Estimation of the Seismic Damage Potential of RC Frames Using Seismic Parameters

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Abstract

Variation of the fundamental period is regarded as one of the methods to assess the damage of the structures under earthquakes. The inter-relationship among seismic parameters and variation of the fundamental period can identify the potential structural damage of an earthquake. For this purpose, the present paper aimed to study the relations among main seismic parameters, incorporating a variety of information about ground motion and variation of fundamental period. Three RC frames were analyzed under far-fault earthquake records by nonlinear dynamic analyses and mathematical methods applied to assay the correlation between seismic parameters and variation of fundamental period. Based on the results, high correlations were observed between some seismic parameters and variation of fundamental period. Further, based on regression equations, new parameters with a very strong correlation with variations of fundamental periods were achieved, which can be regarded as appropriate indices to estimate the potential structural damage of an earthquake.

Keywords: Seismic parameters, Seismic damage potential, Fundamental period, RC frames, Correlation coefficient, Regression equation

1. Introduction

The vulnerability assessment of structures under an earthquake is regarded as one of the most important problems for estimating their efficiency and capability for their utilization, predicting the possibility of future servicing, as well as rehabilitating and repairing the defects caused by damages.

Since the earthquakes claim to damage structures worldwide every year (Comartin, et al., 2004), the estimation of structural damage, caused by earthquakes has attracted a lot of attention in recent years. The damage indexes aim to evaluate the intensity of damage structures under earthquake loading (Williams & Sexsmith, 1995) and (Rodriguez, 2017). Therefore, researchers emphasized the inter-relationship between seismic parameters and structural damage to find the best seismic parameters which can predict the potential structural damage of an earthquake. Variation of the fundamental period is considered as one of the methods to assess the structural damage (Massumi and Moshtagh, 2013). A large number of parameters have been proposed to characterize a seismic event. No single ground motion parameter provides an ideal index of damage. The correlation of some seismic parameters with actual damage has shown a complicated multi-parameter subject of research (Musson, 2000). Elenas et al. claimed that spectral acceleration and energy parameters are highly correlated with the damage (Elenas, 1996, 1997, and 2000). Also, Samimifar et al. (Samimifar, Massumi, & Moghadam, 2019) stated that energy based seismic evaluation (EBSE) is a rational approach for seismic assessment considering the accumulated earthquake induced damage. According to Danciu (2006), peak ground velocity, Arias Intensity, and spectral intensity are greatly related to the damage (Danciu, 2006). Alvanitopoulos et al. (2010) studied the correlation between damage indices and ground motion parameters and proposed the two new seismic parameters: maximum amplitude (AHHT_max) and the mean amplitude (AHHT_mean), as seismic parameters, which played a significant role in the use of the Hilbert–Huang transform (HHT) (Alvanitopoulos, Andreadis, & Elenas, 2010). Nanos (2011), in his study, emphasized the selection of seismic parameters for the vulnerability assessment of mid-rise reinforced concrete structures and concluded that the energy parameters of earthquakes and Arias intensity are highly correlated with the damage intensity of earthquakes (Nanos, 2011) and (Nanos, Elenas, and Ponterosso, 2008). Chen and Wei (2012) considered the correlation between ground motion parameters and lining damage indices for mountain tunnels. Based on the results, overall lining damage indices were found to be highly correlated to the velocity-related seismic parameters while a low correlation was reported for spectra-related parameters (Chen & Wei, 2012). Regarding the correlation between the spectral parameters of an earthquake and damage intensity in 3-story RC frame indicated that Housner Intensity (Housner, 1959), Acceleration Spectrum Intensity, and Velocity Spectrum Intensity could provide high correlations with the Park-Ang index while a weak correlation was reported for the predominant period (Massumi and

Rahmati Selkisari, 2017), (Rahmati Selkisari, 2015). Further, the relationship between earthquake energy parameters and damage in different RC frames indicated that a_{RMS} , I_a , I_c , and A95 parameters are regarded as proper parameters to represent potential damage of an earthquake (Rahmati Selkisari and Massumi, 2014). The results of Massumi and Gholami (2015) indicated that frequency-dependent parameters could better predict damage criterion comparison to time-dependent parameters and there was no unique time-dependent parameter that could describe the structural damage satisfactorily (Massumi and Gholami, 2015). Wang, Zhang, Zhou, and Lu (2015) discussed the correlation between durations and damage measures of gravity dams. Comparison of the correlation between the different durations of the ground motion and damage measures revealed that strong motion durations calculated from different definitions have no significant influence on damage measure based on the peak displacement response of the dam, but are positively correlated to the accumulated damage measures such as the local damage index, global damage index, and damage energy dissipation (Wang, Zhang, Zhou, & Lu, 2015). Diaz, Pujades, Barbat, Vargas, and Hidalgo-Leiva (2017) proposed a new damage index based on two energy functions. Their new damage index can link damage to certain characteristics of seismic actions, such as their intensity and duration (Diaz, Pujades, Barbat, Vargas, & Hidalgo-Leiva, 2017). Qiu et al. (2020) investigated the correlation between structural damages of high-rise chimneys and a spectral-acceleration-based earthquake intensity measure, which considered the higher modes effect and period elongation effect. Three RC high-rise chimneys were established and analyzed under far-field ground motion records. The results illustrated that the proposed intensity measure has a high correlation with the structural damage indices, especially with maximum inter-story drift ratio and maximum roof displacement and is a suitable parameter to predict the structural damage of high-rise chimneys (Qiu, Zhou, & A, 2020). Chen and Wang studied multi-pulse characteristics of near-fault ground motions by an automatic detection procedure, which was conducted on the rough pulse signal. The statistical methods between multi-pulse parameters and earthquake parameters, including moment magnitudes, site conditions, rupture distances, and types of faults were discussed. The results demonstrated that pulse periods which can be described by the period of the pulse with the largest energy are almost identical to periods of the first pulse in the time domain. They are related not only to magnitudes but also to fault-types and site conditions (Chen & Wang, 2020). The summary of the literature is presented in Table 1.

