Comparative Evaluation of Seismic Parameters for Near-Fault and Far- Fault Earthquakes

H. R. Tavakoli, H. Gilani & G. R. Abdollahzadeh
Department of Civil Engineering Faculty, Noshivani University of Technology, Babol, Iran

SUMMARY:
The study of earthquake ground motion is a key issue in the field of earthquake resistance. Near-fault ground motions are more severe than other ground motions recorded during the same event and under similar conditions because proximity to the seismic source does not allow considerable attenuation of ground motion. Near-fault ground motion is characterized by its long-period velocity or displacement pulse-like time histories. Pulse-like records are much different from ordinary records as they are typically very intense and have been observed to cause severe damage to structures in past earthquakes. So this paper compares the characteristics of seismic parameters of earthquake ground motion records obtained in near-fault records with far-field records.

Keywords: Near-fault and Far-fault records; seismic parameters; pulse-like records

1. INTRODUCTION

Far-fault ground motions have been observed as differing dramatically from their near-fault counterparts recorded within a few kilometers of the fault rupture plane. Near-fault ground motions often exhibit distinguishable pulse- like features in their velocity time histories, occasionally also observed in acceleration time histories. The main causes for the velocity pulses are the rupture forward directivity and fling-step effect (Somerville. 1997, Abrahamson. 2000). The forward rupture directivity, which occurs when the fault rupture propagates toward a site at a velocity close to the shear wave velocity and the direction of slip on the fault is aligned with the site, causes most of the seismic energy from the fault rupture to arrive in a single large long-period pulse near the beginning of ground shaking representing the cumulative effect of almost all the seismic radiation from the moving dislocation on the fault and generate long-period, short duration, and large-amplitude pulses (Somerville. 2000). In addition, fling-step effect, which is associated with the permanent tectonic offset of the ground, can also result in one-sided velocity pulse in the fault-normal direction for dip-slip faults or in the fault-parallel direction for strike-slip faults (Abrahamson. 2000). On the other hand, the pulse contents in acceleration time histories (e.g. local acceleration pulses that override the long period velocity pulses) have also been found important for structural responses (Tang. 2011). These near-fault effects were first noticed in the 1971 San Fernando, California, earthquake and serious concern was raised following the 1994 Northridge, California, and 1995 Hyogo-ken Nanbu (Kobe), Japan, earthquakes (Cox. 2002).

This study, compares seismic parameters for near-fault and far-fault earthquakes. Seismic parameters that consider in this study are acceleration and velocity response spectrum, peak ground acceleration (PGA), peak ground velocity (PGV), Arias intensity (AI), cumulative absolute velocity (CAV), root mean square of acceleration (a_{rms}), damage potential parameter (I) and duration.

2. STRONG MOTION DATABASE

44 Strong motion records used in this study that provided from PEER internet site. The Source-to-site distance is defined in term of $R_{rupture}$, where $R_{rupture}$ is the shortest distance between the recording site

and the rupture plane of earthquake. Near fault earthquakes select in $R_{rup} \le 15$ km, and far fault earthquakes select in $R_{rup} \ge 40$ km. All of the records that used in this study have a moment magnitude more than 6 ($M_w \ge 6$). Records that used in this study classified based on soil type ш ($175 \le V_s \le 375$) according to the ground categories defined by the Iranian Earthquake Code of practice, (Standard No. 2800. 2005)

The characteristics and seismic parameters of near-fault and far-fault earthquakes are summarize in table 1 and 2, respectively.

