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

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Abstract

This research investigated the relation between the main earthquake parameters by incorporating information about ground motions and the difference in the fundamental period. This difference in the fundamental period is one method of assessing structural damage because it can express potential damage from an earthquake. Three RC (3-, 9- and 12-story) frames have been analyzed under far-fault earthquake records using nonlinear dynamic analysis. Mathematical methods then were applied to assess the correlation between the difference in the fundamental period and the principle seismic parameters of PGA, \( a_{\text{RMS}} \), \( I_a \), \( I_c \), A95, ASI and VSI that have been extracted from the records. The best correlations as calculated by the Pearson correlation coefficient values were between \( I_a \), \( I_c \) and VSI and the difference in the fundamental period. The Pearson coefficients for \( I_a \) and \( I_c \) were between 0.621 and 0.767, which signifies a strong correlation. Regression equations indicated new parameters (\( I_c \)VS) with even higher Pearson coefficients of 0.757–0.782 between every parameter and the difference in the fundamental period. The very strong correlation between the newly achieved parameters and the fundamental period indicates that they are appropriate indices for estimating potential structural damage from an earthquake.

Keywords Seismic parameters • Damage potential • Fundamental period • RC frames • Correlation coefficient • Regression equation

1 Introduction

Assessment of the vulnerability of structures to earthquake motion estimates their efficiency and their ability for use after such an event. It predicts the need for maintenance in the future, as well as of rehabilitation and repair of defects caused by damage. Earthquakes damage structures worldwide every year [1] making the estimation of structural damage from earthquakes a point of focus. The resulting damage indices should evaluate the intensity of damage to structures under earthquake loading [2, 3].

Researchers have emphasized the inter-relationship between seismic parameters and structural damage to determine the best seismic parameters for predicting potential structural damage. Those with a high correlation with damage represent the likelihood of damage to a structure caused by an earthquake. A high value indicates that the earthquake will cause major damage to a reinforced concrete (RC) building.

The difference in the fundamental period is one method used to assess structural damage [4] A large number of parameters have been proposed to characterize a seismic event, but no single ground-motion parameter provides an ideal index for damage. The correlation of some seismic parameters with actual damage has been a complex multiparameter subject of research [5]. Elenas et al. claimed that spectral acceleration and energy parameters are highly correlated with damage [6–8]. Samimifar et al. [9] stated that energy based seismic evaluation is a rational approach for seismic assessment of accumulated earthquake induced damage. Danciu [10] identified the peak ground velocity, Arias intensity and spectral intensity as being related to damage.

Alvanitopoulos et al. studied the correlation between damage indices and ground-motion parameters and
proposed the new parameters of maximum amplitude (AHHT_max) and mean amplitude (AHHT_mean) as seismic parameters that play significant roles in the Hilbert–Huang transform [11]. Nanos emphasized the selection of seismic parameters for vulnerability assessment of mid-rise RC structures and concluded that the energy parameters of earthquakes and the Arias intensity are highly correlated with the damage intensity [12, 13].

Chen and Wei [14] considered the correlation between ground-motion parameters and lining damage indices for mountain tunnels. They found the overall lining damage indices to be highly correlated with velocity-related seismic parameters and poorly correlated with spectral parameters. The correlation between the spectral parameters of an earthquake and damage intensity in 3-story RC frames indicated that the Housner intensity [15], acceleration spectrum intensity, and velocity spectrum intensity showed strong correlations with the Park–Ang index, but a weak correlation with the predominant period [16, 17]. Further, the relationship between the earthquake energy parameters and damage to RC frames indicated that $a_{95}$, $I_a$, $I_c$, and A95 are proper parameters for representing potential damage by an earthquake [18].

The results of Massumi and Gholami [19] indicated that frequency-dependent parameters better predicted the damage criteria compared to time-dependent parameters and that no unique time-dependent parameter could satisfactorily describe the structural damage. Wang et al. [20] discussed the correlation between the earthquake duration and damage measures for gravity dams. Comparison of the correlation between the ground-motion duration and damage measures revealed that the strong motion duration calculated using different definitions had no significant influence on damage measures based on the peak displacement response of the dam, but were positively correlated with accumulated damage measures, such as the local damage index, global damage index, and damage energy dissipation. Diaz et al. [21] proposed a new damage index based on two energy functions. Their new damage index linked damage to the characteristics of seismic action, such as its intensity and duration.

Qiu et al. investigated the correlation between structural damage to high-rise chimneys and spectral-acceleration-based earthquake intensity measures which considered the higher mode and period elongation effects. Three RC high-rise chimneys were established and analyzed under far-field ground-motion records. The results showed that the proposed intensity measure had a high correlation with the structural damage indices, especially with the maximum inter-story drift ratio and maximum roof displacement, and was a suitable parameter for predicting structural damage to high-rise chimneys [22].

Chen and Wang studied multipulse characteristics of near-fault ground motions by an automatic detection procedure, which was conducted using a rough pulse signal. The statistical methods between the multipulse and earthquake parameters, including moment magnitudes, site conditions, rupture distances, and types of fault, were discussed. The results demonstrated that pulse periods, which can be described as the period of the pulse with the largest amount of energy, are almost identical to periods of the first pulse in the time domain. They are related not only to magnitudes but also to the fault type and site conditions [23].

Mase et al. [24] researched the ground-motion parameters and site investigations in northern Thailand during the Tarlay earthquake of 2011. The horizontal to vertical ($H/V$) spectral ratio was derived from the fast Fourier transform (FFT) of the ambient noise from microtremor measurements. The spectral acceleration ratios were analyzed to determine the possibility of resonance during the earthquake. They concluded that the (north–south) component of the ground motion recorded had the greatest effect for the ground motion during this strong earthquake in northern Thailand. The $H/V$ spectral ratio could properly determine the possibility of resonance during a strong earthquake. The summary of the literature is presented in Table 1.