Table 1. Summary of the literature

Researchers	Year	Highly correlated with the damage
Elenas	1996, 1997, and 2000	Spectral acceleration and energy parameters
Danciu	2006	Peak ground velocity, Arias Intensity, and spectral intensity
Alvanitopoulos, Andreadis and Elenas	2010	Maximum amplitude (AHHT_max) and the mean amplitude (AHHT_mean)
Nanos	2011	Energy parameters of earthquakes and Arias intensity
Chen and Wei	2012	Velocity-related seismic parameters
Massumi and Rahmati Selkisari	2014, 2015	a_{RMS} , I_a , I_c , A_{95} ASI and VSI
Massumi and Gholami	2015	Frequency-dependent parameters
Wang, Zhang, Zhou, and Lu	2015	Strong motion durations (correlated only with the accumulated damage measures)
Diaz, Pujades, Barbat, Vargas, and Hidalgo-Leiva	2017	A damage index based on two energy functions
Qiu, Zhou, and A	2020	High correlation between structural damages of high-rise chimneys and a proposed intensity measure
Chen and Wang	2020	Pulse periods are related to magnitudes, fault-types and site conditions

In the present study, three reinforced concrete frames were analyzed and subjected to far-fault earthquake records. Pearson correlation coefficient was used to evaluate the strength of the linear inter-relationship between two sets of data (Spiegel, 1992) and (Hauke & Kossowski, 2011). By utilization regression equations between seismic parameters and variations of the fundamental period, new parameters, having a considerable correlation with the variations of the fundamental period were obtained.

2. Seismic parameters

Numerous parameters including peak ground motion parameters, Energy parameters, Spectral parameters, and duration parameters have been defined to characterize a seismic event. In this paper, the main seismic parameters extracted from records of earthquakes are selected, which have shown a high correlation with damage intensity in the previous studies.

2.1. Earthquake energy parameters

The calculation of the input energy of a seismic event leads to energy parameters. Energy parameters convey information from both amplitude and duration characteristics of seismic motion. It is worth noting that some researchers such as Danciu (2006) classified these parameters based on the intensity of ground motion parameters. Some of the important energy parameters selected for the purpose of this study are as follows:

Root mean square of accelerations (a_{RMS}): it considers amplitude and frequency content of an earthquake record, and is defined as:

$$a_{RMS} = \left(\frac{1}{T_d} \int_0^{T_d} [a(t)]^2 dt \right)^{\frac{1}{2}} = (\lambda_0)^{\frac{1}{2}} \quad (1)$$

where, T_d is the duration of the earthquake record, $a(t)$ represents the acceleration at the time of t , and λ_0 indicates the average intensity.

Arias intensity (I_a): it is regarded as a parameter to measure the intensity of ground motion (Arias, 1970), which represents the total energy at the recording station, and is defined as:

$$I_a = \frac{\pi}{2g} \int_0^{T_d} a^2(t) dt \quad (2)$$

where, T_d is the duration of the earthquake record, $a(t)$ indicates the acceleration at the time of t , and the unit of Arias intensity is similar to velocity.

Characteristic Intensity (I_c): it is obtained based on root mean square of accelerations (Ang, 1990), and is defined as:

$$I_c = (a_{RMS})^{\frac{3}{2}} \cdot (T_d)^{\frac{1}{2}} \quad (3)$$

where, a_{RMS} represents the root mean square of accelerations and T_d indicates the duration of the earthquake record.

A95: it is the level of acceleration involving up to 95% of the Arias Intensity (Fig. 1) (Sarma & Yang, 1987).

Fig. 1. Schematic diagram for calculation of A95

The E_x is the area bounded by the curve $a^2(t)$ and the horizontal line at A^2 level. When the acceleration level A is zero acceleration, the area E_s gives the Arias Intensity. The acceleration level which gives E_x/E_s equal to 0.05 is A95.

2.2. Spectral parameters of earthquakes

Spectral parameters consider both the characteristics of peak ground motion and frequency content, based on the spectral characteristics of a seismic recording. A number of spectral parameters were proposed by the researchers.

Acceleration Spectrum Intensity (ASI): it is the area under the acceleration response spectrum between the period of 0.1 and 0.5 seconds. This parameter was first introduced for concrete dams, such as concrete dams, which generally have fundamental periods of less than 0.5 seconds (Von Thun, Roehm, Scott, & Wilson, 1988). It is defined as:

$$ASI = \int_{0.1}^{0.5} S_a(\xi=0.05, T) dT \quad (4)$$

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

Velocity Spectrum Intensity (VSI): it is regarded as the response spectrum intensity for a damping coefficient of 5%, and was first proposed for earth and rock fill dams, which generally have fundamental periods between 0.6 and 2.0 seconds (Von Thun, Roehm, Scott, & Wilson, 1988).

$$VSI = \int_{0.1}^{2.5} S_v(\xi=0.05, T) dT \quad (5)$$

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

2.3. Peak ground motion parameters

Peak parameters represent ground-motion amplitude, including peak ground acceleration (PGA), peak ground velocity (PGV), and peak ground displacement (PGD). In this paper, PGA is used since it was regarded as an efficient parameter to present the potential damage of an earthquake in the previous research.

3. Earthquake Records

One hundred and twenty-five far-fault records of different earthquakes were selected from the Strong Motion Database (PEER). The magnitudes of the selected earthquakes are between 5.9 and 7.6 on Richter scale. The details of earthquakes are shown in Table 2.