Table 1. Near-fault records

Event	**Station**	**M_w**	**Distance** km	Component	**PGA** g	**PGV** cm/s	**I_a** m/s	**CAV** Cm/s	**a_{rms}** g	**I** $cm.s^{-0.75}$	**Duration** sec
Imperial Valley	Meloland	6.53	0.070	000	0.314	71.76	0.858	667.20	0.037	121.5	8.22
				270	0.296	90.45	1.080	758.50	0.042	145.7	6.74
Imperial Valley	Array #6	6.53	1.350	140	0.410	64.85	1.480	966.00	0.05	119.3	11.45
				230	0.440	109.8	1.750	1023.8	0.054	187.4	8.49
Imperial Valley	Array #7	6.53	0.560	140	0.340	47.62	0.860	639.40	0.039	76.9	6.82
				230	0.460	109.2	1.700	795.10	0.055	161.5	4.79
Erzincan	Erzincan	6.69	4.380	EW	0.500	64.30	1.800	867.50	0.075	105.8	7.34
				NS	0.515	83.95	1.510	771.00	0.068	138.7	7.46
Kobe	KJMA	6.9	0.960	000	0.820	81.30	8.400	2091.3	0.106	138.2	8.36
				090	0.600	74.35	5.430	1783.5	0.086	130.6	9.52
Kocaeli	Duzce	7.51	15.37	180	0.312	58.80	1.080	849.00	0.051	109	11.8
				270	0.356	46.40	1.330	793.20	0.056	83.6	10.56
Koccaeli	Yarimca	7.51	4.830	060	0.270	65.70	1.330	1047.1	0.05	129.9	15.3
				330	0.350	62.20	1.320	991.30	0.05	123.6	15.6
N. Palm Springs	N.Palm	6.06	4.040	210	0.590	73.20	2.000	819.70	0.081	107.1	4.58
				300	0.690	33.75	1.570	700.50	0.07	50.84	5.15
Northridge	New Hall	6.69	5.920	090	0.583	74.90	4.360	1456.0	0.084	116.6	5.88
				360	0.590	96.94	5.670	1617.2	0.096	148.6	5.52
Northridge	Rinaldi	6.69	6.500	228	0.825	160.1	7.500	1799.2	0.156	262.7	7.25
				318	0.486	74.50	4.230	1526.0	0.117	130	9.28
Northridge	74 Sylmar	6.69	5.350	052	0.610	117.4	5.830	2039.1	0.097	231.4	15.1
				142	0.897	102.2	5.280	1628.8	0.093	169	7.47
Northridge	75 Sylmar	6.69	5.190	018	0.828	117.5	4.490	1465.5	0.085	190.4	6.9
				288	0.493	74.60	2.900	1257.2	0.068	123.5	7.52
Chi-Chi	CHY 101	7.62	9.96	N	0.440	115.0	3.000	2119.0	0.0465	260.9	26.5
				E	0.350	70.60	2.320	1962.1	0.0409	165.8	30.4
Chi-Chi	17 WGK	7.62	9.96	N	0.484	74.50	3.000	1918.5	0.0572	166.9	25.2
				E	0.334	69.00	2.270	1849.7	0.05	159.1	28.3

Table 2. Far-fault records

Event	**Station**	**M_w**	**Distance** km	Component	**PGA** g	**PGV** cm/s	**I_a** m/s	**CAV** Cm/s	**a_{rms}** g	**I** $cm.s^{-0.75}$	**Duration** sec
Borrego Mtn	Elcentro #9	6.63	45.66	180	0.130	26.30	0.210	478.60	0.0185	59.2	25.6
				270	0.057	13.20	0.123	403.30	0.0141	30.5	28.6
Imperial Valley	Coachela #4	6.53	50.10	045	0.115	12.50	0.116	264.40	0.0162	22.8	11.11
				135	0.128	15.60	0.200	337.50	0.0214	27.7	9.95
Victoria	Casa Flores	6.33	39.30	010	0.101	7.800	0.122	258.00	0.022	14.1	10.64
				280	0.068	9.000	0.080	203.10	0.0182	16.4	11.03
Morgan Hill	Los Banos	6.19	63.16	090	0.050	5.800	1.750	169.20	0.0085	11.5	15.7
				180	0.057	8.200	1.900	180.10	0.0088	16.9	18.1
Morgan Hill	SF Airport	6.19	70.93	050	0.048	3.200	0.400	145.60	0.009	6.2	14.6
				320	0.048	2.700	0.500	155.20	0.0095	5.2	14.1
Chalfant Valley	Tinemaha	6.19	51.98	000	0.037	3.600	1.110	149.50	0.006	7.4	17.7
				090	0.037	6.300	1.200	155.60	0.0067	12.4	15.05
Kobe	HIK	6.90	95.72	000	0.141	15.60	3.100	636.40	0.017	31.7	17
				090	0.147	15.40	2.000	605.00	0.018	28.1	11.1
Chi-chi	TCU 113	6.20	46.66	N	0.030	5.110	1.190	214.50	0.0057	11.8	28.15
				E	0.023	2.600	0.810	170.20	0.0042	6.4	37.15
Chi-Chi	TTN 008	6.20	87.09	N	0.012	2.130	0.530	68.100	0.0024	4.6	22.8

