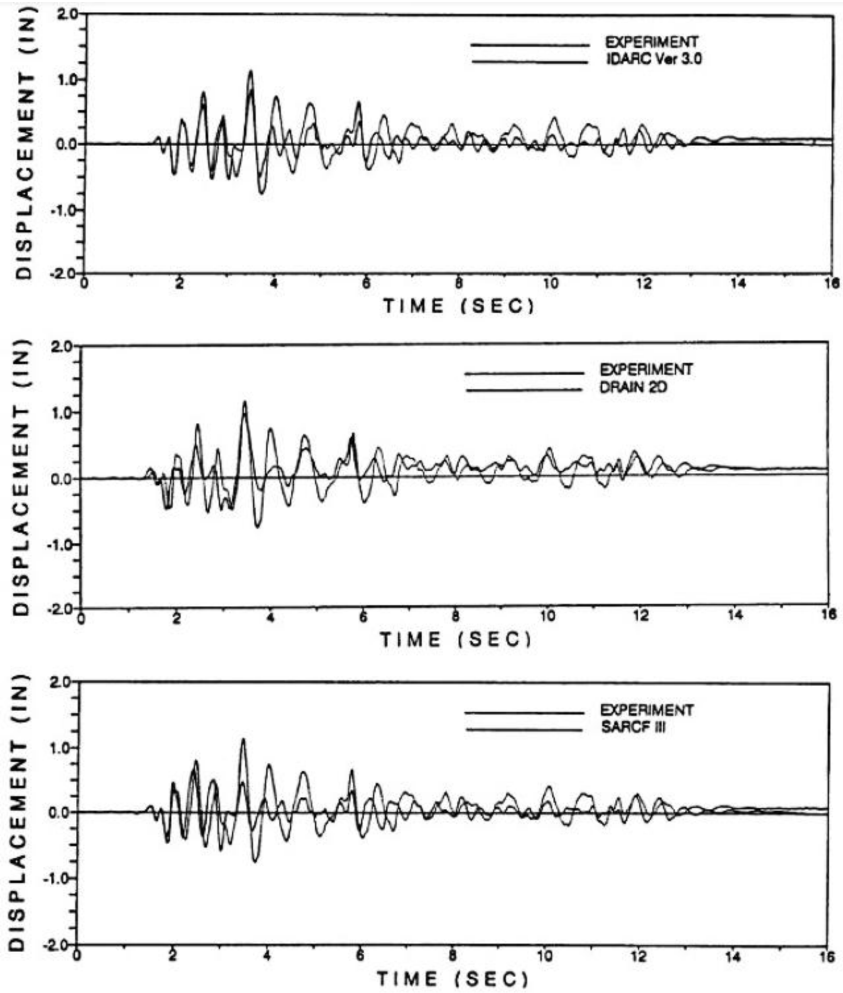

Figure 3. Comparison with other programs

The frames are 3, 6 and 9-story, respectively. As shown in Figure 4 to 6, the frames have 3 storys and 4 bays. The dimensions of each bay and story are 4.0 m and 3.2 m, respectively. The frames are compatible with Iranian Seismic Code (Standard No. 2800) [12] and Iranian national building codes, Part 9: design and construction of reinforced concrete buildings [13].

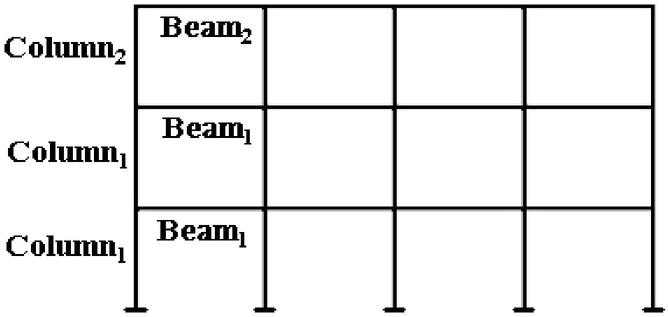

Figure 4. 3-story RC frame

Table 1. Details of Column sections in 3-story RC frame

Type	B×D (mm)	Reinforcement	Critical Stirrups	Other Stirrups
Column$_1$	350×350	8**Φ**18	**Φ**10@150	**Φ**10@200
Column$_2$	300×300	8**Φ**16	**Φ**10@150	**Φ**10@200