Table 2. Data of earthquake records

No	Earthquake	Station	M	PGA (g)	a _{RMS} (g)	I _a (m/sec)	I _c	A95 (g)	ASI (g.sec)	VSI (cm)
1	Taiwan SMART1(5) 1981/01/29	25 SMART1 C00	5.9	0.114	0.021	0.134	0.013	0.112	0.125	43.150
2	Taiwan SMART1(5) 1981/01/29	25 SMART1 C00	5.9	0.096	0.016	0.081	0.009	0.096	0.113	23.259
3	Taiwan SMART1(5) 1981/01/29	27 SMART1 I12	5.9	0.113	0.017	0.129	0.012	0.111	0.127	40.690
4	Taiwan SMART1(5) 1981/01/29	28 SMART1 M01	5.9	0.178	0.025	0.232	0.019	0.175	0.186	51.708
5	Taiwan SMART1(5) 1981/01/29	29 SMART1 M07	5.9	0.111	0.014	0.104	0.010	0.110	0.114	25.790
6	Taiwan SMART1(5) 1981/01/29	29 SMART1 M07	5.9	0.109	0.015	0.109	0.010	0.108	0.096	39.703
7	Taiwan SMART1(5) 1981/01/29	30 SMART1 O01	5.9	0.115	0.015	0.109	0.010	0.114	0.116	42.916
8	Whittier Narrows 1987/10/01 14:42	951 Brea Dam (Downstream)	6	0.163	0.020	0.191	0.016	0.161	0.151	22.209
9	Whittier Narrows 1987/10/01 14:42	951 Brea Dam (Downstream)	6	0.313	0.030	0.417	0.029	0.312	0.260	45.690
10	Whittier Narrows 1987/10/01 14:42	14403 LA - 116th St School	6	0.294	0.027	0.463	0.029	0.291	0.207	67.493
11	Whittier Narrows	24399 Mt Wilson -	6	0.123	0.015	0.147	0.012	0.121	0.073	15.251

	1987/10/01 14:42	CIT Seis Sta								
12	Whittier Narrows 1987/10/01 14:42	90012 Burbank - N Buena Vista	6	0.191	0.026	0.386	0.025	0.187	0.204	41.871
13	Whittier Narrows 1987/10/01 14:42	90081 Carson - Water St	6	0.104	0.020	0.189	0.016	0.102	0.113	39.820
14	Whittier Narrows 1987/10/01 14:42	90081 Carson - Water St	6	0.133	0.021	0.202	0.017	0.131	0.085	45.130
15	Whittier Narrows 1987/10/01 14:42	90091 LA - Saturn St	6	0.099	0.015	0.111	0.011	0.097	0.100	20.242
16	Whittier Narrows 1987/10/01 14:42	90060 La Crescenta - New York	6	0.134	0.017	0.130	0.012	0.133	0.110	37.106
17	Whittier Narrows 1987/10/01 14:42	90060 La Crescenta - New York	6	0.141	0.023	0.237	0.019	0.138	0.128	44.874
18	Whittier Narrows 1987/10/01 14:42	90084 Lakewood - Del Amo Blvd	6	0.277	0.038	0.644	0.040	0.274	0.230	104.200
19	Whittier Narrows 1987/10/01 14:42	90084 Lakewood - Del Amo Blvd	6	0.178	0.024	0.272	0.021	0.176	0.149	38.602
20	Whittier Narrows 1987/10/01 14:42	951 Brea Dam (L Abut)	6	0.118	0.015	0.112	0.011	0.116	0.094	19.904
21	Whittier Narrows 1987/10/01 14:42	951 Brea Dam (L Abut)	6	0.149	0.020	0.186	0.015	0.147	0.141	33.818
22	Whittier Narrows 1987/10/01 14:42	697 Orange Co. Reservoir	6	0.185	0.024	0.260	0.020	0.184	0.192	34.630
23	Coalinga 1983/05/02 23:42	36177 Parkfield - Vineyard Cany 2E	6.4	0.161	0.025	0.393	0.025	0.158	0.199	80.177
24	Coalinga 1983/05/02 23:42	46314 Cantua Creek School	6.4	0.227	0.035	0.738	0.041	0.224	0.210	101.736
25	Coalinga 1983/05/02 23:42	46314 Cantua Creek School	6.4	0.281	0.043	1.151	0.057	0.277	0.338	112.487
26	Coalinga 1983/05/02 23:42	36456 Parkfield - Fault Zone 14	6.4	0.274	0.038	0.880	0.046	0.270	0.215	141.347
27	Coalinga 1983/05/02 23:42	36457 Parkfield - Fault Zone 16	6.4	0.195	0.024	0.363	0.024	0.193	0.172	71.214
28	Imperial Valley 1979/10/15 23:16	6617 Cucapah	6.5	0.309	0.041	1.024	0.052	0.305	0.271	128.809
29	Imperial Valley 1979/10/15 23:16	5059 El Centro Array #13	6.5	0.117	0.021	0.265	0.019	0.113	0.113	54.499
30	Imperial Valley 1979/10/15 23:16	6605 Delta	6.5	0.351	0.046	3.290	0.099	0.336	0.273	163.343
31	Imperial Valley 1979/10/15 23:16	6605 Delta	6.5	0.229	0.039	2.397	0.078	0.214	0.236	115.162
32	San Fernando 1971/02/09 14:00	24278 Castaic - Old Ridge Route	6.6	0.268	0.045	0.946	0.053	0.263	0.225	90.941
33	San Fernando 1971/02/09 14:00	135 LA - Hollywood Stor Lot	6.6	0.210	0.039	0.650	0.040	0.206	0.217	79.199
34	San Fernando 1971/02/09 14:00	135 LA - Hollywood Stor Lot	6.6	0.174	0.032	0.447	0.031	0.170	0.157	55.872