In the current study, three RC frames were analyzed and subjected to far-fault earthquake records. The Pearson’s correlation coefficient was used to evaluate the strength of the linear inter-relationship between the sets of data [25, 26]. Using the regression equations between the seismic parameters and the fundamental period as the damage index, new parameters are proposed that show considerable correlation with the fundamental period.

## 2 Seismic Parameters

The parameters of peak ground motion, energy, spectral intensity, and duration have been defined to characterize the seismic event. The main seismic parameters extracted from earthquakes records were selected and have shown a high correlation with the damage intensity in previous studies.

### 2.1 Earthquake Energy Parameters

Calculation of the input energy of a seismic event produces the energy parameters. These parameters convey information about both the amplitude and duration of seismic motion. Some researchers, such as Danciu [10], have classified these parameters based on the intensity of the
ground-motion parameters. Some of these vital energy parameters selected are as follows:

- **Root mean square of acceleration** ($a_{\text{RMS}}$), which considers the amplitude and frequency content of an earthquake record and is defined as:

$$a_{\text{RMS}} = \left( \frac{1}{T_d} \int_0^{T_d} |a(t)|^2 \, dt \right)^{1/2} = (\lambda_0)^2$$

where $T_d$ is the duration of the earthquake record, $a(t)$ represents acceleration at time $t$ and $\lambda_0$ denotes the average intensity.

- **Arias intensity** ($I_a$), which measures the intensity of the ground motion [27] and represents the total energy at the recording station as:

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

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

- **Characteristic intensity** ($I_c$), which is based on the root mean square of acceleration [28] and is defined as:

$$I_c = (a_{\text{RMS}})^3 \times (T_d)^{1/2}$$

where $a_{\text{RMS}}$ represents the root mean square of acceleration and $T_d$ denotes the duration of the earthquake record.

- **A95**, which is the level of acceleration up to 95% of the Arias intensity (Fig. 1) [29].

$$\text{E}_a \text{ is the area bounded by curve } a^2(t) \text{ and the horizontal line at level } A^2, \text{ where } A \text{ is at zero acceleration and area } \text{E}_a$$

gives the Arias intensity. This acceleration level, which gives an $E_a/E_s = 0.05$, 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 have been proposed by researchers. The acceleration spectrum intensity (ASI) is the area under the acceleration response spectrum for periods of between 0.1 and 0.5 s. This parameter was introduced for concrete dams, which generally have fundamental periods of less than 0.5 s [30]. It is defined as:

![Schematic diagram for calculation of A95](image)

**Fig. 1** Schematic diagram for calculation of A95
ASI = \int_{0.1}^{0.5} S_a(\xi = 0.05, T) dT \quad (4)

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

The velocity spectrum intensity (VSI) is the response spectrum intensity for a damping coefficient of 5% and was proposed for earth and rock fill dams, which generally have fundamental periods of between 0.6 and 2.0 s. It can be calculated as:

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

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

2.3 Peak Ground-Motion Parameters

Peak parameters represent the ground-motion amplitude and include the peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD). In this paper, PGA has been used as it is an efficient parameter to represent the potential damage of an earthquake.

3 Evaluation of Damage Intensity

The first attempts to determine the overall damage based on the dynamic characteristics involved changes in the fundamental period or frequency. This index was obtained from testing of laboratory samples of RC elements [31]. Natural frequencies usually decrease with an increase in the structural damage; thus, mathematically, the difference in frequency will have a negative value. This damage index based on frequency difference in the first mode is:

\[
D_G = \frac{\Delta \omega_i}{\omega_0} = \frac{\omega_d - \omega_0}{\omega_0} \quad (6)
\]

where \( \omega_0 \) is the initial frequency of the building and \( \omega_d \) is the frequency of the damaged building.

In order to calculate this index, it is necessary to determine the natural frequencies of the structure. In the current study, differences in the fundamental period were used to assess the damage magnitude in the current study.

4 Earthquake Records

Earthquake records from 125 far-fault earthquakes were selected from the Strong Motion Database [32]. The magnitudes of these earthquakes were between 5.9 and 7.6 on the Richter scale. The details about these earthquakes are shown in Table 2.

5 Structural Modeling and Analysis

The IDARC computer program [33] was used to model the RC frames. A ten-story frame was modeled to confirm the results of the program based on the results of shaking table tests [34]. The program is able to extract response information on selected sub-assemblages and outputs specified by 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 single-step correction is applied to control the unbalanced forces during event transition (changes in stiffness during loading and unloading) [35]. The three-parameter Park hysteretic model, which is used for modeling members in IDARC, is shown in Fig. 2.

Figure 3 shows a comparison of the analytical and experimental results in terms of peak acceleration. Figure 4 shows the results in terms of peak displacement. The maximum displacements reported by Cecen [34] are based on the one half of the double amplitude, while the IDARC values are the absolute peak. A comparison of the analytical and experimental results confirmed the verification of the IDARC results. It can be seen that fairly good agreement was obtained using IDARC. The slight difference between the results can relate to the high possibility of error in the experimental results. However, the known history of IDARC and a review of the previous research has confirmed its reliability.

Figures 5, 6 and 7 display schematic models of three RC frames (3-, 9- and 12-story). In all frames, the height and length of each story was 3.2 and 4.0 m, respectively. Tables 3, 4 and 5 provide details of the frame sections. Dead and live loads of 29,700 N/m and 4800 N/m were applied to the beams at all the stories. The concrete was assumed to have a compressive strength of 25 MPa and the steel to have a yield strength of 400 MPa and a modulus of elasticity of 210,000 MPa. The frames have been designed based on ACI provisions [36]. The frames were subjected to the selected records of the earthquakes and nonlinear dynamic analysis was conducted.