Event	**Station**	**M_w**	**Distance** km	Component	**PGA** g	**PGV** cm/s	**I_a** m/s	**CAV** Cm/s	**a_{rms}** g	**I** $cm.s^{-0.75}$	**Duration** sec
				E	0.015	2.700	0.710	87.700	0.0031	5.5	17.5
Landers	Amboy	7.28	69.21	000	0.115	18.30	0.565	931.40	0.0271	42.7	29.8
				090	0.146	20.00	0.755	1064.6	0.0313	44.8	25.2
Landers	Riverside	7.28	96.00	180	0.042	3.000	0.066	325.20	0.0093	6.9	27.8
				270	0.041	3.100	0.062	305.00	0.009	7	26.5
Gulf of Aqaba	Eilat	7.20	44.10	NS	0.086	10.60	0.186	489.70	0.014	23.2	23
				EW	0.097	14.00	0.225	531.90	0.0156	30	21.2
Kocaeli	Atakoy	7.51	58.28	000	0.105	22.40	0.236	683.00	0.0107	54.8	35.9
				090	0.164	16.10	0.281	701.30	0.0117	38.2	31.8
Duzce	Yarimca	7.14	97.53	060	0.022	7.900	0.017	191.50	0.0039	19.5	36.9
				330	0.016	4.400	0.013	167.50	0.0034	11.2	42.6
Manjil	Qazvin	7.37	49.97	066	0.184	15.50	0.450	710.00	0.022	32.1	18.4
				336	0.130	11.00	0.417	777.50	0.0212	24.8	25.7
Hector Mine	Coachella	7.13	73.55	090	0.095	12.30	0.135	451.70	0.0121	29	30.8
				360	0.086	13.67	0.154	467.40	0.0129	30.2	23.8
San Fernando	Via Tejon	6.61	55.20	065	0.026	3.800	0.025	230.30	0.005	10	47.8
				155	0.041	4.200	0.032	257.30	0.0054	11.3	52.4
San Fernando	CalEdison	6.61	96.81	090	0.032	1.770	0.011	63.500	0.0088	2.9	7.03
				180	0.038	2.210	0.024	89.050	0.013	3.6	7.23
Coalinga	Cholame 1E	6.36	43.68	000	0.090	10.80	0.158	414.70	0.016	24.3	25.5
				090	0.089	15.20	0.230	488.50	0.02	32	19.7
Coalinga	Cholame8W	6.36	51.75	000	0.100	8.500	0.170	383.90	0.019	16.7	15
				270	0.100	8.000	0.176	372.10	0.019	15	12.5
N. Palm Springs	Anza Fire St	6.1	42.36	225	0.100	5.820	0.044	104.90	0.016	9.1	5.87
				315	0.067	4.000	0.021	77.800	0.011	6.4	6.77
Loma Prieta	Hayward	6.93	52.68	000	0.170	13.70	0.420	617.00	0.026	25.9	12.75
				090	0.138	11.50	0.290	509.20	0.022	21.8	13
Loma Prieta	Emeryville	6.93	76.97	260	0.260	41.10	0.910	758.60	0.039	71	8.92
				350	0.210	21.50	0.520	682.70	0.03	42.3	15.05
Northridge	Anaheim	6.69	68.62	000	0.072	5.200	0.118	346.70	0.015	10.8	18.4
				090	0.066	5.140	0.112	324.80	0.014	10.8	19.7
Northridge	Arcadia	6.69	41.41	009	0.090	4.700	0.127	334.00	0.0154	9.6	17.5
				279	0.110	8.100	0.170	378.40	0.018	16.1	15.66
Tabas	Ferdows	7.35	91.14	L	0.087	5.600	0.190	473.50	0.0175	12.1	21.8
				T	0.107	8.500	0.215	520.60	0.0187	18.8	24.2
Cape Mendocino	Eureka	7.01	41.97	000	0.154	20.10	0.300	556.60	0.0211	42.9	20.8
				090	0.178	28.20	0.330	579.10	0.0221	59.5	19.8
Chi-Chi	CHY 063	7.6	72.23	N	0.068	9.400	0.161	613.70	0.0108	24.1	43.4
				E	0.060	7.900	0.119	507.80	0.0093	19.9	40.4
Chi-Chi	KAU 063	7.62	92.38	N	0.041	10.45	0.101	495.60	0.0085	27.4	47.1
				E	0.039	12.50	0.123	542.50	0.0094	32.5	45.5
St. Elias	Yakutat	7.54	80.00	009	0.083	25.40	0.317	910.00	0.0157	65.3	43.7
				279	0.065	42.50	0.290	868.50	0.0151	110.1	45

3. STUDY OF SEISMIC PARAMETERS

3.1. Ground Motion Parameters

In order to compare the effect of near-fault and far-fault earthquakes, seismic parameters are investigated. Seismic parameters that considered in this study are peak ground acceleration (PGA), peak ground velocity (PGV), Arias intensity (AI), cumulative absolute velocity (CAV), root mean square of acceleration (a_{rms}), damage potential parameter (I) and duration.

Peak ground acceleration (PGA) is a measure of earthquake acceleration on the ground and an important input parameter for earthquake engineering. The peak horizontal acceleration (PHA) is the most commonly used type of ground acceleration in engineering applications, and is used to set building codes and design hazard risks. In an earthquake, damage to buildings and infrastructure is related more closely to ground motion, rather than the magnitude of the earthquake. For moderate earthquakes, PGA is the best determinate of damage; in severe earthquakes, damage is more often correlated with peak ground velocity. PGV has been found to be particularly useful as an indicator of the potential for the ground motion to cause damage in structures of intermediate response period, which is reflected in the damage parameter proposed by Fajfar *et al.* (1990), which is the product of PGV and the fourth-root of the strong-motion duration. More recently Akkar and O zen (2005) explored the influence of various ground-motion parameters on the inelastic demand on single-degree-of-freedom (SDOF) oscillators, finding a good correlation between PGV and the inelastic demand in the intermediate period range.