35	San Fernando 1971/02/09 14:00	126 Lake Hughes #4	6.6	0.192	0.021	0.248	0.018	0.190	0.115	25.478
36	San Fernando 1971/02/09 14:00	126 Lake Hughes #4	6.6	0.153	0.019	0.207	0.016	0.151	0.120	36.675
37	Northridge 1994/01/17 12:31	24278 Castaic - Old Ridge Route	6.7	0.568	0.067	2.788	0.110	0.561	0.524	212.356
38	Northridge 1994/01/17 12:31	24278 Castaic - Old Ridge Route	6.7	0.514	0.072	3.163	0.121	0.505	0.422	254.427
39	Northridge 1994/01/17 12:31	24303 LA - Hollywood Stor FF	6.7	0.231	0.039	0.937	0.049	0.225	0.210	96.157
40	Northridge 1994/01/17 12:31	24303 LA - Hollywood Stor FF	6.7	0.358	0.057	2.005	0.086	0.350	0.336	114.997
41	Northridge 1994/01/17 12:31	90014 Beverly Hills - 12520 Mulhol	6.7	0.617	0.090	2.991	0.132	0.609	0.522	135.052
42	Northridge 1994/01/17 12:31	90049 Pacific Palisades - Sunset Blvd	6.7	0.197	0.041	0.647	0.041	0.194	0.206	60.364
43	Northridge 1994/01/17 12:31	24538 Santa Monica City Hall	6.7	0.370	0.044	1.179	0.058	0.365	0.271	126.349
44	Northridge 1994/01/17 12:31	24538 Santa Monica City Hall	6.7	0.883	0.068	2.846	0.112	0.877	0.628	171.943
45	Northridge 1994/01/17 12:31	78 Stone Canyon	6.7	0.252	0.040	0.981	0.050	0.245	0.293	99.040
46	Northridge 1994/01/17 12:31	78 Stone Canyon	6.7	0.388	0.042	1.065	0.054	0.385	0.332	104.294
47	Northridge 1994/01/17 12:31	5081 Topanga - Fire Sta	6.7	0.266	0.047	0.811	0.050	0.261	0.248	45.095
48	Northridge 1994/01/17 12:31	90015 LA - Chalon Rd	6.7	0.225	0.036	0.615	0.038	0.223	0.213	80.513
49	Northridge 1994/01/17 12:31	90015 LA - Chalon Rd	6.7	0.185	0.037	0.647	0.039	0.181	0.183	107.234
50	Northridge 1994/01/17 12:31	90016 LA - N Faring Rd	6.7	0.273	0.038	0.667	0.041	0.270	0.194	74.469
51	Northridge 1994/01/17 12:31	90016 LA - N Faring Rd	6.7	0.242	0.043	0.845	0.048	0.239	0.212	95.334
52	Northridge 1994/01/17 12:31	90017 LA - Wonderland Ave	6.7	0.172	0.021	0.201	0.017	0.171	0.125	50.426
53	Northridge 1994/01/17 12:31	90017 LA - Wonderland Ave	6.7	0.112	0.018	0.143	0.013	0.110	0.095	34.293
54	Northridge 1994/01/17 12:31	90017 LA - Wonderland Ave	6.7	0.178	0.031	0.448	0.030	0.174	0.187	48.909
55	Northridge 1994/01/17 12:31	90017 LA - Wonderland Ave	6.7	0.159	0.025	0.289	0.022	0.156	0.133	38.547
56	Northridge 1994/01/17 12:31	90054 LA - Centinela St	6.7	0.322	0.046	0.994	0.055	0.319	0.264	117.359
57	Northridge 1994/01/17 12:31	90013 Beverly Hills - 14145 Mulhol	6.7	0.416	0.082	3.073	0.128	0.408	0.353	266.127

