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Improvement of Iranian Seismic Design Code Considering the Near-Fault Effects

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ABSTRACT

Characteristics of ground motions close to the earthquake source can be considerably different from those of far-field motions which should be considered in design process of structures. The current study aimed to present new design response spectra for Iranian seismic design code taking into account the near-fault effects. For this purpose, a new attenuation relation based on the ground motion records obtained from fault-normal orientation of near-fault earthquakes at different parts of the world including Iran, has been derived. Subsequently, near-fault modification factors for short and long periods were extracted to present the modified design response spectra for the Iranian design code. The proposed factors are relatively comparable with those of UBC97, Chinese and Taiwanese seismic design codes. Analyses also showed that the distance criterion that defines near-fault region consistence with design spectra of Iranian seismic code can be taken as 18 km.

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1. INTRODUCTION[1]

The study of near-field effects has been attended since the 1971 while San Fernando earthquake with severe acceleration pulse occurred in California. Over the last decade, new valuable information about the near-fault features due to several large earthquakes was obtained. It is well recognized that near-fault earthquakes have different distinct characteristics from far-fault earthquakes in which motions are mainly influenced by directivity and fling step effects [1]. Directivity effects can be classified as forward, reverse, and neutral directivity. Forward directivity which has the most destructive effects occurs when the rupture front expands toward the site and the direction of slip direction is aligned with the site. In this manner, when rupture spreads from the hypocenter to the site, the released waves reach the site at once like a strong vibration. This strong vibration is recognizable like an outstanding pulse in the beginning of the earthquake records, generally in velocity and displacement time histories [1]. This feature was observed clearly in the near-fault records of recent destructive events including the ones in Northridge, California, United States (1994), Kobe, Japan (1995), Chi-Chi, Taiwan (1999), Duzce, Turkey (1999) and Bam, Iran (2003) earthquakes [2, 3]. The other key characteristic of near-fault records is the permanent displacement of ground due to the static deformation in those regions that named “fling step” effect and has been observed recently in the near-fault records obtained from the Izmit, Turkey (1999) and Chi-Chi, Taiwan (1999) earthquakes [4].

The great importance of the near-fault ground motion characteristics on the elastic and inelastic dynamic behavior of engineered structures has been noted evidently by several researchers [5-9]. The difference between the near-fault and far-fault earthquakes characteristics, beside the difference between the structural behavior in near-fault earthquakes and high amount of damage caused by near-fault earthquakes, have turned the near-fault earthquakes to immense importance from both seismological and seismic engineering points of view. In line with growth of earthquake engineering knowledge and practice, most of the countries which have been located in the high seismic potential areas are attempting to interpret engineering implications of these important ground motions through the design response spectra which have played a major role as the most conventional tool in design application [10, 11]. In general, design spectrum needs to be adjusted to reflect the near-fault in such a way to increase the seismic demand of the structure [12]. UBC 97 code was the first code which incorporated the distance dependent near-fault factors to modify the design response spectra after

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the Northridge 1994 earthquake [13]. As well, Japan after the Kobe 1995 and China and Taiwan after the Chi-Chi 1999 earthquakes revised their design codes to include the near-fault effects [14].

The Iranian Plateau which is characterized by active faulting, active folding, recent volcanic activities, mountainous terrain, and variable crustal thickness, has been frequently struck by catastrophic earthquakes with high death tolls. Different areas in Iran have suffered from large earthquake in the past. On December 26 2003, an earthquake of relatively moderate size-Mw = 6.6, occurred in south-west part of Iran (about 1 km of Bam city). The most distinctive feature of the accelerograms recorded at the Bam site was the large and relatively long-period pulse recorded shortly after the P-wave arrival which was the main cause of the extensive damage. Figure 1 shows the velocity time history of the ground motion of the 2003 Bam event recorded at Bam station [15]. The foregoing explanation and considering the fact that most of the metropolitan cities such as Tehran with highly dense population are located in high-risk seismic regions [16], close to active faults and knowledge of the significant effects of these earthquakes accompanied with a high death toll, point out the importance of applying near-fault effects in the Iranian seismic design code.