6 Analytical Results and Discussion

The correlation between the fundamental periods and seismic parameters which were extracted from the records were calculated after nonlinear dynamic analysis. The
| No. | Earthquake          | Station                  | M  | PGA (g) | $a_{RMS}$ (g) | $I_p$ (m/s) | $I_c$ (g) | A95 (g) | ASI (g s) | VSI (cm) |
|-----|---------------------|--------------------------|----|---------|---------------|-------------|-----------|---------|-----------|----------|
| 1   | Taiwan SMART1(5)   | 25 SMART1 C00            | 5.9| 0.114   | 0.021         | 0.134       | 0.013     | 0.112   | 0.125     | 43.150   |
| 2   | Taiwan SMART1(5)   | 25 SMART1 C00            | 5.9| 0.096   | 0.016         | 0.081       | 0.009     | 0.096   | 0.113     | 23.259   |
| 3   | Taiwan SMART1(5)   | 27 SMART1 I12            | 5.9| 0.113   | 0.017         | 0.129       | 0.012     | 0.111   | 0.127     | 40.690   |
| 4   | Taiwan SMART1(5)   | 28 SMART1 M01            | 5.9| 0.178   | 0.025         | 0.232       | 0.019     | 0.175   | 0.186     | 51.708   |
| 5   | Taiwan SMART1(5)   | 29 SMART1 M07            | 5.9| 0.111   | 0.014         | 0.104       | 0.010     | 0.110   | 0.114     | 25.790   |
| 6   | Taiwan SMART1(5)   | 29 SMART1 M07            | 5.9| 0.109   | 0.015         | 0.109       | 0.010     | 0.108   | 0.096     | 39.703   |
| 7   | Taiwan SMART1(5)   | 30 SMART1 O01            | 5.9| 0.115   | 0.015         | 0.109       | 0.010     | 0.114   | 0.116     | 42.916   |
| 8   | Whittier Narrows   | 951 Brea Dam (Downstream)| 6  | 0.163   | 0.020         | 0.191       | 0.016     | 0.161   | 0.151     | 22.209   |
| 9   | Whittier Narrows   | 951 Brea Dam (Downstream)| 6  | 0.313   | 0.030         | 0.417       | 0.029     | 0.312   | 0.260     | 45.690   |
| 10  | Whittier Narrows   | 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—CIT Seis Sta| 6   | 0.123   | 0.015         | 0.147       | 0.012     | 0.121   | 0.073     | 15.251   |
| 12  | Whittier Narrows   | 90012 Burbank—N Buena Vista| 6   | 0.191   | 0.026         | 0.386       | 0.025     | 0.187   | 0.204     | 41.871   |
| 13  | Whittier Narrows   | 90081 Carson—Water St    | 6  | 0.104   | 0.020         | 0.189       | 0.016     | 0.102   | 0.113     | 39.820   |
| 14  | Whittier Narrows   | 90081 Carson—Water St    | 6  | 0.133   | 0.021         | 0.202       | 0.017     | 0.131   | 0.085     | 45.130   |
| 15  | Whittier Narrows   | 90091 LA—Saturn St       | 6  | 0.099   | 0.015         | 0.111       | 0.011     | 0.097   | 0.100     | 20.242   |
| 16  | Whittier Narrows   | 90060 La Crescenta—New York| 6   | 0.134   | 0.017         | 0.130       | 0.012     | 0.133   | 0.110     | 37.106   |
| 17  | Whittier Narrows   | 90060 La Crescenta—New York| 6   | 0.141   | 0.023         | 0.237       | 0.019     | 0.138   | 0.128     | 44.874   |
| 18  | Whittier Narrows   | 90084 Lakewood—Del Amo Blvd| 6   | 0.277   | 0.038         | 0.644       | 0.040     | 0.274   | 0.230     | 104.200  |
| 19  | Whittier Narrows   | 90084 Lakewood—Del Amo Blvd| 6   | 0.178   | 0.024         | 0.272       | 0.021     | 0.176   | 0.149     | 38.602   |
| 20  | Whittier Narrows   | 951 Brea Dam (L. Abut)   | 6  | 0.118   | 0.015         | 0.112       | 0.011     | 0.116   | 0.094     | 19.904   |
| 21  | Whittier Narrows   | 951 Brea Dam (L. Abut)   | 6  | 0.149   | 0.020         | 0.186       | 0.015     | 0.147   | 0.141     | 33.818   |
| 22  | Whittier Narrows   | 697 Orange Co. Reservoir | 6  | 0.185   | 0.024         | 0.260       | 0.020     | 0.184   | 0.192     | 34.630   |
| 23  | Coalinga           | 36177 Parkfield—Vineyard Cany 2E| 6.4| 0.161   | 0.025         | 0.393       | 0.025     | 0.158   | 0.199     | 80.177   |
| 24  | Coalinga           | 46314 Cantua Creek School| 6.4| 0.227   | 0.035         | 0.738       | 0.041     | 0.224   | 0.210     | 101.736  |
Table 2 (continued)