58	SupersttnHills(A) 1987/11/24 05:14	5210 Wildlife Liquef. Array	6.7	0.134	0.023	0.253	0.020	0.131	0.127	54.161
59	Supersttn Hills(A) 1987/11/24 05:14	5210 Wildlife Liquef. Array	6.7	0.132	0.024	0.264	0.020	0.130	0.124	50.167
60	Supersttn Hills(B) 1987/11/24 13:16	5052 Plaster City	6.7	0.121	0.030	0.299	0.024	0.119	0.137	52.374
61	Supersttn Hills(B) 1987/11/24 13:16	5052 Plaster City	6.7	0.186	0.043	0.632	0.042	0.183	0.207	87.011
62	Supersttn Hills(B) 1987/11/24 13:16	5210 Wildlife Liquef. Array	6.7	0.181	0.032	0.694	0.038	0.175	0.146	102.162
63	Supersttn Hills(B) 1987/11/24 13:16	5210 Wildlife Liquef. Array	6.7	0.207	0.043	1.229	0.058	0.201	0.229	171.133
64	Supersttn Hills(B) 1987/11/24 13:16	5061 Calipatria Fire Station	6.7	0.180	0.031	0.337	0.026	0.177	0.134	57.923
65	Supersttn Hills(B) 1987/11/24 13:16	5061 Calipatria Fire Station	6.7	0.247	0.040	0.539	0.037	0.244	0.183	66.419
66	Supersttn Hills(B) 1987/11/24 13:16	5062 Salton Sea Wildlife Refuge	6.7	0.119	0.023	0.177	0.016	0.116	0.097	41.923
67	Supersttn Hills(B) 1987/11/24 13:16	5062 Salton Sea Wildlife Refuge	6.7	0.167	0.032	0.360	0.028	0.163	0.129	75.229
68	Spitak, Armenia 1988/12/07	12 Gukasian	6.8	0.199	0.030	0.279	0.023	0.196	0.139	84.914
69	Spitak, Armenia 1988/12/07	12 Gukasian	6.8	0.175	0.031	0.299	0.025	0.172	0.185	58.006
70	Kobe 1995/01/16 20:46	Station: 0 Kakogawa	6.9	0.251	0.040	1.031	0.052	0.245	0.229	106.281
71	Kobe 1995/01/16 20:46	Station: 0 Kakogawa	6.9	0.345	0.052	1.687	0.075	0.337	0.330	153.574
72	Loma Prieta 1989/10/18 00:05	57425 Gilroy Array #7	6.9	0.223	0.036	0.775	0.042	0.219	0.250	61.218
73	Loma Prieta 1989/10/18 00:05	57425 Gilroy Array #7	6.9	0.318	0.037	0.841	0.045	0.315	0.321	62.428
74	Loma Prieta 1989/10/18 00:05	57217 Coyote Lake Dam	6.9	0.484	0.049	1.503	0.069	0.480	0.301	146.233
75	Loma Prieta 1989/10/18 00:05	57217 Coyote Lake Dam	6.9	0.151	0.026	0.428	0.027	0.149	0.147	72.943
76	Loma Prieta 1989/10/18 00:05	57504 Coyote Lake Dam (Downst)	6.9	0.160	0.024	0.352	0.023	0.157	0.173	55.524
77	Loma Prieta 1989/10/18 00:05	57504 Coyote Lake Dam (Downst)	6.9	0.179	0.027	0.464	0.029	0.177	0.192	86.475
78	Loma Prieta 1989/10/18 00:05	1652 Anderson Dam (Downstream)	6.9	0.244	0.036	0.797	0.043	0.238	0.249	85.336
79	Loma Prieta 1989/10/18 00:05	1652 Anderson Dam (Downstream)	6.9	0.240	0.036	0.801	0.043	0.236	0.215	82.211
80	Loma Prieta 1989/10/18 00:05	58223 SF Intern. Airport	6.9	0.329	0.038	0.901	0.047	0.326	0.261	118.259
81	Loma Prieta	58223 SF Intern.	6.9	0.236	0.037	0.857	0.046	0.232	0.263	103.645

	1989/10/18 00:05	Airport								
82	Loma Prieta 1989/10/18 00:05	1656 Hollister Diff. Array	6.9	0.269	0.036	0.801	0.043	0.265	0.203	159.902
83	Loma Prieta 1989/10/18 00:05	1656 Hollister Diff. Array	6.9	0.279	0.041	1.036	0.053	0.278	0.273	136.563
84	Loma Prieta 1989/10/18 00:05	1695 Sunnyvale - Colton Ave	6.9	0.207	0.033	0.651	0.037	0.203	0.151	100.940
85	Loma Prieta 1989/10/18 00:05	1695 Sunnyvale - Colton Ave	6.9	0.208	0.035	0.755	0.042	0.205	0.217	104.878
86	Loma Prieta 1989/10/18 00:05	57066 Agnews State Hospital	6.9	0.172	0.027	0.442	0.028	0.168	0.182	62.067
87	Loma Prieta 1989/10/18 00:05	57066 Agnews State Hospital	6.9	0.159	0.025	0.374	0.024	0.156	0.135	76.225
88	Irpinia, Italy 1980/11/23 19:34	Bagnoli Irpino	6.9	0.139	0.024	0.338	0.023	0.135	0.112	81.387
89	Irpinia, Italy 1980/11/23 19:34	Bagnoli Irpino	6.9	0.202	0.028	0.434	0.028	0.198	0.129	123.055
90	Irpinia, Italy 1980/11/23 19:34	Sturno	6.9	0.247	0.044	1.212	0.059	0.242	0.258	134.207
91	Cape Mendocino 1992/04/25 18:06	89486 Fortuna - Fortuna Blvd	7.1	0.116	0.020	0.261	0.018	0.114	0.098	76.638
92	Cape Mendocino 1992/04/25 18:06	89486 Fortuna - Fortuna Blvd	7.1	0.114	0.019	0.239	0.017	0.111	0.100	70.280
93	Landers 1992/06/28 11:58	23 Coolwater	7.3	0.283	0.053	1.215	0.065	0.278	0.334	85.675
94	Landers 1992/06/28 11:58	23 Coolwater	7.3	0.417	0.071	2.172	0.100	0.409	0.383	180.009
95	Landers 1992/06/28 11:58	12149 Desert Hot Springs	7.3	0.171	0.030	0.707	0.037	0.165	0.167	64.024
96	Landers 1992/06/28 11:58	22074 Yermo Fire Station	7.3	0.152	0.032	0.677	0.037	0.147	0.174	94.596
97	Landers 1992/06/28 11:58	5070 North Palm Springs	7.3	0.135	0.024	0.638	0.032	0.130	0.130	63.777
98	Landers 1992/06/28 11:58	5070 North Palm Springs	7.3	0.133	0.025	0.693	0.034	0.125	0.116	78.062
99	Chi-Chi, Taiwan 1999/09/20	CHY034	7.6	0.248	0.022	1.461	0.046	0.243	0.204	173.391
100	Chi-Chi, Taiwan 1999/09/20	CHY034	7.6	0.309	0.024	1.770	0.053	0.301	0.204	194.495
101	Chi-Chi, Taiwan 1999/09/20	CHY036	7.6	0.203	0.034	1.560	0.058	0.196	0.194	122.216
102	Chi-Chi, Taiwan 1999/09/20	CHY036	7.6	0.291	0.037	1.864	0.067	0.281	0.220	178.792
103	Chi-Chi, Taiwan 1999/09/20	CHY092	7.6	0.111	0.020	0.943	0.035	0.105	0.080	106.444
104	Chi-Chi, Taiwan 1999/09/20	CHY092	7.6	0.081	0.015	0.537	0.023	0.077	0.061	76.809