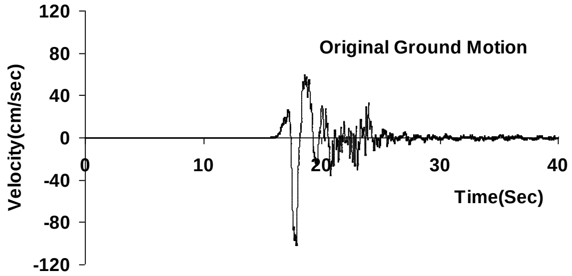

Fig 1. Velocity time history of the ground motion of the 2003 Bam event recorded at Bam station [15]

For applying near-fault effects in design process of structures, modification factors consistence with design response spectra of Iranian design code (Standard No.2800 [17]) based on UBC97 concepts will be presented. For this purpose, by providing a data set of near-fault records from different parts of the world including Iran, a new attenuation relationship for rotated records in fault-normal direction is derived and then the near-fault factors for the long period (acceleration-related) and short period (velocity-related) are calculated. Ultimately, by applying the near-field factors, design response spectra of current Iranian seismic code (3rd edition) which is being widely used by Iranian engineers is modified. These revisions allow for the application of developed spectra in seismic design of structures in near-fault area.

2. Imrovment of Seismic Design Codes to Consider the Near-Fault Effects

The pulse-like ground motions which are induced normally by forward rupture directivity are able to amplify the spectral scaling specified by current codes differently in a wide range of periods which should be considered in seismic design of structures in a straight forward technique. UBC 97 code was the first design code that developed the near-fault design response spectrum to increase directly the seismic capacity of structures due to the near-fault ground motions with introducing two near-fault factors, *Na* for short periods (acceleration sensitivity range) and *Nv* for long periods (velocity sensitivity range). These factors are applied in the area within seismic zone 4 (Z-factor of 0.4) where there are active faults capable of generating large magnitude earthquakes. The values of *Na* in UBC97 are calculated based on the ratio of response spectrum obtained from attenuation relation in 0.3 seconds to response spectrum value of UBC 97 code for stiff soil and corresponding peak ground acceleration of 0.4 g. The values of *Nv* are calculated similarly for a period of 1.0 second. Seismic source types in UBC 97 which are defined based on the maximum moment magnitude and slip rate along with the near-fault effect factors are presented in Table 1 to 3.

TABLE 1. Seismic source definitions in UBC97 code [13]

Seismic source type	Descriptions	Maximum moment magnitude	Slip rate (SR) (mm/year)
A	Faults that are capable of producing large magnitude events and that have a high rate of seismic activity	$M \geq 7.0$	$SR \geq 5$
B	All faults other than Types A and C	$M \geq 7.0$	$SR < 5$
		$M < 7.0$	$SR > 2$
		$M \geq 6.5$	$SR < 2$
C	Faults that are not capable of producing large magnitude earthquakes and that have a relatively low rate of seismic activity	$M < 6.5$	$SR \leq 2$

TABLE 2. Near-fault factor, *Na* in UBC97 code [13]

Seismic source type	Closest distance to known seismic source		
	≤2 km	5 km	≥10 km
A	1.5	1.2	1.0
B	1.3	1.0	1.0
C	1.0	1.0	1.0

TABLE 3. Near-fault factor, *Nv* in UBC97 code [13]

Seismic source type	Closest distance to known seismic source			
	≤2 km	5 km	10 km	≥15 km
A	2.0	1.6	1.2	1.0
B	1.6	1.2	1.0	1.0
C	1.0	1.0	1.0	1.0

Chai et al. modified the design response spectrum of the Taiwanese seismic design code used for sites located near Chelungpu fault based on UBC97 design concepts [18]. They considered the potential moment magnitude of the Chelungpu fault, 7.3 (the fault that caused Chi-Chi 1999 earthquake), and relative peak ground acceleration, 0.33 in the analysis. The data of strong motion recorded in CWB stations near the Chelungpu fault (with distance less than 15 km from the fault) during the Chi-Chi earthquake has been adopted by them to determine the near-fault factor. The general view of design spectrum, modified design spectrum and near-fault effect factors of rock sites for Taiwanese design code are presented in Tables 4 to 7.