Table 2. Details of Beam sections in 3-story RC frame

	Type	B×D (mm)	Reinforcement	Critical Stirrups	Other Stirrups
Beam$_1$	350×350	3**Φ**20	3**Φ**16	**Φ**10@80	**Φ**10@175
		3**Φ**14	---		
Beam$_2$	300×300	3**Φ**20	3**Φ**14	**Φ**10@75	**Φ**10@150
		3**Φ**14	---		

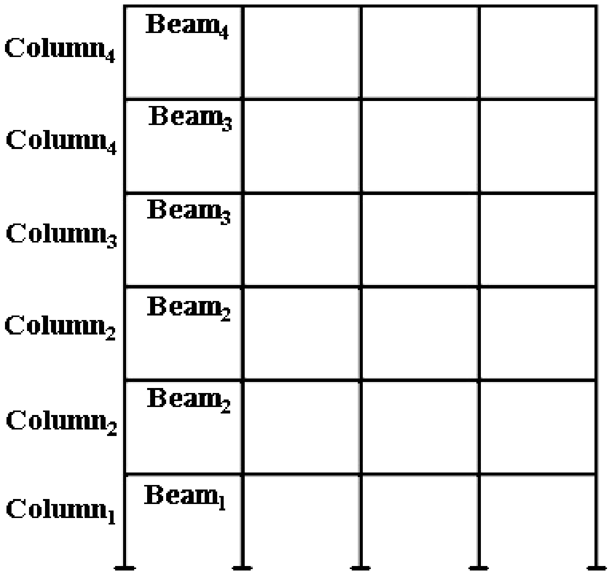

Figure 5. 6-story RC frame

Table 3. Details of Column sections in 6-story RC frame

Type	B×D (mm)	Reinforcement	Critical Stirrups	Other Stirrups
$Column_1$	450×450	12**Φ**20	**Φ**10@150	**Φ**10@200
$Column_2$	450×450	8**Φ**20	**Φ**10@150	**Φ**10@200
$Column_3$	400×400	8**Φ**20	**Φ**10@150	**Φ**10@200
$Column_4$	400×400	8**Φ**16	**Φ**10@150	**Φ**10@200

Table 4. Details of Beam sections in 6-story RC frame

Type	B×D (mm)	Reinforcement		Critical Stirrups	Other Stirrups
$Beam_1$	450×400	3**Φ**20	3**Φ**18	**Φ**8@100	**Φ**8@200
		3**Φ**18	2**Φ**14		
$Beam_2$	450×400	3**Φ**20	3**Φ**18	**Φ**8@100	**Φ**8@200
		3**Φ**16	2**Φ**14		
$Beam_3$	400×350	3**Φ**18	3**Φ**16	**Φ**8@85	**Φ**8@175
		3**Φ**16	1**Φ**16		
$Beam_4$	400×350	3**Φ**16	1**Φ**16	**Φ**8@85	**Φ**8@175
		3**Φ**16	---		