105	Chi-Chi, Taiwan 1999/09/20	CHY104	7.6	0.162	0.025	1.468	0.049	0.153	0.141	149.957
106	Chi-Chi, Taiwan 1999/09/20	TCU107	7.6	0.158	0.031	1.330	0.052	0.151	0.124	158.642
107	Chi-Chi, Taiwan 1999/09/20	TCU107	7.6	0.124	0.029	1.194	0.048	0.115	0.121	142.700
108	Chi-Chi, Taiwan 1999/09/20	TCU040	7.6	0.122	0.019	0.523	0.026	0.118	0.099	67.844
109	Chi-Chi, Taiwan 1999/09/20	TCU040	7.6	0.148	0.022	0.650	0.030	0.142	0.133	78.630
110	Chi-Chi, Taiwan 1999/09/20	TCU042	7.6	0.199	0.026	0.925	0.039	0.191	0.175	99.508
111	Chi-Chi, Taiwan 1999/09/20	TCU042	7.6	0.245	0.029	1.140	0.046	0.237	0.206	103.714
112	Chi-Chi, Taiwan 1999/09/20	TCU111	7.6	0.099	0.023	0.702	0.032	0.094	0.075	88.376
113	Chi-Chi, Taiwan 1999/09/20	TCU111	7.6	0.136	0.025	0.870	0.038	0.129	0.086	105.793
114	Chi-Chi, Taiwan 1999/09/20	TCU141	7.6	0.101	0.017	0.706	0.028	0.094	0.079	85.646
115	Chi-Chi, Taiwan 1999/09/20	TCU141	7.6	0.080	0.015	0.506	0.022	0.076	0.059	84.460
116	Chi-Chi, Taiwan 1999/09/20	TCU038	7.6	0.168	0.027	1.034	0.043	0.159	0.175	103.257
117	Chi-Chi, Taiwan 1999/09/20	TCU038	7.6	0.140	0.023	0.757	0.034	0.136	0.135	75.459
118	Chi-Chi, Taiwan 1999/09/20	Station: TCU047	7.6	0.301	0.032	1.452	0.055	0.292	0.230	159.983
119	Chi-Chi, Taiwan 1999/09/20	CHY002	7.6	0.117	0.018	0.732	0.029	0.111	0.085	98.499
120	Chi-Chi, Taiwan 1999/09/20	CHY002	7.6	0.146	0.019	0.794	0.031	0.138	0.094	84.326
121	Chi-Chi, Taiwan 1999/09/20	CHY010	7.6	0.219	0.019	0.716	0.030	0.214	0.225	76.909
122	Chi-Chi, Taiwan 1999/09/20	CHY010	7.6	0.171	0.018	0.665	0.028	0.165	0.206	80.776
123	Chi-Chi, Taiwan 1999/09/20	CHY046	7.6	0.179	0.023	0.763	0.034	0.175	0.168	98.069
124	Chi-Chi, Taiwan 1999/09/20	CHY046	7.6	0.141	0.020	0.566	0.027	0.137	0.123	88.499

4. Structural modeling and analysis

The IDARC computer program (Valles & Reinhorn, 2010) was used to model the RC frames. A ten-story frame was modeled to confirm the results of the program, based on shaking table tests (Cecen, 1979). The program can extract response information on selected sub-assemblages and output specified displacement, drift, and story shear histories. It uses a generalized fiber model for the generation of moment-curvature envelopes based on cross-sectional data. P-Delta effects are included in the step-by-step analysis, and a single-step correction is applied to control unbalanced forces during event transition (stiffness changes during loading and unloading) (Monavari & Massumi, 2012). The three-parameter Park hysteretic model, which is used for modeling members in IDARC, is shown in Fig. 2.

Fig. 2. Hysteretic model used in the analysis

The comparison of the analytical and experimental results in terms of (i) peak accelerations is illustrated in Fig. 3, and (ii) peak displacements are shown in Fig. 4. The maximum displacements reported in Cecen (1979) are based on one-half of the double amplitudes, while the IDARC values are absolute peak. Based on the comparison of the analytical and experimental results, the verification of the IDARC results is confirmed.

Fig. 3. Computed versus observed peak acceleration response

Fig. 4. Computed versus observed peak displacement response

Figs. 5-7 display the schematic model of three different RC frames (3, 9, and 12 story). In all these frames, the height and length of each story are 3.2, and 4.0 m, respectively. Tables 3-5 indicates the details of the frame sections, which are designed based on the 2800 Standard of Iran for earthquake loading (Iranian code of practice for seismic resistance design of buildings: Standard no. 2800 2005) and Iranian National Building Codes, Part 9: Design and Construction of Reinforced Concrete Buildings (Iranian national building codes,

Part 9 2013). The distributed dead and live loads of 29700 N/m and 4800 N/m are applied to the beams at all the stories. The concrete is assumed to have a compressive strength of 25 MPa. The steel has a yield strength of 400 MPa and a modulus of elasticity of 210000 MPa. The frames are designed based on ACI provisions (American Concrete Institute, 2008). The frames were subjected to the selected records of the earthquakes and nonlinear dynamic analyses were conducted.