Another seismic parameters that considered in this study are Arias intensity (I_a) and cumulative absolute velocity (CAV). The Arias intensity (Arias, 1970) is given by the equation (1.1) :

$$I_a = \frac{\pi}{2g}\int_0^{T_d} (a(t)^2)dt \qquad (1.1)$$

Where g is the acceleration due to gravity, a(t) is the recorded acceleration time history, T_d is the duration of ground motion. The Arias intensity is a measure of earthquake intensity given by the integration of squared accelerations over time and it is related to energy content of the recorded signal.

Cumulative absolute velocity (CAV), is defined as the integral of the absolute value of the acceleration time series, is presented mathematically by the equation (2.1) (EPRI, 1988):

$$CAV = \int_0^{t_{max}} |a(t)|dt \qquad (2.1)$$

Where |a(t)| is the absolute value of the acceleration time series at the time t and t_{max} is total duration of the time series. CAV was initially developed and proposed as an index to indicate the one set of structural damage to engineered structures.

CAV includes the cumulative effects of ground motion duration. This is a key advantage of CAV over peak response parameters and is one of the reasons that EPRI found it to be the instrumental intensity measure that best correlated with the one set of structural damage. However, it should be noted that CAV does not account for the timing of the arrival of different phases of energy such as large velocity pulse.

The root mean square acceleration (a_{rms}), defined as

$$a_{rms} = \sqrt{\frac{1}{t_D}\int_{t_D} a_g^2(t)dt} \qquad (3.1)$$

Where $a_g(t)$, is the ground acceleration and t_D is the duration of strong motion according to Trifunac and Brady (1975). This index accounts for the effects of amplitude and frequency content of a strong-motion record and is directly proportional to the square root of the gradient of the specified interval of Arias Intensity.

The damage potential parameter proposed by Fajfar et al. (1990), defined as

$$I = PGV.\ T_D^{0.25} \qquad (4.1)$$

The expression is proposed as an instrumental measure of earthquake ground motion capacity to damage structures with fundamental periods in the medium-period (velocity-controlled) region. Only two of the basic ground motion parameters which can be routinely predicted in the design procedure (peak ground velocity and the duration of strong shaking) are included in the formula. Expressions for determining the bounds of the medium-period region are also proposed as a function of the basic ground motion parameters.

Also, strong motion duration defined as the significant duration of the strong ground motion the time interval between the 5% and the 95% of the Arias intensity that presented by Trifunac and Brady (1975). When the duration of ground motion increases, the input energy to structure increases, too (Ghodrati Amiri *et al,* (2007) .

Seismic parameter values for near-fault and far-fault records indicated in figures 1 to7. As indicated in figures 1 to 6, the values of PGA, PGV, I_a, CAV, RMS_a and I for the near-fault records are more than far-fault records. The average value of PGA for near-fault records is 0.505g but far-fault records have PGA about 0.087g. Mean value of PGV for near-fault records is 81.72 (cm/s) whereas far-fault records have the mean value of PGV about 11.25 (cm/s). Also these mean values for I_a, CAV and I for near-fault records are 3 (m/s), 1293 (cm/s) and 144.8 ($cm.s^{-0.75}$), and for far-fault records, mean values are 0.18 (m/s), 419 (cm/s) and 24.4 ($cm.s^{-0.75}$), respectively. As discuss before, the values of PGV, I_a, CAV

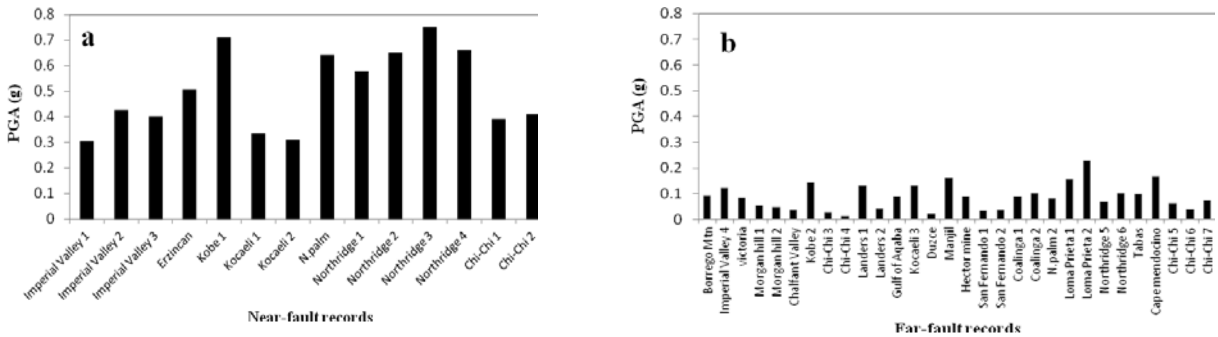

Figure 1. comparison of PGA for near-fault records (a) and far-fault records (b)