TABLE 4. Response spectrum coefficients for rock sites in Taiwanese seismic design code [18]

Period range	Extremely short	Very short	Short	Moderate	Long
(second)	T≤0.03	0.03≤T≤0.15	0.15≤T≤0.333	0.333≤T≤1.315	T≥1.315
C(T)	1.0	1.25T+0.625	2.5	1.2/T2/3	1.0

TABLE 5. Near-fault factor, *Na* for sites near Chelungpu fault [18]

Fault rupture distance	R≤2 km	R=4 km	R≥6 km
Na	1.34	1.16	1.0

TABLE 6. Near-fault factor, *Nv* for sites near Chelungpu fault [18]

Fault rupture distance	R≤2 km	R=6 km	R≥10 km
Nv	1.70	1.30	1.0

TABLE 7. Near-fault response spectrum for rock sites near Chelungpu fault [18]

Period range	Extremely short	Very short	Short	Moderate	Long
(second)	T≤0.03	0.03≤T≤0.15	0.15≤T≤0.333	0.333≤T≤1.315	T≥1.315
C (T)	*Na*	*Na* (1.25T+0.625)	2.5 *Na*	*Nv* (1.2/T2/3)	*Nv*

TABLE 8. Near-fault factors for stiff soil site in Chinese seismic design code [12, 19]

Intensity	Distance (R, km)	*Na*	*Nv*
VII	2	1.0	1.7
	15	1.0	1.0
VIII	2	1.8	1.9
	8	-	1.0
	15	1.2	1.0
IX	2	1.2	1.8
	6	1.2	-
	9	-	1.6
	15	1.0	1.5

Modified design spectral curves for Chinese seismic design code considering the near-fault effects have been presented by Li et al. in 2007 [12, 19]. They proposed a new attenuation expression by collecting about 137 records which were recorded in a less than 15 km distance from causative faults of strong ground motions in United-States, Turkey, China, Taiwan and Japan. Finally, near-fault factors for Chinese seismic design code were calculated for short periods (T=0.3) and long periods (T=1.0) and are presented for stiff soils condition in Table 8.

3. Design Response Spectra of Iranian Seismic Design Code (Standard No. 2800)

The third edition of Iranian seismic (Standard No.2800 [17]), published by the Building and Housing Research Center in 2004, in three chapters and six appendices, follows the conventional force based design method (seismic coefficient method) for design of structures. The designed seismic force in this code is determined in terms of spectral response acceleration corresponding to a uniform seismic hazard level of 10% probability of exceedance within 50 years. It is apparent that near-fault effects have not been considered at present Iranian seismic code and the code-specified spectra cannot provide adequate design base shear force for a structure located in near-fault zone.

The seismic base shear coefficient for different seismic regions (1, 2, 3 and 4) in Iranian seismic design code (3rd edition) is defined as follows:

$$C = \frac{ABI}{R} \qquad (1)$$

where, *I* is building importance factor, *R* is behavior factor of structure that accounts for the capability of structures to experience earthquake ground motions out of elastic range of response and *B* is the reflection factor that is obtained from smoothed-elastic design response spectrum in the following form:

$$\begin{aligned} B &= 1+S\left(T/T_0\right) && 0 \le T \le T_0 \\ B &= 1+S && T_0 \le T \le T_s \\ B &= (S+1)\left(T_s/T\right)^{2/3} && T \ge T_s \end{aligned} \qquad (2)$$

In this equation, *T* is the structural fundamental period of vibration (in second); T_0,T_s and *S* are parameters related to site soil conditions and seismic potential of the region as given in Table 9.