Fig. 5. 3-story RC frame

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

Type	B×D (mm)	Reinforcement		Critical Stirrups	Other Stirrups
Column ₁	350×350	8Φ18		Φ10@150	Φ10@200
Column ₂	300×300	8Φ16		Φ10@150	Φ10@200
Beam ₁	350×350	3Φ20	3Φ16	Φ10@80	Φ10@175
		3Φ14	---		
Beam ₂	300×300	3Φ20	3Φ14	Φ10@75	Φ10@150

Fig. 6. 9-story RC frame

Table 4. Details of Column and Beam 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
Beam ₁	450×500	3Φ22	3Φ22	Φ8@100	Φ8@200
		3Φ22	1Φ16		
Beam ₂	450×450	3Φ18	3Φ20	Φ8@100	Φ8@200
		3Φ18	2Φ14		
Beam ₃	400×450	3Φ18	3Φ20	Φ8@85	Φ8@175
		3Φ16	1Φ14		
Beam ₄	350×400	3Φ18	3Φ16	Φ8@85	Φ8@175
		3Φ16	1Φ16		
Beam ₅	350×400	3Φ16	1Φ16	Φ8@85	Φ8@175

Fig. 7. 12-story RC frame

Table 5. Details of Column and Beam sections in 12-story RC frame

Type	B×D (mm)	Reinforcement		Critical Stirrups	Other Stirrups
Column ₁	600×600	16Φ24		Φ10@100	Φ10@200
Column ₂	500×500	12Φ22		Φ10@150	Φ10@200
Column ₃	450×450	12Φ20		Φ10@150	Φ10@200
Column ₄	450×450	8Φ20		Φ10@150	Φ10@200
Column ₅	400×400	8Φ16		Φ10@150	Φ10@200
Beam ₁	600×500	4Φ22	3Φ24	Φ8@100	Φ8@200
		3Φ22	2Φ16		
Beam ₂	500×450	3Φ22	3Φ24	Φ8@100	Φ8@200
		3Φ22	1Φ16		

Beam ₃	450×450	$\frac{3\Phi 18}{3\Phi 16}$	$\frac{3\Phi 20}{2\Phi 14}$	$\Phi 8@100$	$\Phi 8@200$
Beam ₄	450×400	$\frac{3\Phi 18}{3\Phi 16}$	$\frac{3\Phi 20}{1\Phi 14}$	$\Phi 8@100$	$\Phi 8@200$
Beam ₅	400×350	$\frac{3\Phi 18}{3\Phi 16}$	$\frac{1\Phi 16}{---}$	$\Phi 8@100$	$\Phi 8@200$

5. Analytical results and discussion

The correlation among the variations of fundamental period and seismic parameters which were extracted from the records were calculated by mathematical methods after the nonlinear dynamic analyses of frame variations of the fundamental period were obtained.

Pearson correlation coefficient is used to evaluate the strength of the linear inter-relationship between two sets of variables X and Y, as follows:

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

where $\bar{X}$ and $\bar{Y}$ represent the mean values of X_i and Y_i and n indicates the number of pairs (X_i, Y_i) . The results of Pearson coefficients between seismic parameters and variations of the fundamental period in three RC frames are shown in Fig. 8-10.

Fig. 8. Pearson coefficient between seismic parameters and variations of the fundamental period in 3 Story frame

Fig. 9. Pearson coefficient between seismic parameters and variations of the fundamental period in 9 Story frame

Fig. 10. Pearson coefficient between seismic parameters and variations of the fundamental period in 12 Story frame

Based on the results of Pearson coefficients in Fig. 8-10, in all the frames, I_a , I_c and VSI are highly correlated with the variations of the fundamental period although all the selected parameters have almost high correlations with variations of the fundamental period in 3 and 9 story frames. The comparison between Pearson coefficients in three frames is shown in Fig. 11.

Fig. 11. Comparison between Pearson coefficients in three frames

As illustrated in Fig. 11, the Pearson coefficients in the 12-story frame are lower than the 3 and 9 story frames although Pearson coefficients are almost similar to each other in all the frames.

A regression is a mathematical analysis assessing the relationship between two or more variables. A non-standard regression equation is defined as:

$$Y = b_0 + b_1x_1 + b_2x_2 + \dots + b_rx_r + \varepsilon \quad (7)$$

where b_0 , b_1 , ..., and b_r are non-standard regression coefficients and ε represents a standard error of the regression.

A standard regression equation is defined as:

$$Y_z = \beta_1z_1 + \beta_2z_2 + \dots + \beta_rz_r \quad (8)$$

where β_1 , β_2 and β_r are the standard regression coefficients.

Regression equations among I_a , I_c , and VSI, and variations of the fundamental period were calculated in the three frames. The results are presented in Tables 6-8.

Table 6. Regression coefficient between seismic parameters and variations of the fundamental period in 3 story frame

Model	Unstandardized Coefficients		Standardized Coefficients
	B	Std. Error	Beta
3 Story	(Constant)	.040	.053
	I_a	.550	.051
	(Constant)	-.116	.066
	I_c	15.251	1.423
	(Constant)	-.310	.065
	VSI	.009	.001

Table 7. Regression coefficient between seismic parameters and variations of the fundamental period in 9 story frame

Model	Unstandardized Coefficients		Standardized Coefficients
	B	Std. Error	Beta
9 Story	(Constant)	-.041	.067
	I_a	.603	.064
	(Constant)	-.235	.080
	I_c	17.306	1.737
	(Constant)	-.462	.081
	VSI	.010	.001

Table 8. Regression coefficient between seismic parameters and variations of the fundamental period in 12 story frame

Model	Unstandardized Coefficients		Standardized Coefficients
	B	Std. Error	Beta
12 Story	(Constant)	-.014	.072
	I_a	.586	.069
	(Constant)	-.188	.088
	I_c	16.447	1.903
	(Constant)	-.495	.081
	VSI	.011	.001

By fitting the regression equation between each parameter and variation of the fundamental period in three frames, the relations between the selected seismic parameters and variation of the fundamental period are obtained as follows:

$$dT = 0.6 I_a \quad (9)$$

$$dT = 16 I_c - 0.2 \quad (10)$$

$$dT = 0.01 VSI - 0.4 \quad (11)$$

where, dT represents the variation of the fundamental period.