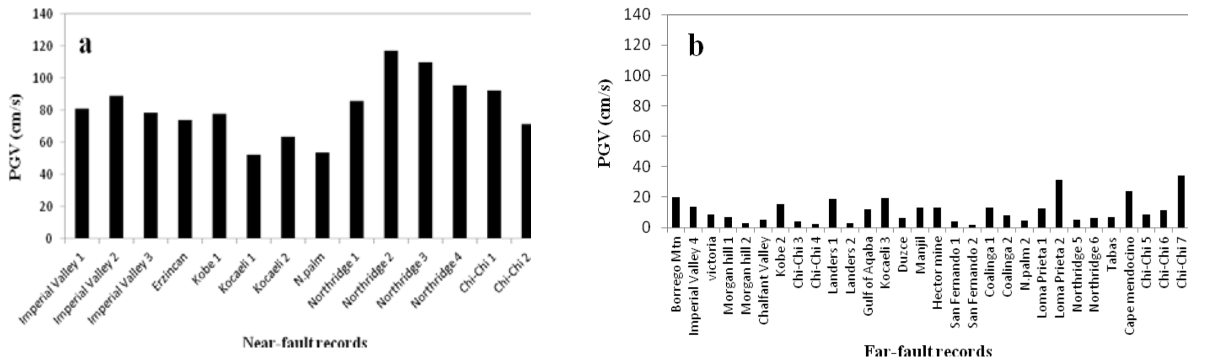

Figure2. Comparison of PGV for near-fault records (a) and far-fault records (b)

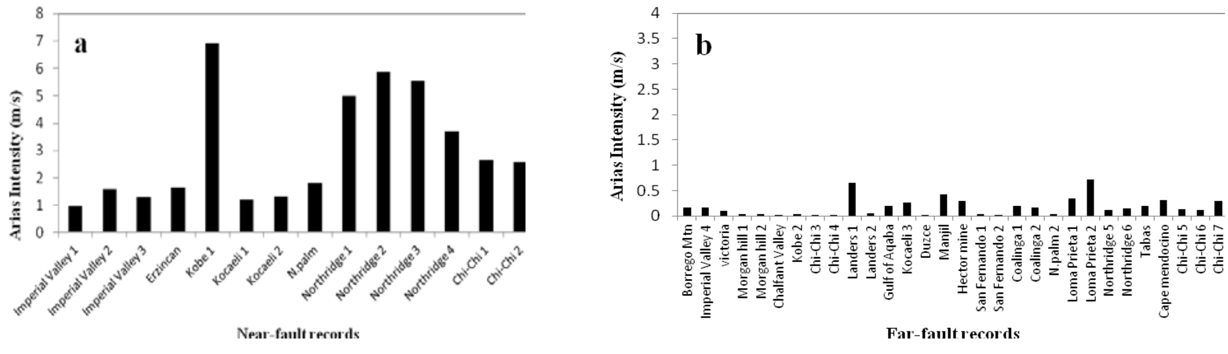

Figure3. Comparison of Arias Intensity for near-fault records (a) and far-fault records (b)

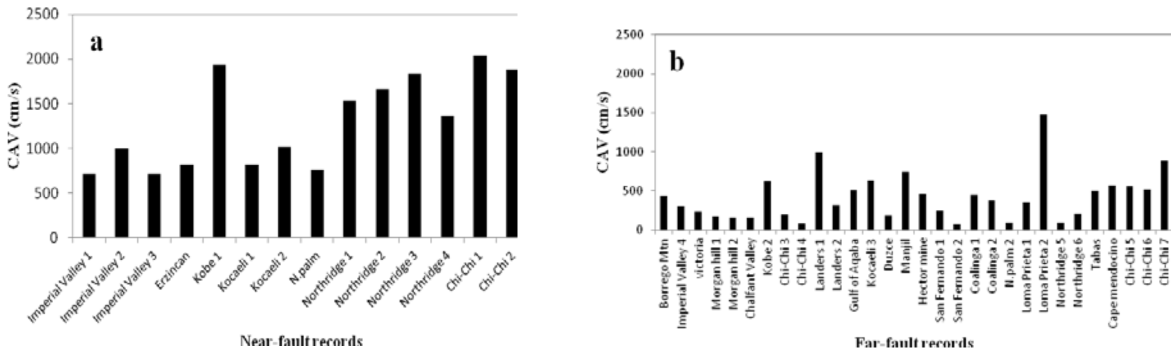

Figure4. Comparison of CAV for near-fault records (a) and far-fault records (b)