TABLE 9. Associated parameters with reflection factor (*B*) based on Iranian seismic code ([17])

Soil type	T_0	T_s	Zone 1,2	Zone 3,4
			S	S
I	0.1	0.4	1.5	1.5
II	0.1	0.5	1.5	1.5
III	0.15	0.7	1.75	1.75
IV	0.15	1.0	1.75	2.25

Local site conditions could play the most important role in damage distribution as well as in the recorded strong ground motion amplitudes and should be considered in the design process of structures. The site classification criterion of the Standard No. 2800 is based on averaged shear wave velocity in the upper 30 m which is known as a more direct indicator of local site effects. Based on this code, four different site classes are defined as rock site, very dense soil and soft rock site, stiff soil site and soft soil site (soil type I to IV) which are respectively compatible with site classification of 2003 NEHRP namely; B, C, D and E [20]. It should be noted that, based on the Iranian seismic code, four seismic zones are defined as: very high, high, medium and low seismic potential zones (seismic zone 1 to 4). Reflection factors for different seismic regions and soil types are illustrated in Figs. 2 and 3.

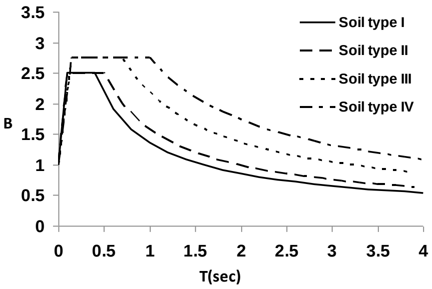

Fig. 2. Reflection factor of Iranian seismic code for seismic zones 1, 2 [17]

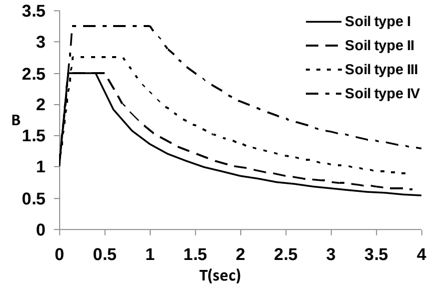

Fig. 3. Reflection factor of Iranian seismic code for seismic zones 3, 4 [17]

4. Proposed Near-Fault Attenuation Relationship

One of the most significant issues in seismic hazard analysis is the prediction of ground motion parameters for an earthquake, given the magnitude, distance and soil type. The accurate prediction values of attenuation equations can help us to make more reliable earthquake-resistant structures.

The characteristic of ground motions could be affected when the seismic waves propagate from fault rupture area through an irregular layer medium, in a complicated manner that should be considered properly in attention relationship. Accelerograms recorded near active faults have some important characteristics that make them different from those recorded in far-fault regions which has been discussed in section 1. High-frequency components in acceleration records and long-period velocity pulses are among notable specifications of such ground motions [21, 22].

Thus, estimating of ground motion parameters based on a suitable attenuation relation in near-fault area that could take into account its effect is needed. Considering the limited number of records in near-fault regions, generally the number of attenuation relations for near-fault regions are limited. In 2003, Campbell and Bozorgnia (abbreviated as CB03) presented an attenuation relationship for vertical and horizontal peak ground acceleration (PGA) and pseudo spectral acceleration that included near-source effects [23]. Ambraseys and Douglas also developed a new ground motion prediction equation for PGA in near-fault regions (abbreviated as AD05) [24].

In this paper, a new attenuation relationship of 5% damped acceleration response spectra based on near-fault ground motion is presented. For this purpose, 143 near-fault records from 26 earthquakes occurred over the 40-year time period from 1966 to 2006 at different parts of the world including Iran, Turkey, Japan, Taiwan and the United-States were used. General information regarding the earthquakes used in this work is listed in Table 10.