Further, standard regression equations between each parameter and variation of the fundamental period in three frames are obtained as follows:

$$dT = 0.7 I_a \quad (12)$$

$$dT = 0.7 I_c \quad (13)$$

$$dT = 0.7 VSI \quad (14)$$

Standard regression equations only indicate the relative effect of the variables. Based on the standard regression equations between I_a , I_c , and VSI, and variations of the fundamental period, all three seismic parameters have almost the same correlations with variations of the fundamental period.

By a linear combination of three seismic parameters, I_a , I_c , and VSI, a new parameter is obtained, having more correlation with variations of fundamental period. The results of correlations between the combined parameter and variations of the fundamental period are shown in Table 9.

Table 9. Pearson coefficients between the combined parameter and variations of the fundamental period

Model	Pearson coefficient
3 Story	.782
9 Story	.766
12 Story	.775

Based on the results in Table 9, the Pearson correlations between the combined parameter and variations of the fundamental period are more than the correlation between every single parameter and variation of the fundamental period. Therefore, it can be regarded as an efficient parameter to show the variation of the fundamental period.

Regression equations between combined parameters and variations of the fundamental period were calculated for three frames. The results are shown in Tables 10-12.

Table 10. Regression coefficient between seismic combined parameter and variations of the fundamental period in 3 story frame

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
3 Story	(Constant)	-.332	.088	
	Ia	-.068	.186	-.086
	Ic	4.926	4.846	.225
	VSI	.008	.001	.663

Table 11. Regression coefficient between seismic combined parameter and variations of the fundamental period in 9 story frame

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
9 Story	(Constant)	-.607	.107	
	Ia	-.455	.226	-.491
	Ic	13.865	5.894	.537
	VSI	.010	.002	.726

Table 12. Regression coefficient between seismic combined parameter and variations of the fundamental period in 12 story frame

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
12 Story	(Constant)	-.627	.109	
	Ia	-.419	.229	-.438
	Ic	7.422	5.984	.278
	VSI	.013	.002	.910

The regression coefficients are not close to each other in three frames. Further, it is considered as one of the two parameters I_a or I_c , which seems appropriate to be combined with the other parameters. Accordingly, a new parameter can be extracted by combining I_c and VSI parameters. Table 13 displays the correlation results for the combined parameter and variations of the fundamental period.

Table 13. Pearson coefficient between the combined parameter and variations of the fundamental period

Model	Pearson coefficient
3 Story	.782
9 Story	.757
12 Story	.768

In addition, based on the results in Table 12, the Pearson correlations between the combined parameter and variations of the fundamental period are higher than the correlation between every single parameter and variation of the fundamental period.

Then, regression equations between the combined parameter and variations of the fundamental period were calculated for the three frames. The results are presented in Tables 14-16.

Table 14. Regression coefficients between new seismic combined parameter and variations of the fundamental period in 3 story frame

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
3 Story	(Constant)	-.310	.065	
	Ic	3.368	2.266	.154
	VSI	.007	.001	.649

Table 15. Regression coefficients between new seismic combined parameter and variations of the fundamental period in 9 story frame

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
9 Story	(Constant)	-.463	.081	
	Ic	3.384	2.801	.131
	VSI	.009	.001	.644

Table 16. Regression coefficients between new seismic combined parameter and variations of the fundamental period in 12 story frame

Model		Unstandardized Coefficients		Standardized Coefficients
		B	Std. Error	Beta
12 Story	(Constant)	-.494	.081	
	Ic	2.235	2.835	.094
	VSI	.012	.001	.637

By fitting the regression equation between each parameter and variation of the fundamental period in the three frames, the relations between the selected seismic parameters and variation of the fundamental period are as follows:

$$dT = 3 I_c + 0.01 VSI - 0.4 \quad (15)$$

Furthermore, the standard regression equation between the proposed combined parameter and variation of the fundamental period in three frames is as follows:

$$dT = 0.1 I_c + 0.6 VSI \quad (16)$$

Based on the results, the proposed parameter is highly correlated with variation of fundamental period. In addition, it can be regarded as a valid parameter to present variation of the fundamental period of RC frames under earthquakes since the relations between this parameter and variation of the fundamental period in three frames are close to each other.

6. Conclusions

Three RC frames with various heights were modeled by IDARC program and were subjected to the 124 far-fault records of earthquakes. Then, the seven principle seismic parameters including PGA, a_{RMS} , I_a , I_c , A95, ASI, and VSI were extracted from the records. After the nonlinear dynamic analyses, the damage responses of frames were identified by variation of fundamental period. Eventually, Pearson correlation coefficients were used to study the relations between seismic parameters and variations of the fundamental period in three frames.

The results indicated that Pearson correlations between I_a , I_c , and VSI, and variation of the fundamental period are strong in all the frames while all the selected parameters have almost high correlations with variations of the fundamental period in 3 and 9 story frames.

Regression equations between I_a , I_c , and VSI, and variations of the fundamental period were calculated in three frames and unique equations were achieved by fitting the equations in three frames.

A new parameter was achieved by a linear combination of I_c and VSI which indicated a high correlation with the variation of the fundamental period. Then, the unique equations were achieved between this new parameter and the variation of the fundamental period. This

new parameter can be regarded as a reliable parameter to indicate the variation of the fundamental period under earthquakes since a notable correlation was reported between this new parameter and variation of fundamental period and their relations in three frames are almost similar to each other.

Declarations

Ethical statements (The developed method is the original effort of the authors which is not submitted or published elsewhere)

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Conflict of interest/Competing interests (The Authors declare that they have no conflict of interest)

Availability of data and material (Data and material are available)

Code availability (The developed codes are available)

Plant reproducibility (Not applicable)

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Gels and bolts/ Image manipulation (Not applicable)

High-risk content (Not applicable)

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