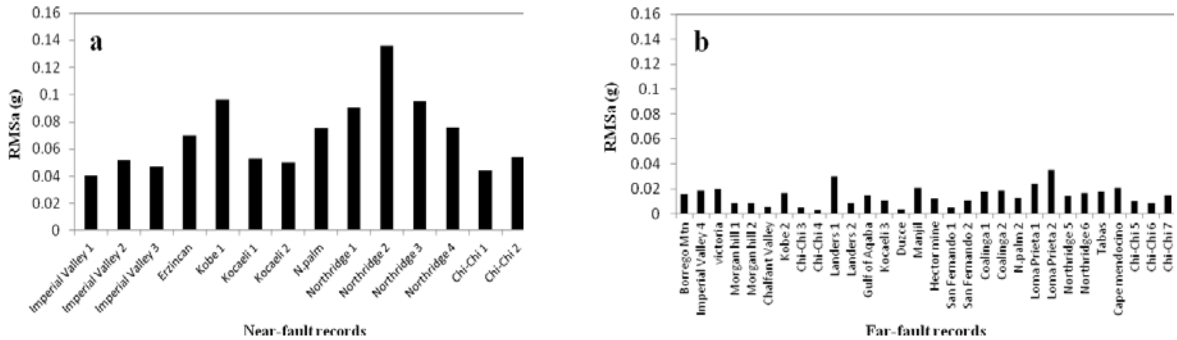

Figure5. Comparison of RMS_a for near-fault records (a) and far-fault records (b)

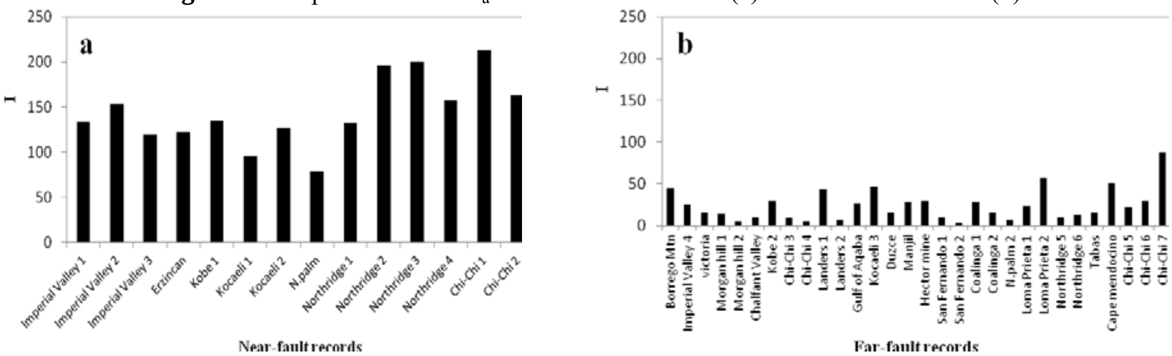

Figure6. Comparison of I for near-fault records (a) and far-fault records (b)

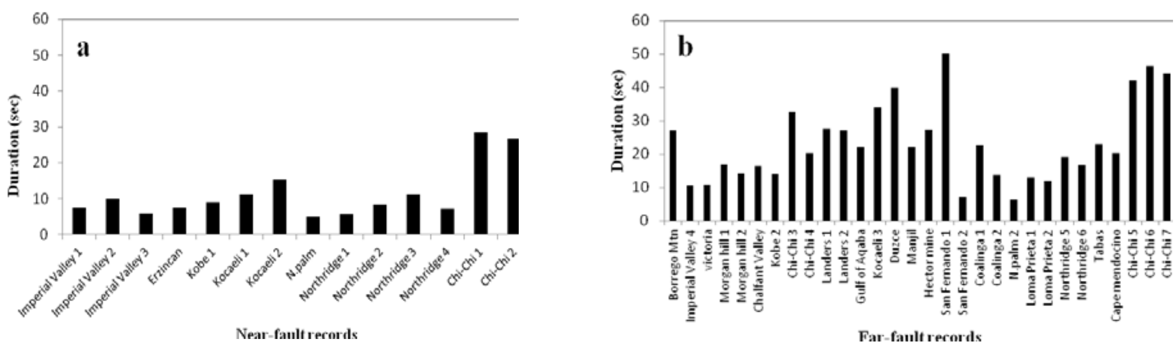

Figure7. Comparison of duration for near-fault records (a) and far-fault records (b)

and I indicates the measures of energy and damage potential. Thus, near-fault ground motions are more severe than the ground motions recorded far from the ruptured in the same event, without accounting for directivity effects. As indicated in figure 5, mean value of a_{rms} is 0.07g for near-fault records but for far-fault records this value is 0.014g. Figure 7, illustrated the strong motion duration of near-field and far-field records. According to definition of strong motion duration that based on energy, near-field records have a lower duration than far-field. Earthquakes in near-field region transmit a large high-energy pulse and have a short duration. The duration mean values are 11.3 sec and 23.3 sec for near-fault and far-fault records, respectively.