| No. | Earthquake      | Station                                | M   | PGA  (g) | $a_{\text{RMS}}$ (g) | $L_a$ (m/s) | $I_c$ (g) | $A_95$ (g) | ASI (g s) | VSI (cm) |
|-----|-----------------|----------------------------------------|-----|---------|----------------------|-------------|-----------|------------|-----------|----------|
| 25. | Coalinga        | 46314 Cantua Creek School              | 6.4 | 0.281   | 0.043                | 1.151       | 0.057     | 0.277      | 0.338     | 112.487  |
| 26. | Coalinga        | 36456 Parkfield—Fault Zone 14          | 6.4 | 0.274   | 0.038                | 0.880       | 0.046     | 0.270      | 0.215     | 141.347  |
| 27. | Coalinga        | 36457 Parkfield—Fault Zone 16          | 6.4 | 0.195   | 0.024                | 0.363       | 0.024     | 0.193      | 0.172     | 71.214   |
| 28. | Imperial Valley | 6617 Cucapah                           | 6.5 | 0.309   | 0.041                | 1.024       | 0.052     | 0.305      | 0.271     | 128.809  |
| 29. | Imperial Valley | 5059 El Centro Array #13               | 6.5 | 0.117   | 0.021                | 0.265       | 0.019     | 0.113      | 0.113     | 54.499   |
| 30. | Imperial Valley | 6605 Delta                             | 6.5 | 0.351   | 0.046                | 3.290       | 0.099     | 0.336      | 0.273     | 163.343  |
| 31. | Imperial Valley | 6605 Delta                             | 6.5 | 0.229   | 0.039                | 2.397       | 0.078     | 0.214      | 0.236     | 115.162  |
| 32. | San Fernando    | 24278 Castaic—Old Ridge Route          | 6.6 | 0.268   | 0.045                | 0.946       | 0.053     | 0.263      | 0.225     | 90.941   |
| 33. | San Fernando    | 135 LA—Hollywood Stor Lot              | 6.6 | 0.210   | 0.039                | 0.650       | 0.040     | 0.206      | 0.217     | 79.199   |
| 34. | San Fernando    | 135 LA—Hollywood Stor Lot              | 6.6 | 0.174   | 0.032                | 0.447       | 0.031     | 0.170      | 0.157     | 55.872   |
| 35. | San Fernando    | 126 Lake Hughes #4                    | 6.6 | 0.192   | 0.021                | 0.248       | 0.018     | 0.190      | 0.115     | 25.478   |
| 36. | San Fernando    | 126 Lake Hughes #4                    | 6.6 | 0.153   | 0.019                | 0.207       | 0.016     | 0.151      | 0.120     | 36.675   |
| 37. | Northridge      | 24278 Castaic—Old Ridge Route          | 6.7 | 0.568   | 0.067                | 2.788       | 0.110     | 0.561      | 0.524     | 212.356  |
| 38. | Northridge      | 24278 Castaic—Old Ridge Route          | 6.7 | 0.514   | 0.072                | 3.163       | 0.121     | 0.505      | 0.422     | 254.427  |
| 39. | Northridge      | 24303 LA—Hollywood Stor FF             | 6.7 | 0.231   | 0.039                | 0.937       | 0.049     | 0.225      | 0.210     | 96.157   |
| 40. | Northridge      | 24303 LA—Hollywood Stor FF             | 6.7 | 0.358   | 0.057                | 2.005       | 0.086     | 0.350      | 0.336     | 114.997  |
| 41. | Northridge      | 90014 Beverly Hills—12520 Mulhol       | 6.7 | 0.617   | 0.090                | 2.991       | 0.132     | 0.609      | 0.522     | 135.052  |
| 42. | Northridge      | 90049 Pacific Palisades—Sunset Blvd    | 6.7 | 0.197   | 0.041                | 0.647       | 0.041     | 0.194      | 0.206     | 60.364   |
| 43. | Northridge      | 24538 Santa Monica City Hall           | 6.7 | 0.370   | 0.044                | 1.179       | 0.058     | 0.365      | 0.271     | 126.349  |
| 44. | Northridge      | 24538 Santa Monica City Hall           | 6.7 | 0.883   | 0.068                | 2.846       | 0.112     | 0.877      | 0.628     | 171.943  |
| 45. | Northridge      | 78 Stone Canyon                        | 6.7 | 0.252   | 0.040                | 0.981       | 0.050     | 0.245      | 0.293     | 99.040   |
| 46. | Northridge      | 78 Stone Canyon                        | 6.7 | 0.388   | 0.042                | 1.065       | 0.054     | 0.385      | 0.332     | 104.294  |
| 47. | Northridge      | 5081 Topanga—Fire Sta                  | 6.7 | 0.266   | 0.047                | 0.811       | 0.050     | 0.261      | 0.248     | 45.095   |
| 48. | Northridge      | 90015 LA—Chalon Rd                     | 6.7 | 0.225   | 0.036                | 0.615       | 0.038     | 0.223      | 0.213     | 80.513   |
| No. | Earthquake         | Station                          | $M$ | PGA (g) | $a_{RMS}$ (g) | $I_a$ (m/s) | $I_c$ | A95 (g) | ASI (g s) | VSI (cm) |
|-----|--------------------|----------------------------------|-----|---------|---------------|-------------|-------|---------|-----------|----------|
| 49. | Northridge         | 90015 LA—Chalon Rd               | 6.7 | 0.185  | 0.037         | 0.647       | 0.039 | 0.181   | 0.183     | 107.234  |
| 50. | Northridge         | 90016 LA—N Faring Rd             | 6.7 | 0.273  | 0.038         | 0.667       | 0.041 | 0.270   | 0.194     | 74.469   |
| 51. | Northridge         | 90016 LA—N Faring Rd             | 6.7 | 0.242  | 0.043         | 0.845       | 0.048 | 0.239   | 0.212     | 95.334   |
| 52. | Northridge         | 90017 LA—Wonderland Ave          | 6.7 | 0.172  | 0.021         | 0.201       | 0.017 | 0.171   | 0.125     | 50.426   |
| 53. | Northridge         | 90017 LA—Wonderland Ave          | 6.7 | 0.112  | 0.018         | 0.143       | 0.013 | 0.110   | 0.095     | 34.293   |
| 54. | Northridge         | 90017 LA—Wonderland Ave          | 6.7 | 0.178  | 0.031         | 0.448       | 0.030 | 0.174   | 0.187     | 48.909   |
| 55. | Northridge         | 90054 LA—Centinela St            | 6.7 | 0.322  | 0.046         | 0.994       | 0.055 | 0.319   | 0.264     | 117.359  |
| 56. | Northridge         | 90013 Beverly Hills—14145 Mulhol | 6.7 | 0.416  | 0.082         | 3.073       | 0.128 | 0.408   | 0.353     | 266.127  |
| 57. | Superstition Hills(A) | 5210 Wildlife Liquef. Array     | 6.7 | 0.134  | 0.023         | 0.253       | 0.020 | 0.131   | 0.127     | 54.161   |
| 58. | Superstition Hills(B) | 5052 Plaster City               | 6.7 | 0.121  | 0.030         | 0.299       | 0.024 | 0.119   | 0.137     | 52.374   |
| 59. | Superstition Hills(B) | 5061 Calipatria Fire Station     | 6.7 | 0.186  | 0.043         | 0.632       | 0.042 | 0.183   | 0.207     | 87.011   |
| 62. | Superstition Hills(B) | 5062 Salton Sea Wildlife Refuge | 6.7 | 0.119  | 0.023         | 0.177       | 0.016 | 0.116   | 0.097     | 41.923   |
| 63. | Superstition Hills(B) | 5062 Salton Sea Wildlife Refuge | 6.7 | 0.167  | 0.032         | 0.360       | 0.028 | 0.163   | 0.129     | 75.229   |
| 66. | Spitak, Armenia    | 12 Gukasian                      | 6.8 | 0.199  | 0.030         | 0.279       | 0.023 | 0.196   | 0.139     | 84.914   |
| 67. | Kobe               | 12 Gukasian                      | 6.8 | 0.175  | 0.031         | 0.299       | 0.025 | 0.172   | 0.185     | 58.006   |
| 70. | Kobe               | Station: 0 Kakogawa              | 6.9 | 0.251  | 0.040         | 1.031       | 0.052 | 0.245   | 0.229     | 106.281  |
| 71. | Kobe               | Station: 0 Kakogawa              | 6.9 | 0.345  | 0.052         | 1.687       | 0.075 | 0.337   | 0.330     | 153.574  |
| 72. | Loma Prieta        | 57425 Gilroy Array #7            | 6.9 | 0.223  | 0.036         | 0.775       | 0.042 | 0.219   | 0.250     | 61.218   |
Table 2 (continued)