TABLE 10. Summary of database used in this study

No.	Event	Location	Year	Magnitude (Mw)	Fault Mechanism	Number of records
1	Parkfield	USA	1966	6.1	Strike slip	3
2	San Fernando	USA	1971	6.6	reverse	1
3	Gazli	Uzbakistan	1976	6.8	reverse	1
4	Tabas	Iran	1978	7.4	thrust	1
5	Coyote lake	USA	1979	5.8	Strike slip	6
6	Imperial valley	USA	1979	6.5	Strike slip	16
7	Morgan Hill	USA	1984	6.2	Strike slip	3
8	Nahanni	Canada	1985	6.8	thrust	2
9	Palm Springs	USA	1986	6.0	Strike slip	5
10	Whittier Narrows	USA	1987	6.0	thrust	16
11	Superstition Hills	USA	1987	6.7	Strike slip	6
12	Loma Prieta	USA	1989	6.9	reverse	9
13	Manjil	Iran	1990	7.4	Strike slip	1
14	Petrolia	USA	1992	7.0	thrust	4
15	Landers	USA	1992	7.3	Strike slip	2
16	Erzincan	Turkey	1992	6.9	Strike slip	1
17	Northridge	USA	1994	6.7	thrust	22
18	Kobe	Japan	1995	6.9	Strike slip	6
19	Kocaeli	Turkey	1999	7.4	Strike slip	5
20	Chi-Chi	Taiwan	1999	7.6	reverse	25
21	Duzce	Turkey	1999	7.1	Strike slip	2
22	Bam	Iran	2003	6.5	Strike slip	1

The distance of all the stations from the projection of fault rupture (R) which adopted as distance measure in this paper was less than 15 km. The moment magnitude (Mw) range of the selected earthquakes in our database was 5.8 to 7.8 and horizontal peak ground acceleration in all records was at minimum 0.3 g. The distribution of magnitude versus the distance is provided as a plot in Fig. 4.

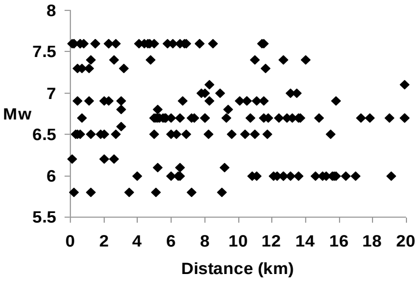

Fig. 4. Distribution of earthquake ground motion dataset used in this study

The ground motions recorded in near-fault earthquake are strongly influenced by the orientation effects in which the pulse effects of such motions in fault-normal component are more noticeable than parallel ones and can significantly influence the results of provided response spectra. According to [1], the radiation pattern of the shear dislocation on the fault causes this large pulse of motion to be oriented in the direction perpendicular to the fault, causing the strike-normal ground motions to be larger than the strike-parallel ground motions at periods longer than about 0.5 second. That's why the structural response in near-fault earthquakes is concentrated on larger effects of the fault-normal components [5, 25]. This concern justifies the use of the fault-normal component that has not been considered in most existing attenuation relations. In consequence, before doing the regression analyses, all ground motion time histories for each event were first rotated to fault-normal orientation by using a simple vector rotation proposed by Somerville [1].

The mathematical relationship used for modeling the attenuation of spectral acceleration (with 5% viscous damping ratio; $\xi = 5\%$) in near-fault area is adopted in the following simple form:

$$Ln(S_a)=b_1+b_2\times M_w+b_3\times Ln(R+10)^{0.5}+b_4\times S_R+b_5\times S_S \quad (3)$$

where, *Sa* is the spectrum acceleration, *Mw* is the moment magnitude, *R* is the distance from the projection of fault rupture in kilometers, S_R is considered 1.0 for hard and rock sites (soil type *I* and *II* according to [17]) and takes the value of zero for all other sites, S_S for soft and loose sites is considered 1.0 (soil types *III* and *IV*) and otherwise zero. Nonlinear regression analysis was carried out to compute the coefficients b1 to b5 for both none-rotated and rotated cases (fault-normal component) at 11 periods ranging from 0.1 to 2 second. Results of analysis are summarized in Tables 11 and 12. It is important to note that, deriving of ground motion prediction in non-rotated case as a conventional form, enable us to i) make a better comparison with some well-established equations for near-fault motion, ii) enhanced capture the difference of predicted values of spectral acceleration for fault-normal components with non-rotated case.