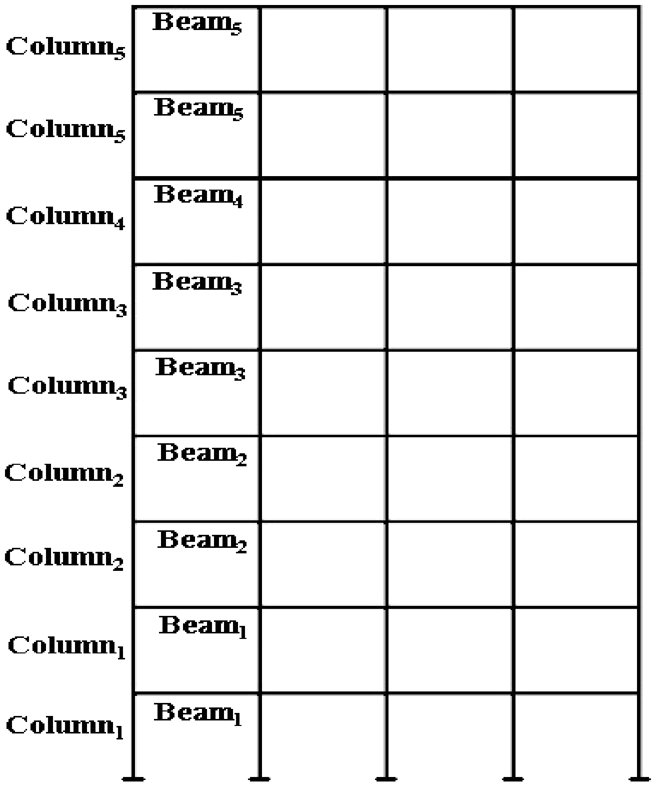

Figure 6. 9-story RC frame

Table 5. Details of Column sections in 9-story RC frame

Type	B×D (mm)	Reinforcement	Critical Stirrups	Other Stirrups
Column$_1$	500×500	12Φ22	Φ10@150	Φ10@200
Column$_2$	450×450	12Φ20	Φ10@150	Φ10@200
Column$_3$	450×450	8Φ20	Φ10@150	Φ10@200
Column$_4$	400×400	8Φ20	Φ10@150	Φ10@200
Column$_5$	400×400	8Φ16	Φ10@150	Φ10@200

Far-fault records were selected from different stations of fourteen earthquakes. They were obtained from PEER strong motion database [14]. The magnitudes of the selected earthquakes are between 5.9 and 7.6 in Richter scale. The details of earthquakes are shown in Table 7.

Table 6. Details of Beam sections in 9-story RC frame

Type	B×D (mm)	Reinforcement		Critical Stirrups	Other Stirrups
Beam$_1$	500×450	3Φ22	3Φ24	Φ8@100	Φ8@200
		3Φ22	1Φ16		
Beam$_2$	450×450	3Φ18	3Φ20	Φ8@100	Φ8@200
		3Φ18	2Φ14		
Beam$_3$	450×400	3Φ18	3Φ20	Φ8@85	Φ8@175
		3Φ16	1Φ14		
Beam$_4$	400×350	3Φ18	3Φ16	Φ8@85	Φ8@175
		3Φ16	1Φ16		
Beam$_5$	400×350	3Φ16	1Φ16	Φ8@85	Φ8@175

Table 7. Data of Earthquakes Recordes

No	Earthquake	Station	M_w
1	Taiwan SMART1(5) 1981/01/29	SMART1 C00	5.9
2	Taiwan SMART1(5) 1981/01/29	SMART1 C00	5.9
3	Taiwan SMART1(5) 1981/01/29	SMART1 I12	5.9
4	Taiwan SMART1(5) 1981/01/29	SMART1 M01	5.9
5	Taiwan SMART1(5) 1981/01/29	SMART1 M07	5.9
6	Taiwan SMART1(5) 1981/01/29	SMART1 M07	5.9
7	Taiwan SMART1(5) 1981/01/29	SMART1 O01	5.9