| No. | Earthquake | Station                      | $M$ | PGA (g) | agMS (g) | Ia (m/s) | Ic | A95 (g) | ASI (g s) | VSI (cm) |
|-----|------------|------------------------------|-----|---------|----------|---------|----|--------|----------|---------|
| 73. | Loma Prieta | 57425 Gilroy Array #7        | 6.9 | 0.318   | 0.037    | 0.841   | 0.045| 0.315  | 0.321    | 62.428  |
| 74. | Loma Prieta | 57217 Coyote Lake Dam        | 6.9 | 0.484   | 0.049    | 1.503   | 0.069| 0.480  | 0.301    | 146.233 |
| 75. | Loma Prieta | 57217 Coyote Lake Dam        | 6.9 | 0.151   | 0.026    | 0.428   | 0.027| 0.149  | 0.147    | 72.943  |
| 76. | Loma Prieta | 57504 Coyote Lake Dam (Downst) | 6.9 | 0.160   | 0.024    | 0.352   | 0.023| 0.157  | 0.173    | 55.524  |
| 77. | Loma Prieta | 57504 Coyote Lake Dam (Downst) | 6.9 | 0.179   | 0.027    | 0.464   | 0.029| 0.177  | 0.192    | 86.475  |
| 78. | Loma Prieta | 1652 Anderson Dam (Downstream) | 6.9 | 0.244   | 0.036    | 0.797   | 0.043| 0.238  | 0.249    | 85.336  |
| 79. | Loma Prieta | 1652 Anderson Dam (Downstream) | 6.9 | 0.240   | 0.036    | 0.801   | 0.043| 0.236  | 0.215    | 82.211  |
| 80. | Loma Prieta | 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. Airport      | 6.9 | 0.236   | 0.037    | 0.857   | 0.046| 0.232  | 0.263    | 103.645 |
| 82. | Loma Prieta | 1656 Hollister Diff. Array   | 6.9 | 0.269   | 0.036    | 0.801   | 0.043| 0.265  | 0.203    | 159.902 |
| 83. | Loma Prieta | 1656 Hollister Diff. Array   | 6.9 | 0.279   | 0.041    | 1.036   | 0.053| 0.278  | 0.273    | 136.563 |
| 84. | Loma Prieta | 1695 Sunnyvale—Colton Ave    | 6.9 | 0.207   | 0.033    | 0.651   | 0.037| 0.203  | 0.151    | 100.940 |
| 85. | Loma Prieta | 1695 Sunnyvale—Colton Ave    | 6.9 | 0.208   | 0.035    | 0.755   | 0.042| 0.205  | 0.217    | 104.878 |
| 86. | Loma Prieta | 57066 Agnews State Hospital  | 6.9 | 0.172   | 0.027    | 0.442   | 0.028| 0.168  | 0.182    | 62.067  |
| 87. | Loma Prieta | 57066 Agnews State Hospital  | 6.9 | 0.159   | 0.025    | 0.374   | 0.024| 0.156  | 0.135    | 76.225  |
| 88. | Irpinia, Italy | Bagnoli Irpino | 6.9 | 0.139   | 0.024    | 0.338   | 0.023| 0.135  | 0.112    | 81.387  |
| 89. | Irpinia, Italy | Bagnoli Irpino | 6.9 | 0.202   | 0.028    | 0.434   | 0.028| 0.198  | 0.129    | 123.055 |
| 90. | Irpinia, Italy | Sturno              | 6.9 | 0.247   | 0.044    | 1.212   | 0.059| 0.242  | 0.258    | 134.207 |
| 91. | Cape Mendocino | 89486 Fortuna—Fortuna Blvd | 7.1 | 0.116   | 0.020    | 0.261   | 0.018| 0.114  | 0.098    | 76.638  |
| 92. | Cape Mendocino | 89486 Fortuna—Fortuna Blvd | 7.1 | 0.114   | 0.019    | 0.239   | 0.017| 0.111  | 0.100    | 70.280  |
| 93. | Landers     | 23 Coolwater           | 7.3 | 0.283   | 0.053    | 1.215   | 0.065| 0.278  | 0.334    | 85.675  |
| 94. | Landers     | 23 Coolwater           | 7.3 | 0.417   | 0.071    | 2.172   | 0.100| 0.409  | 0.383    | 180.009 |
| 95. | Landers     | 12149 Desert Hot Springs | 7.3 | 0.171   | 0.030    | 0.707   | 0.037| 0.165  | 0.167    | 64.024  |
| 96. | Landers     | 22074 Yermo Fire Station | 7.3 | 0.152   | 0.032    | 0.677   | 0.037| 0.147  | 0.174    | 94.596  |
Table 2 (continued)