TABLE 11. Coefficients of the regression parameters for the proposed model (non-rotated case)

T (sec)	b1	b2	b3	b4	b5
0.1	0.189	0.0094	-0.330	0.114	0.227
0.15	-1.221	0.2375	-0.3118	0.130	0.260
0.2	-1.685	0.288	-0.264	0.140	0.278
0.3	-1.794	0.308	-0.283	0.153	0.306
0.4	-3.050	0.493	-0.333	0.140	0.2806
0.5	-4.286	0.650	-0.3423	0.168	0.336
0.75	-5.140	0.757	-0.415	0.158	0.3150
1	-6.590	0.854	-0.1482	0.145	0.290
1.2	-7.755	0.985	-0.1595	0.172	0.341
1.5	-8.923	1.123	-0.185	0.1963	0.392
2	-9.119	1.147	-0.332	0.276	0.550

TABLE 12. Coefficients of the regression parameters for the proposed model (rotated case in normal orientation)

T (sec)	b1	b2	b3	b4	b5
0.1	0.201	0.0101	-0.3303	0.1196	0.2383
0.15	-1.298	0.2524	-0.311	0.1368	0.2725
0.2	-1.790	0.3065	-0.2644	0.146	0.2916
0.3	-1.907	0.3280	-0.2834	0.1607	0.3202
0.4	-3.241	0.5245	-0.3333	0.1473	0.2935
0.5	-4.554	0.690	-0.3423	0.1765	0.3517
0.75	-5.461	0.8045	-0.4152	0.1654	0.3294
1	-7.003	0.9075	-0.1482	0.1524	0.3037
1.2	-8.24	1.0471	-0.1595	0.1790	0.3566
1.5	-9.482	1.1935	-0.1851	0.2059	0.4103
2	-9.689	1.219	-0.3324	0.2892	0.5760

Fig. 5 and 6 compare the predicted values by the proposed attenuation relationship for non-rotated case with those from CB03 and AD05 models in rock sites, distance of 10 km and magnitude of 6 and 7, respectively.

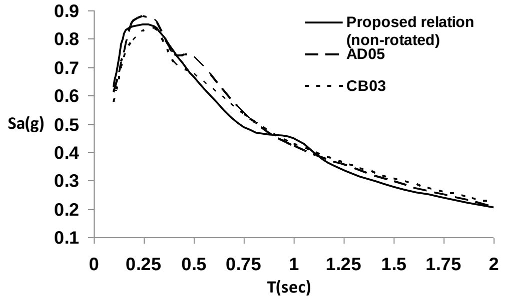

Fig. 5. Comparison of the proposed attenuation relation in non-rotated case (Rock site, R =10 km, *Mw*=6.5)

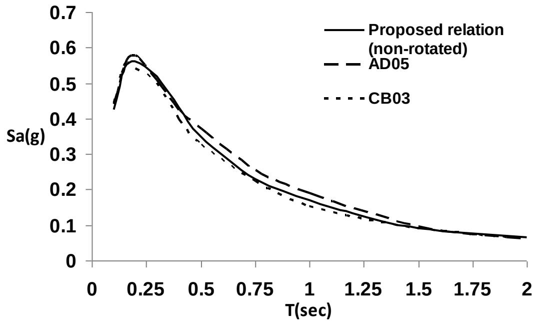

Fig. 6. Comparison of the proposed attenuation in non-rotated (Rock site, R=10 km, *Mw*=7.5)

It can be appreciated that the difference between the predicted values in a wide range of periods is not significant. A similar comparison has been made between the proposed equation for fault-normal component with those from CB03 and AD05 models. It reveals that the values of near-fault response spectrum calculated by the proposed attenuation relation for periods between 0.1 to 0.6 (second) are approximately 15 to 20 percent more than the values of response spectra calculated from CB03 and AD05 models. These comparisons for rock sites with distance of 10 km from the fault rupture and two magnitude values of 6.5 and 7.5 are shown in Fig. 7 and 8.