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No	Earthquake	Station	M_w
8	Whittier Narrows 1987/10/01 14:42	Brea Dam (Downstream)	6
9	Whittier Narrows 1987/10/01 14:42	Brea Dam (Downstream)	6
10	Whittier Narrows 1987/10/01 14:42	LA - 116th St School	6
11	Whittier Narrows 1987/10/01 14:42	Mt Wilson - CIT Seis Sta	6
12	Whittier Narrows 1987/10/01 14:42	Burbank - N Buena Vista	6
13	Whittier Narrows 1987/10/01 14:42	Carson - Water St	6
14	Whittier Narrows 1987/10/01 14:42	Carson - Water St	6
15	Whittier Narrows 1987/10/01 14:42	LA - Saturn St	6
16	Whittier Narrows 1987/10/01 14:42	La Crescenta - New York	6
17	Whittier Narrows 1987/10/01 14:42	La Crescenta - New York	6
18	Whittier Narrows 1987/10/01 14:42	Lakewood - Del Amo Blvd	6
19	Whittier Narrows 1987/10/01 14:42	Lakewood - Del Amo Blvd	6
20	Whittier Narrows 1987/10/01 14:42	Brea Dam (L Abut)	6
21	Whittier Narrows 1987/10/01 14:42	Brea Dam (L Abut)	6
22	Whittier Narrows 1987/10/01 14:42	Orange Co. Reservoir	6
23	Coalinga 1983/05/02 23:42	Parkfield - Vineyard Cany 2E	6.4
24	Coalinga 1983/05/02 23:42	Cantua Creek School	6.4
25	Coalinga 1983/05/02 23:42	Cantua Creek School	6.4
26	Coalinga 1983/05/02 23:42	Parkfield - Fault Zone 14	6.4
27	Coalinga 1983/05/02 23:42	Parkfield - Fault Zone 16	6.4
28	Imperial Valley 1979/10/15 23:16	Cucapah	6.5
29	Imperial Valley 1979/10/15 23:16	El Centro Array #13	6.5
30	Imperial Valley 1979/10/15 23:16	Delta	6.5
31	Imperial Valley 1979/10/15 23:16	Delta	6.5
32	San Fernando 1971/02/09 14:00	Castaic - Old Ridge Route	6.6
33	San Fernando 1971/02/09 14:00	LA - Hollywood Stor Lot	6.6
34	San Fernando 1971/02/09 14:00	LA - Hollywood Stor Lot	6.6

No	Earthquake	Station	M_w
35	San Fernando 1971/02/09 14:00	Lake Hughes #4	6.6
36	San Fernando 1971/02/09 14:00	Lake Hughes #4	6.6
37	Northridge 1994/01/17 12:31	Castaic - Old Ridge Route	6.7
38	Northridge 1994/01/17 12:31	Castaic - Old Ridge Route	6.7
39	Northridge 1994/01/17 12:31	LA - Hollywood Stor FF	6.7
40	Northridge 1994/01/17 12:31	LA - Hollywood Stor FF	6.7
41	Northridge 1994/01/17 12:31	Beverly Hills - 12520 Mulhol	6.7
42	Northridge 1994/01/17 12:31	Pacific Palisades - Sunset Blvd	6.7
43	Northridge 1994/01/17 12:31	Santa Monica City Hall	6.7
44	Northridge 1994/01/17 12:31	Santa Monica City Hall	6.7
45	Northridge 1994/01/17 12:31	Stone Canyon	6.7
46	Northridge 1994/01/17 12:31	Stone Canyon	6.7
47	Northridge 1994/01/17 12:31	Topanga - Fire Sta	6.7
48	Northridge 1994/01/17 12:31	LA - Chalon Rd	6.7
49	Northridge 1994/01/17 12:31	LA - Chalon Rd	6.7
50	Northridge 1994/01/17 12:31	LA - N Faring Rd	6.7
51	Northridge 1994/01/17 12:31	LA - N Faring Rd	6.7
52	Northridge 1994/01/17 12:31	LA - Wonderland Ave	6.7
53	Northridge 1994/01/17 12:31	LA - Wonderland Ave	6.7
54	Northridge 1994/01/17 12:31	LA - Wonderland Ave	6.7
55	Northridge 1994/01/17 12:31	LA - Wonderland Ave	6.7
56	Northridge 1994/01/17 12:31	LA - Centinela St	6.7
57	Northridge 1994/01/17 12:31	Beverly Hills - 14145 Mulhol	6.7
58	Superstitn Hills(A) 1987/11/24 05:14	Wildlife Liquef. Array	6.7
59	Superstitn Hills(A) 1987/11/24 05:14	Wildlife Liquef. Array	6.7
60	Superstitn Hills(B) 1987/11/24 13:16	Plaster City	6.7
61	Superstitn Hills(B) 1987/11/24 13:16	Plaster City	6.7