| No. | Earthquake       | Station         | M     | PGA (g) | $a_{rms}$ (g) | $I_e$ (m/s) | $I_c$ | A95 (g) | ASI (g s) | VSI (cm) |
|-----|------------------|-----------------|-------|---------|---------------|-------------|-------|---------|-----------|----------|
| 97. | Landers          | 5070 North Palm Springs | 7.3   | 0.135   | 0.024         | 0.638       | 0.032 | 0.130   | 0.130     | 63.777   |
| 98. | Landers          | 5070 North Palm Springs | 7.3   | 0.133   | 0.025         | 0.693       | 0.034 | 0.125   | 0.116     | 78.062   |
| 99. | Chi-Chi, Taiwan  | CHY034          | 7.6   | 0.248   | 0.022         | 1.461       | 0.046 | 0.243   | 0.204     | 173.391  |
| 100.| Chi-Chi, Taiwan  | CHY034          | 7.6   | 0.309   | 0.024         | 1.770       | 0.053 | 0.301   | 0.204     | 194.495  |
| 101.| Chi-Chi, Taiwan  | CHY036          | 7.6   | 0.203   | 0.034         | 1.560       | 0.058 | 0.196   | 0.194     | 122.216  |
| 102.| Chi-Chi, Taiwan  | CHY036          | 7.6   | 0.291   | 0.037         | 1.864       | 0.067 | 0.281   | 0.220     | 178.792  |
| 103.| Chi-Chi, Taiwan  | CHY092          | 7.6   | 0.111   | 0.020         | 0.943       | 0.035 | 0.105   | 0.080     | 106.444  |
| 104.| Chi-Chi, Taiwan  | CHY092          | 7.6   | 0.081   | 0.015         | 0.537       | 0.023 | 0.077   | 0.061     | 76.809   |
| 105.| Chi-Chi, Taiwan  | CHY104          | 7.6   | 0.162   | 0.025         | 1.468       | 0.049 | 0.153   | 0.141     | 149.957  |
| 106.| Chi-Chi, Taiwan  | TCU107          | 7.6   | 0.158   | 0.031         | 1.330       | 0.052 | 0.151   | 0.124     | 158.642  |
| 107.| Chi-Chi, Taiwan  | TCU107          | 7.6   | 0.124   | 0.029         | 1.194       | 0.048 | 0.115   | 0.121     | 142.700  |
| 108.| Chi-Chi, Taiwan  | TCU040          | 7.6   | 0.122   | 0.019         | 0.523       | 0.026 | 0.118   | 0.099     | 67.844   |
| 109.| Chi-Chi, Taiwan  | TCU040          | 7.6   | 0.148   | 0.022         | 0.650       | 0.030 | 0.142   | 0.133     | 78.630   |
| 110.| Chi-Chi, Taiwan  | TCU042          | 7.6   | 0.199   | 0.026         | 0.925       | 0.039 | 0.191   | 0.175     | 99.508   |
| 111.| Chi-Chi, Taiwan  | TCU042          | 7.6   | 0.245   | 0.029         | 1.140       | 0.046 | 0.237   | 0.206     | 103.714  |
| 112.| Chi-Chi, Taiwan  | TCU111          | 7.6   | 0.099   | 0.023         | 0.702       | 0.032 | 0.094   | 0.075     | 88.376   |
| 113.| Chi-Chi, Taiwan  | TCU111          | 7.6   | 0.136   | 0.025         | 0.870       | 0.038 | 0.129   | 0.086     | 105.793  |
| 114.| Chi-Chi, Taiwan  | TCU141          | 7.6   | 0.101   | 0.017         | 0.706       | 0.028 | 0.094   | 0.079     | 85.646   |
| 115.| Chi-Chi, Taiwan  | TCU141          | 7.6   | 0.080   | 0.015         | 0.506       | 0.022 | 0.076   | 0.059     | 84.460   |
| 116.| Chi-Chi, Taiwan  | TCU038          | 7.6   | 0.168   | 0.027         | 1.034       | 0.043 | 0.159   | 0.175     | 103.257  |
| 117.| Chi-Chi, Taiwan  | TCU038          | 7.6   | 0.140   | 0.023         | 0.757       | 0.034 | 0.136   | 0.135     | 75.459   |
| 118.| Chi-Chi, Taiwan  | Station: TCU047 | 7.6   | 0.301   | 0.032         | 1.452       | 0.055 | 0.292   | 0.230     | 159.983  |
| 119.| Chi-Chi, Taiwan  | CHY002          | 7.6   | 0.117   | 0.018         | 0.732       | 0.029 | 0.111   | 0.085     | 98.499   |
| 120.| Chi-Chi, Taiwan  | CHY002          | 7.6   | 0.146   | 0.019         | 0.794       | 0.031 | 0.138   | 0.094     | 84.326   |
Pearson’s correlation coefficient was used to evaluate the strength of the linear inter-relationship between the sets of variables $X$ and $Y$ as follows:
\[ P_{\text{Pearson}} = \frac{\sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^{n} (X_i - \bar{X})^2 \sum_{i=1}^{n} (Y_i - \bar{Y})^2}}, \quad (7) \]

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 for the three RC frames are shown in Figs. 8, 9 and 10.