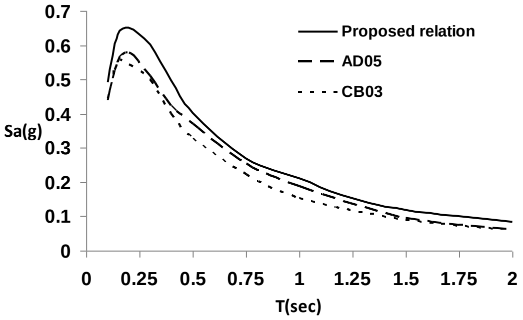

Fig. 7. Comparison of the proposed attenuation relation in fault normal case (Rock site, R=10 km, Mw=6.5)

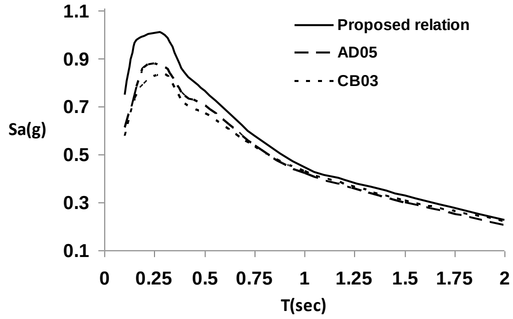

Fig. 8. Comparison of the proposed attenuation in fault normal (Rock site, R=10 km, *Mw*=7.5)

5. Near-Fault Factors for Iranian Seismic Design Code

In this section of paper, the near-fault factors in short and long periods (*Na, Nv*) are calculated for structures located in highest seismicity zone of Iran (with effective peak ground acceleration of 0.35 g) respectively based on the spectrum acceleration in 0.3 and 1.0 seconds.
For this purpose, the corresponding values of spectral acceleration obtained from the proposed attenuation relation in 0.3 second ($S_{a0.3}(M_w, R)$) and 1.0 second ($S_{a1.0}(M_w, R)$) are compared with the seismic demands defined by design spectral acceleration of the Iranian seismic code in these periods as $B(T)_{T=0.3\ or\ 1.0} \times A_{code}$. Maximum values of these comparisons lead to calculating $S_{a0.3}$ and $S_{a1.0}$ that could be used simply for calculating of near-fault factors as follows:

$$S_{a0.3\ or\ 1.0} = max\ [S_{a0.3\ or 1.0}(M_W, R), (B(T)_{T=0.3 or 1.0} \times A_{code})] \quad (4)$$

$$Na = \frac{S_{a0.3}}{B(T)_{T=0.3} \times A_{code}} \quad (5)$$

$$Nv = \frac{S_{a1.0}}{B(T)_{T=1} \times A_{code}} \quad (6)$$

In the above relations, *B* is the reflection factor obtained from the design response spectrum, S_a is the spectrum acceleration and *A* is the seismic zone factor that is taken as 0.35 for seismic zone 4 in Iran. By applying Eqs. (5) and (6) and using Table 9, near-fault factors for sites with different soil conditions with different magnitude ranges (M<6.5, 6.5<M<7, M>7) were calculated and presented in Tables 13 to 15.