No	Earthquake	Station	M_w
62	Superstitn Hills(B) 1987/11/24 13:16	Wildlife Liquef. Array	6.7
63	Superstitn Hills(B) 1987/11/24 13:16	Wildlife Liquef. Array	6.7
64	Superstitn Hills(B) 1987/11/24 13:16	Calipatria Fire Station	6.7
65	Superstitn Hills(B) 1987/11/24 13:16	Calipatria Fire Station	6.7
66	Superstitn Hills(B) 1987/11/24 13:16	Salton Sea Wildlife Refuge	6.7
67	Superstitn Hills(B) 1987/11/24 13:16	Salton Sea Wildlife Refuge	6.7
68	Spitak, Armenia 1988/12/07	Gukasian	6.8
69	Spitak, Armenia 1988/12/07	Gukasian	6.8
70	Kobe 1995/01/16 20:46	Station: 0 Kakogawa	6.9
71	Kobe 1995/01/16 20:46	Station: 0 Kakogawa	6.9
72	Loma Prieta 1989/10/18 00:05	Gilroy Array #7	6.9
73	Loma Prieta 1989/10/18 00:05	Gilroy Array #7	6.9
74	Loma Prieta 1989/10/18 00:05	Coyote Lake Dam	6.9
75	Loma Prieta 1989/10/18 00:05	Coyote Lake Dam	6.9
76	Loma Prieta 1989/10/18 00:05	Coyote Lake Dam (Downst)	6.9
77	Loma Prieta 1989/10/18 00:05	Coyote Lake Dam (Downst)	6.9
78	Loma Prieta 1989/10/18 00:05	Anderson Dam (Downstream)	6.9
79	Loma Prieta 1989/10/18 00:05	Anderson Dam (Downstream)	6.9
80	Loma Prieta 1989/10/18 00:05	SF Intern. Airport	6.9
81	Loma Prieta 1989/10/18 00:05	SF Intern. Airport	6.9
82	Loma Prieta 1989/10/18 00:05	Hollister Diff. Array	6.9
83	Loma Prieta 1989/10/18 00:05	Hollister Diff. Array	6.9
84	Loma Prieta 1989/10/18 00:05	Sunnyvale - Colton Ave	6.9
85	Loma Prieta 1989/10/18 00:05	Sunnyvale - Colton Ave	6.9
86	Loma Prieta 1989/10/18 00:05	Agnews State Hospital	6.9
87	Loma Prieta 1989/10/18 00:05	Agnews State Hospital	6.9
88	Irpinia, Italy 1980/11/23 19:34	Bagnoli Irpino	6.9

No	Earthquake	Station	M_w
89	Irpinia, Italy 1980/11/23 19:34	Bagnoli Irpino	6.9
90	Irpinia, Italy 1980/11/23 19:34	Sturno	6.9
91	Cape Mendocino 1992/04/25 18:06	Fortuna - Fortuna Blvd	7.1
92	Cape Mendocino 1992/04/25 18:06	Fortuna - Fortuna Blvd	7.1
93	Landers 1992/06/28 11:58	Coolwater	7.3
94	Landers 1992/06/28 11:58	Coolwater	7.3
95	Landers 1992/06/28 11:58	Desert Hot Springs	7.3
96	Landers 1992/06/28 11:58	Yermo Fire Station	7.3
97	Landers 1992/06/28 11:58	North Palm Springs	7.3
98	Landers 1992/06/28 11:58	North Palm Springs	7.3
99	Chi-Chi, Taiwan 1999/09/20	CHY034	7.6
100	Chi-Chi, Taiwan 1999/09/20	CHY034	7.6
101	Chi-Chi, Taiwan 1999/09/20	CHY036	7.6
102	Chi-Chi, Taiwan 1999/09/20	CHY036	7.6
103	Chi-Chi, Taiwan 1999/09/20	CHY092	7.6
104	Chi-Chi, Taiwan 1999/09/20	CHY092	7.6
105	Chi-Chi, Taiwan 1999/09/20	CHY104	7.6
106	Chi-Chi, Taiwan 1999/09/20	TCU107	7.6
107	Chi-Chi, Taiwan 1999/09/20	TCU107	7.6
108	Chi-Chi, Taiwan 1999/09/20	TCU040	7.6
109	Chi-Chi, Taiwan 1999/09/20	TCU040	7.6
110	Chi-Chi, Taiwan 1999/09/20	TCU042	7.6
111	Chi-Chi, Taiwan 1999/09/20	TCU042	7.6
112	Chi-Chi, Taiwan 1999/09/20	TCU111	7.6
113	Chi-Chi, Taiwan 1999/09/20	TCU111	7.6
114	Chi-Chi, Taiwan 1999/09/20	TCU141	7.6
115	Chi-Chi, Taiwan 1999/09/20	TCU141	7.6