Based on the results of the Pearson coefficients in Figs. 8, 9 and 10, in all frames, \( I_a, I_c \) and VSI were highly correlated with the fundamental period. All of the parameters selected showed fairly high correlations with the fundamental period in the 3- and 9-story frames. The comparison between the Pearson coefficients in the three frames is shown in Fig. 11.

Figure 11 shows that the Pearson coefficients for the 12-story frame were lower than for the 3- and 9-story frames, although they were similar to those in all the frames. Regression analysis was used to assess the relationship between two or more variables. A nonstandard regression equation is:

\[ Y = b_0 + b_1x_1 + b_2x_2 + \cdots + b_rx_r + \varepsilon \quad (8) \]

where \( b_0, b_1, \ldots \) and \( b_r \) are nonstandard regression coefficients and \( \varepsilon \) represents the standard error of regression. A standard regression equation is:

\[ Y_z = \beta_1z_1 + \beta_2z_2 + \cdots + \beta_rz_r \quad (9) \]

where \( \beta_1, \beta_2 \) and \( \beta_r \) are the standard regression coefficients. The regression equations between \( I_a, I_c \) and VSI and the fundamental period values were calculated and the results are presented in Tables 6, 7 and 8.

By fitting the regression equation between each parameter and the difference in the fundamental period, relations between them can be obtained by averaging the coefficients between the three frames as follows:

\[ dT = 0.6I_a \quad (10) \]
\[ dT = 16I_c - 0.2 \quad (11) \]
\[ dT = 0.01\text{VSI} - 0.4 \quad (12) \]
where $dT$ represents the difference in the fundamental period.

Standard regression equations between each parameter and the difference in the fundamental period can be obtained for the three frames as follows:

$$dT = 0.7I_a$$  \hspace{1cm} (13)

$$dT = 0.7I_c$$  \hspace{1cm} (14)

$$dT = 0.7\text{VSI}$$  \hspace{1cm} (15)

Standard regression equations only indicate the relative effect of the variables. The standard regression equations between $I_a$, $I_c$ and VSI and the fundamental period indicated that all three seismic parameters had similar correlations with the fundamental period.

Linear combinations of $I_a$, $I_c$ and VSI were done to obtain a new parameter showing greater correlation with the fundamental period. The results of are shown in Table 9.

The results in Table 9 indicate that the Pearson correlations between the combined parameter and the fundamental period were greater than the separate correlations between each parameter and the difference in the fundamental period. Therefore, it can be regarded as an efficient parameter for showing the difference in the fundamental period. The regression equations between combined parameters and the difference in the fundamental period were calculated for the three frames and are shown in Tables 10, 11 and 12.

The regression coefficients were not similar for the three frames. Further, either parameter $I_a$ or $I_c$ should be combined with the other parameters. Accordingly, a new parameter was extracted by combining $I_c$ and the VSI parameters. Table 13 lists the correlation results for the combined parameter and the difference in the fundamental period.

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**Table 3** Details of column and beam sections in 3-story RC frame

| Type  | $B \times D$ (mm) | Reinforcement | Critical stirrups | Other stirrups |
|-------|------------------|---------------|------------------|---------------|
| Column1 | 350 × 350 | 8 φ18 | φ10@150 | φ10@200 |
| Column2 | 300 × 300 | 8 φ16 | φ10@150 | φ10@200 |
| Beam1  | 350 × 350 | 3 φ20 | 3 φ16 | φ10@80 |
| Beam2  | 300 × 300 | 3 φ20 | 3 φ14 | – |

**Table 4** Details of column and beam sections in 9-story RC frame

| Type  | $B \times D$ (mm) | Reinforcement | Critical stirrups | Other stirrups |
|-------|------------------|---------------|------------------|---------------|
| Column1 | 500 × 500 | 12 φ22 | φ10@150 | φ10@200 |
| Column2 | 450 × 450 | 12 φ20 | φ10@150 | φ10@200 |
| Column3 | 450 × 450 | 8 φ20 | φ10@150 | φ10@200 |
| Column4 | 400 × 400 | 8 φ20 | φ10@150 | φ10@200 |
| Column5 | 400 × 400 | 8 φ16 | φ10@150 | φ10@200 |
| Beam1  | 450 × 500 | 3 φ22 | 3 φ22 | φ8@100 |
| Beam2  | 450 × 450 | 3 φ18 | 3 φ20 | φ8@100 |
| Beam3  | 400 × 450 | 3 φ18 | 3 φ20 | φ8@85 |
| Beam4  | 350 × 400 | 3 φ18 | 3 φ16 | φ8@85 |
| Beam5  | 350 × 400 | 3 φ16 | 1 φ16 | φ8@85 |

**Table 5** Details of column and beam sections in 12-story RC frame

| Type  | $B \times D$ (mm) | Reinforcement | Critical stirrups | Other stirrups |
|-------|------------------|---------------|------------------|---------------|
| Column1 | 600 × 600 | 16 φ24 | φ10@100 | φ10@200 |
| Column2 | 500 × 500 | 12 φ22 | φ10@150 | φ10@200 |
| Column3 | 450 × 450 | 12 φ20 | φ10@150 | φ10@200 |
| Column4 | 450 × 450 | 8 φ20 | φ10@150 | φ10@200 |
| Column5 | 400 × 400 | 8 φ16 | φ10@150 | φ10@200 |
| Beam1  | 600 × 500 | 4 φ22 | 4 φ22 | φ8@100 |
| Beam2  | 500 × 450 | 3 φ22 | 3 φ22 | φ8@85 |
| Beam3  | 450 × 450 | 3 φ18 | 3 φ18 | φ8@85 |
| Beam4  | 450 × 400 | 3 φ18 | 3 φ16 | φ8@85 |
| Beam5  | 400 × 350 | 3 φ18 | 1 φ16 | φ8@85 |
The results in Table 12 show that the Pearson correlations between the combined parameter and difference in the fundamental period were greater than for the correlation between each parameter and the difference in the fundamental period. The regression equations between the combined parameter and the difference in the fundamental period were calculated for the three frames and the results are presented in Tables 14, 15 and 16.