3.2. Response Spectrum

The important of the response spectrum approach in the seismic design of structures and equipments is well known to earthquake design engineers. The response spectrum was first introduced by Biot (1933) and latter conveyed to engineering application by Housner (1959) and Newmark *et al*. (1973), the ground motion response spectrum has often been utilized for purpose of recognizing the significant characteristics of accelerograms and evaluating the response of structures to earthquake ground shaking. Due to inherent theoretical simplicity and ease in its computations, the response spectrum has long become the standard tool of structural design and performance assessment.

If one generates sets of response spectra for ground motions recorded at different locations during past earthquakes, large variation would be observed in both the response spectral values and the shape of the spectrum curves from one set to another. These variations depend upon many factors such as energy release mechanism in the vicinity of the focus or hypocentre and along fault interfaces, epicentral distance and focal depth, geology and variations in geology along energy transmission paths, Richter magnitude and local soil conditions at the recording station. Thus the response spectral values S (S_a, S_v and S_d) for earthquake ground motion should be thought of in the form (Clough & Pension, 1993)

$$S = S(SM, ED, FD, GC, M, SC, \xi, T) \tag{5.1}$$

where the independent variables denote source mechanism, epicentral distance, focal depth, geological conditions, Richter magnitude, soil conditions, damping ratio and period, respectively. The effects of *SM* and *GC* on both spectral values and shapes of the response spectra are not well understood; therefore, such effects cannot be quantified when defining response for design purpose. The effects of *ED*, *FD* and *M* are usually taken into consideration while specifying the intensity levels of the design response spectra; however, they are often ignored during specification of the shape of these spectra because of lack of knowledge regarding their influences. On the other hand, the effects of *SC* on both the intensities and shapes of the response spectra are now considered widely for defining design response spectra. The response spectrum introduced by Biot (1933) and Housner (1959) describes the maximum response of a damped single degree of freedom oscillator at various frequencies or periods.
Because the detailed characteristic of future earthquake are not known, the majority of earthquake design spectra are obtained by averaging a set of response spectra from records with common characteristic.

The influence of duration of strong motion on spectral shapes has been studied by Peng *et al*. (1989) who used a random vibration approach to estimate site-dependent probabilistic response spectra. The results show that a longer duration of strong motion increases the response in the low and intermediate frequency regions .This is consistent with the fact that accelerograms with long duration of strong motion have a greater probability of containing long period waves which can result in a higher response in the long-period (low-frequency) region of the spectrum. So, the far-fault records have high amplitude in intermediate and long periods, due to having a longer duration.

Figure 8, shows the average of response spectral acceleration for near-fault and far-fault records. As is illustrated, in intermediate and long periods, near-fault records have higher amplitude. Figure 9 shows that, velocity response spectrum for near-fault records have higher amplitude in intermediate and long period range.