No	Earthquake	Station	M_w
116	Chi-Chi, Taiwan 1999/09/20	TCU038	7.6
117	Chi-Chi, Taiwan 1999/09/20	TCU038	7.6
118	Chi-Chi, Taiwan 1999/09/20	Station: TCU047	7.6
119	Chi-Chi, Taiwan 1999/09/20	CHY002	7.6
120	Chi-Chi, Taiwan 1999/09/20	CHY002	7.6
121	Chi-Chi, Taiwan 1999/09/20	CHY010	7.6
122	Chi-Chi, Taiwan 1999/09/20	CHY010	7.6
123	Chi-Chi, Taiwan 1999/09/20	CHY046	7.6
124	Chi-Chi, Taiwan 1999/09/20	CHY046	7.6

The selected records were applied to the frames and inelastic dynamic analyses were performed. Park-Ang damage indices were obtained as the damage intensity. Also spectral parameters of the records were extracted.

Analytical results and discussion

After the nonlinear dynamic analyses of the frames, the correlations between Park-Ang damage indices and spectral parameters were studied by statistics methods. Two correlation coefficients were applied: Spearman rank correlation [15] and Pearson correlation coefficient [15]. Pearson correlation coefficient is used to identify the strength of the linear inter-relationship between two sets of data. Spearman's coefficient is not a measure of the linear inter-relationship between two sets of data. If the distribution of data makes Pearson correlation coefficient disagreeable, Spearman's coefficient that is a measure of monotone association, will be used [16].

Spearman rank correlation between two sets of variables X and Y, is defined as:

$$\rho_{Spearman}=1-\frac{6\sum d_i^2}{n^3-n} \quad (5)$$

where n represents the number of pairs (X_i, Y_i) and d_i represents the difference between the ranks of X_i and Y_i. It means that if the ranks of X_i and Y_i are respectively $R(X_i)$ and $R(Y_i)$, then $d_i = R(X_i) - R(Y_i)$ [17].

Pearson correlation coefficient between two sets of variables X and Y, is defined as:

$$\rho_{Pearson}=\frac{\sum_{i=1}^{n}(X_i-\bar{X})(Y_i-\bar{Y})}{\sqrt{\sum_{i=1}^{n}(X_i-\bar{X})^2\sum_{i=1}^{n}(Y_i-\bar{Y})^2}} \quad (6)$$

where $\bar{X}$ and $\bar{Y}$ represent the mean values of X_i and Y_i and n represents the number of pairs (X_i, Y_i).

The results of Spearman correlations between spectral parameters and Park-Ang damage indices in three frames are presented in Table 8 to 10.