After averaging the coefficients between the three frames, the relations between the selected seismic parameters and the difference in the fundamental period were as follows:

![Pearson Correlation for 3 Story frame](image1)
![Pearson Correlation for 9 Story frame](image2)
![Pearson Correlation for 12 Story frame](image3)

![Pearson Correlation for 3, 9 & 12 Story frames](image4)

**Fig. 8** Pearson coefficient vs. seismic parameters vs. difference in fundamental period in 3-story frame

**Fig. 9** Pearson coefficient for seismic parameters vs. difference in fundamental period in 9-story frame

**Fig. 10** Pearson coefficient for seismic parameters vs. difference in fundamental period in 12-story frame

**Fig. 11** Comparison between Pearson coefficients in three frames
Furthermore, the standard regression equation between the proposed combined parameter and the difference in the fundamental period for the three frames was:

\[ dT = 3I_c + 0.01 \text{VSI} - 0.4 \quad (16) \]

Furthermore, the standard regression equation between the proposed combined parameter and the difference in the fundamental period for the three frames was:

\[ dT = 0.1I_c + 0.6 \text{VSI} \quad (17) \]

The results indicate that the proposed parameter which is called \( I_c \text{VS} \) correlates highly with the difference in the

Table 6 Regression coefficients between seismic parameters and difference in fundamental period for 3-story frame

| Model   | Nonstandard coefficients | Standard coefficients |
|---------|--------------------------|-----------------------|
|         | \( b \) | Std. error | \( \beta \) |
| 3 story | (Constant) | 0.040 | 0.053 | 0.700 |
|         | \( I_a \) | 0.550 | 0.051 | 0.700 |
|         | (Constant) | -0.116 | 0.066 | 0.696 |
|         | \( I_c \) | 15.251 | 1.423 | 0.696 |
|         | (Constant) | -0.310 | 0.065 | 0.777 |
|         | VSI | 0.009 | 0.001 | 0.777 |

Table 7 Regression coefficient between seismic parameters and difference in fundamental period for 9-story frame

| Model   | Nonstandard coefficients | Standard coefficients |
|---------|--------------------------|-----------------------|
|         | \( b \) | Std. error | \( \beta \) |
| 9 story | (Constant) | -0.041 | 0.067 | 0.651 |
|         | \( I_a \) | 0.603 | 0.064 | 0.670 |
|         | (Constant) | -0.235 | 0.080 | 0.754 |
|         | \( I_c \) | 17.306 | 1.737 | 0.754 |
|         | (Constant) | -0.462 | 0.081 | 0.754 |
|         | VSI | 0.010 | 0.001 | 0.754 |

Table 8 Regression coefficient between seismic parameters and difference in fundamental period for 12-story frame

| Model   | Nonstandard coefficients | Standard coefficients |
|---------|--------------------------|-----------------------|
|         | \( b \) | Std. error | \( \beta \) |
| 12 story | (Constant) | -0.014 | 0.072 | 0.612 |
|         | \( I_a \) | 0.586 | 0.069 | 0.612 |
|         | (Constant) | -0.188 | 0.088 | 0.612 |
|         | \( I_c \) | 16.447 | 1.903 | 0.616 |
|         | (Constant) | -0.495 | 0.081 | 0.767 |
|         | VSI | 0.011 | 0.001 | 0.767 |

Table 9 Pearson coefficients between combined parameter and difference in fundamental period

| Model   | Pearson coefficient |
|---------|---------------------|
| 3 story | 0.782 |
| 9 story | 0.766 |
| 12 story | 0.775 |
fundamental period. It can be regarded as a valid parameter to represent variations in the fundamental period of RC frames under earthquake loading because the relations between this parameter and the difference in the fundamental period were similar in all three frames.

### 7 Conclusions

Three RC frames with different numbers of stories were modeled in IDARC and then were subjected to 124 far-fault earthquake records. The seven principle seismic parameters of PGA, $a_{RMS}$, $I_a$, $I_c$, $A_95$, ASI and VSI then were extracted from the records. After nonlinear dynamic analysis, the damage responses of the frames were identified versus the fundamental period.

Pearson correlation coefficients were used to study the relations between the seismic parameters and the fundamental period of the three frames. The results indicated that the Pearson correlations between $I_a$, $I_c$ and VSI and the difference in the fundamental period were strong in all
frames and that the selected parameters had fairly high correlations with the fundamental periods in the 3- and 9-story frames.

Regression equations between $I_a$, $I_c$ and VSI, and the fundamental period were calculated for the three frames and unique equations were achieved by fitting these equations to the frames. A new parameter was achieved by the linear combination of $I_c$ and VSI that demonstrates a high correlation with the difference in the fundamental period. Unique equations were achieved between this new parameter and the difference in the fundamental period that can be regarded as being reliable indicators of the difference in fundamental period under earthquake loading because notable correlation was found between this new parameter and the difference in the fundamental period. The relations for all three frames were similar.

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Code Availability  The developed codes are available upon request.

Declarations

Conflict of interest  The authors declare that they have no conflict of interest.

Ethical statements  This method is an original effort by the authors and has not been submitted or published elsewhere.

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