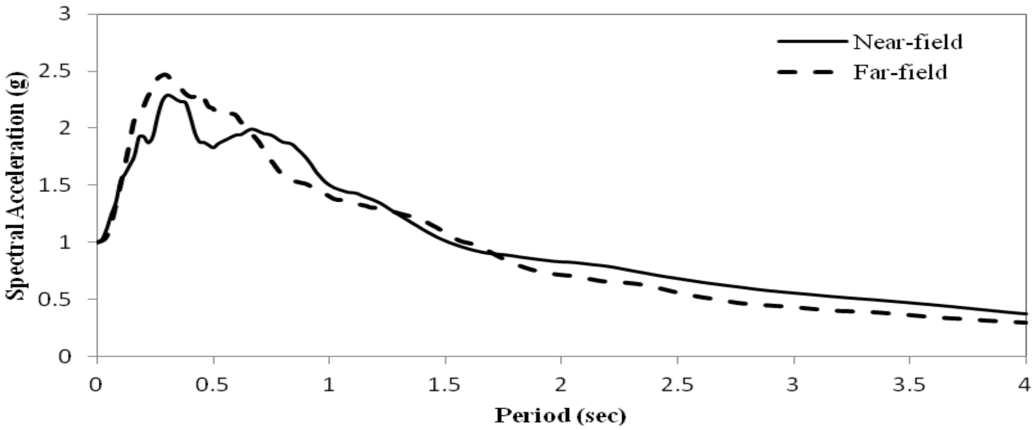

Figure8. Acceleration response spectra from near-fault and far-fault earthquakes

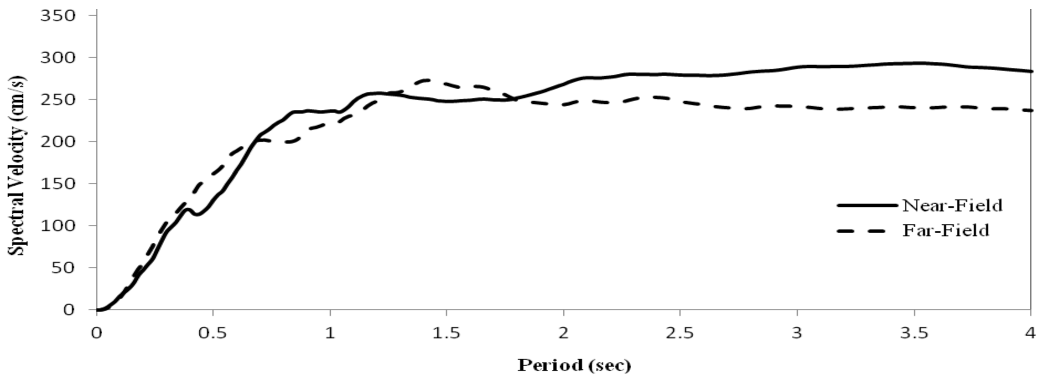

Figure9. Velocity response spectra from near-fault and far-fault earthquake

4. CONCLUSIONS

Near-fault records are characterized by a large high energy pulse and therefore have caused much damage in the vicinity of seismic source. As is indicated in figure 3, I_a that demonstrate the energy value of records, near-fault records is 17 times larger than the far-fault records. Also the damage potential of records, indicated by CAV and I, show that near-fault records are more destructive than far fault records.

Comparison of spectral values, show that in near-fault records, spectral acceleration and spectral velocity have higher amplitude in intermediate and long periods. As, the amplitude differences is clear in velocity response spectrum.

REFERENCES

Abrahamson, N.A. (2000). Near-fault ground motions from the 1999 Chi-Chi earthquake. *In: Proceedings of U.S. - Japan Workshop on the Effects of Near-Field Earthquake Shaking*, San Francisco, CA.

Akkar, S. and Ozen, O. (2005). Effect of peak ground velocity on deformation demands for SDOF systems, Earthquake Eng. Struct. Dyn. **34, no.13**,1551–1571.

Arias, A. (1970). A measure of earthquake intensity. In *Seismic Design for Nuclear Power Plants*, R. J. Hansen (ed.), The MIT press, Cambridge, MA, 438-483.

Biot, M. A. (1933). Theory of elastic systems vibrating under transient impulse with application to earthquake proof buildings. *Proc. Natl. Acad. Sci. U.S.A*. **19**, 262-268.

Clough, R. & Pension, J. (1993). Dynamic of Structures. New York: McGraw Hill.

Cox, K.E. and Ashford, S.A. (2002). Characterization of large velocity pulses for laboratory testing. *Pacific Earthquake Engineering Research Center* (PEER), Report No. **22.**

Electrical Power Research Institute (EPRI), (1988). A Criterion for Determining Exceedance of the Operating Basis Earthquake. Repot No. EPRI NP-5930, Palo Alto, California.

Fajfar, P., Vidic, T. and Fischinger, M. (1990). A measure of earthquake Motion capacity to damage medium period structures, *Soil Dynamics and Earthquake Engineering*. **9**, 236–242.

Ghodrati Amiri, G., Abdollahzadeh Darzi, G. and Khanzadi, M. (2007). Earthquake duration and damping effects on input energy. *International Journal of Civil Engineering*. **5:1.**

Housner, G. W. (1959). Behavior of structures during earthquakes. J. *Eng. Mech. Div*. **85**, 109-129.

Newmark, N. M., Blume, J. A. & Kapur, K. K. (1973). Seismic design criteria for nuclear power plants. *J. Power Div*. **99**, 287-303.

Peng, M.H., Elghadamsi, F.E. and Mohraz, B. (1989). A simple procedure for constructing probabilistic response spectra. Earthquake Spectra. **5:2.**

Permanent Committee for Revising the Iranian Code of Practice for Seismic Resistant Design of Buildings .Iranian code of practice for seismic resistant design of buildings—Standard No. 2800, 3rd ed. Tehran, Iran: Building & Housing Research Center; 2005.

Somerville, P.G., Smith, N.F., Graves, R.W. and Abrahamson, N.A. (1997). Modification of empirical strong motion attenuation relations to include the amplitude and duration effects of rupture directivity. *Seismological Research Letters* **68:1,**199–222.

Tang, Y., Zhang, J. (2011). Response spectrum-oriented pulse identification and magnitude scaling of forward-directivity pulses in near-fault ground motions. *Soil Dynamics and Earthquake Engineering*. **31**,51-76.

Trifunac, M.D. and Brady, A.G. (1975). A study on the duration of strong earthquake ground motion. Bulletin of the Seismological Society of America **65**, 581-626.