Table 8. Spearman coefficients between spectral parameters and Park-Ang in 3-story frame

Spectral parameter	Spearman coefficient
HI (cm)	0.794
ASI (g.sec)	0.693
VSI (cm)	0.840
Tp (sec)	0.154

Table 9. Spearman coefficients between spectral parameters and Park-Ang in 6-story frame

Spectral parameter	Spearman coefficient
HI (cm)	0.791
ASI (g.sec)	0.665
VSI (cm)	0.841
Tp (sec)	0.156

Table 10. Spearman coefficients between spectral parameters and Park-Ang in 9-story frame

Spectral parameter	Spearman coefficient
HI (cm)	0.757
ASI (g.sec)	0.688
VSI (cm)	0.804
Tp (sec)	0.048

In all the three frames, the results of Spearman coefficients show that Housner intensity, acceleration spectrum intensity and velocity spectrum intensity provide strong correlations with Park-Ang index, but predominant period provides weak correlation with Park-Ang index as far as it can be concluded that predominant period has not any correlation with damage index. Among the spectral parameters, Velocity Spectrum Intensity has the maximum correlation with Park-Ang index.

The results of Pearson correlations between spectral parameters of earthquakes and Park-Ang damage indices in three frames are represented in Tables 11 to 13.

Table 11. Pearson coefficients between spectral parameters and Park-Ang in 3-story frame

Spectral parameter	Pearson correlation
HI (cm)	0.834
ASI (g.sec)	0.724
VSI (cm)	0.873
Tp (sec)	0.072

Table 12. Pearson coefficients between spectral parameters and Park-Ang in 6-story frame

Spectral parameter	Pearson correlation
HI (cm)	0.812
ASI (g.sec)	0.712
VSI (cm)	0.855
Tp (sec)	0.092

Table 13. Pearson coefficients between spectral parameters and Park-Ang in 9-story frame

Spectral parameter	Pearson correlation
HI (cm)	0.800
ASI (g.sec)	0.699
VSI (cm)	0.831
Tp (sec)	0.011

In all the three frames, the results of Pearson coefficients are highly similar to the results of Spearman coefficients. The comparison of correlation coefficients in three RC frames is shown in Figures 7 and 8. The figures show that there isn't significant difference in Spearman or Pearson coefficients between spectral parameters and Park-Ang in three RC frames. Therefore it can be concluded that the results aren't related to the heights of the frames and they can be developed to all the RC frames.

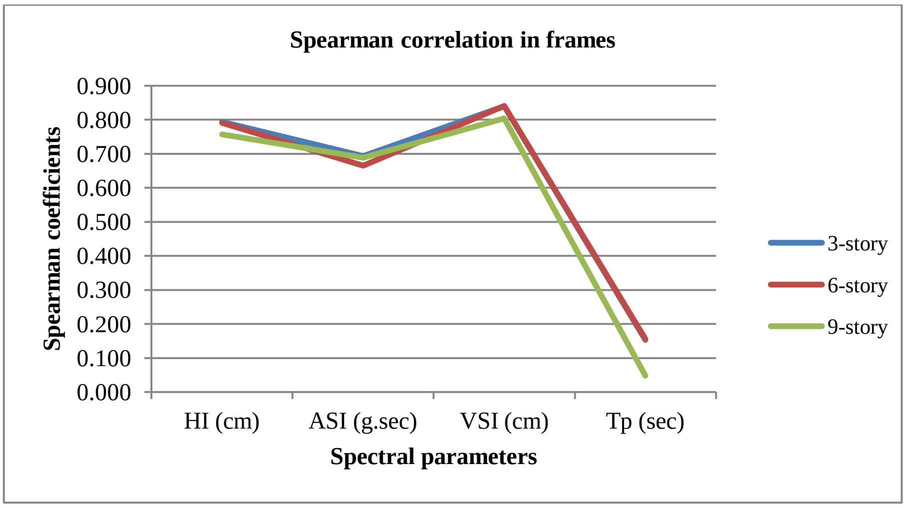

Figure 7. Spearman coefficients between spectral parameters and Park-Ang index in frames

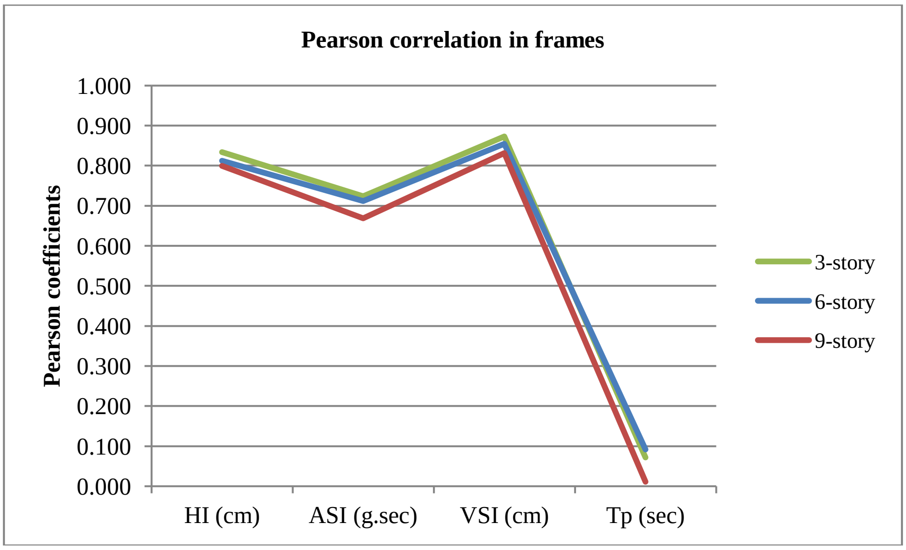

Figure 8. Pearson coefficients between spectral parameters and Park-Ang index in frames

By linear combination of seismic parameters which have strong correlation with damage intensity (HI, ASI and VSI), a new parameter can be achieved. As both of the HI and VSI parameters describe the response spectrum intensity, one of them is chosen in this paper. The regression standardized coefficients between new spectral combined parameter and Park-Ang index is shown in Table 14. It can be seen that regression coefficients are close to each other in all three frames.

Table 14. Regression Standardized Coefficients

Frame	Parameter	Standardized Coefficients
3-story	HI	0.629
	ASI	0.405
6-story	HI	0.607
	ASI	0.404
9-story	HI	0.620
	ASI	0.354

According to Table 14, the new parameter can be written as follows:

$$ID\ (Park\text{-}Ang) = 0.6HI + 0.4ASI \quad (7)$$

The new parameter has more correlation with Park-Ang index. The results of correlations between the combined parameter and variation of fundamental periods are shown in Table 15.

Table 15. Pearson correlations between the combined parameter and Park-Ang index

Model	Pearson correlation
3 Story	0.904
6 Story	0.884
9 Story	0.856

Conclusion

Three 2D RC frames with different height were modeled and subjected to the 124 far-fault records of different earthquakes. Four main spectral parameters were considered: Housner Intensity, acceleration spectrum intensity, velocity spectrum intensity and predominant period. These parameters were extracted from the far-fault records. The selected records were applied to the frames. Inelastic dynamic analyses were performed and Park-Ang damage indices were obtained. Correlation study between spectral parameters of earthquakes and damage indices was done by using Spearman rank correlation and Pearson correlation coefficient. In all the frames, both of the coefficients show that Housner intensity, acceleration spectrum intensity and velocity spectrum intensity provide strong correlations with Park-Ang index, because the mean of Spearman coefficients for HI, ASI and VSI are 0.781, 0.682 and 0.828, respectively. Also the mean of Pearson coefficients for HI, ASI and VSI are 0.815, 0.712 and 0.853, correspondingly. But predominant period provides too weak correlation with Park-Ang index, because the mean of Spearman and Pearson coefficients for Tp are 0.119 and 0.058, respectively. Velocity spectrum intensity has the maximum correlation with Park-Ang index and can well predict the damage potential of an earthquake. As the results in three RC frames are very similar to each other, they can be developed to all the RC frames. Also by linear combining HI and ASI parameter, a new parameter which is described as:

[*0.6HI+0.4ASI*] is introduced. This new spectral parameter has 3% to 4% more correlation with damage intensity than the best single spectral parameter which is used in this paper.

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