TABLE 13. Near-fault factors for Iranian seismic design code, *Mw* <6.5

Distance (km)		R<2			R=6		
Soil Type*Mw*		6.0	6.2	6.4	6.0	6.2	6.4
Na	I	1.0	1.0	1.0	1.0	1.0	1.0
	II	1.0	1.0	1.0	1.0	1.0	1.0
	III	1.0	1.0	1.05	1.0	1.0	1.0
	IV	1.0	1.0	1.0	1.0	1.0	1.0
Nv	I	1.0	1.0	1.1	1.0	1.0	1.0
	II	1.0	1.0	1.05	1.0	1.0	1.0
	III	1.0	1.05	1.1	1.0	1.0	1.0
	IV	1.0	1.1	1.1	1.0	1.0	1.0

TABLE 14. Near-fault factors for Iranian seismic design code, $6.5 \leq Mw \leq 7.0$

Distance (km)		R<2			R=6			R=12		
Soil Type*Mw*		6.6	6.8	7.0	6.6	6.8	7.0	6.6	6.8	7.0
Na	I	1.0	1.0	1.1	1.0	1.0	1.0	1.0	1.0	1.0
	II	1.0	1.1	1.15	1.0	1.0	1.0	1.0	1.0	1.0
	III	1.0	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0
	IV	1.0	1.1	1.1	1.0	1.0	1.0	1.0	1.0	1.0
Nv	I	1.2	1.4	1.5	1.0	1.1	1.1	1.0	1.0	1.0
	II	1.25	1.35	1.5	1.0	1.15	1.2	1.0	1.0	1.0
	III	1.3	1.35	1.45	1.1	1.15	1.2	1.0	1.0	1.0
	IV	1.35	1.4	1.5	1.1	1.2	1.2	1.0	1.0	1.0

TABLE 15. Near-fault factors for Iranian seismic design code, *Mw* > 7.0

Distance (km)		R<2			R=6			R=12			R=18		
Soil Type*Mw*		7.2	7.4	7.6	7.2	7.4	7.6	7.2	7.4	7.6	7.2	7.4	7.6
Na	I	1.1	1.3	1.6	1.0	1.1	1.4	1.0	1.0	1.05	1.0	1.0	1.0
	II	1.1	1.3	1.55	1.0	1.1	1.2	1.0	1.0	1.1	1.0	1.0	1.0
	III	1.15	1.3	1.5	1.1	1.1	1.25	1.0	1.05	1.1	1.0	1.0	1.0
	IV	1.15	1.35	1.5	1.1	1.1	1.15	1.0	1.0	1.1	1.0	1.0	1.0
Nv	I	1.7	1.8	1.85	1.3	1.4	1.5	1.1	1.2	1.3	1.0	1.0	1.0
	II	1.75	1.75	1.85	1.25	1.35	1.4	1.0	1.1	1.25	1.0	1.0	1.0
	III	1.75	1.8	1.85	1.35	1.5	1.55	1.1	1.15	1.3	1.0	1.0	1.0
	IV	1.8	1.85	1.9	1.3	1.45	1. 6	1.1	1.2	1.3	1.0	1.0	1.0

As shown in these tables, there are not significant differences between the near-fault factors values calculated for four different site conditions. Accordingly, we can summarize the near-fault factors for amplification of design spectra presented in Iranian seismic code [17] as summarized in Tables 16 and 17. The near-fault factors for distance other than those shown in these tables could be simply calculated based on the linear interpolation.

TABLE 16. Proposed near-fault factor, *Na* for Iranian seismic design code (Standard No.2800 [17])

Magnitude	Distance from fault rupture (km)		
	R<2	R=6	R>12
Mw>7	1.4	1.2	1.0
$6.6 \le MW \le 7.0$	1.2	1.0	1.0
Mw<6.6	1.0	1.0	1.0

TABLE 17. Proposed near-fault factor, *Nv* for Iranian seismic design code (Standard No.2800 [17])

Magnitude	Distance from fault rupture (km)			
	R<2	R=6	R=12	R>18
Mw>7	1.9	1.5	1.2	1.0
$6.6 \le MW \le 7.0$	1.5	1.2	1.0	1.0
Mw<6.6	1.1	1.0	1.0	1.0

Generally, near-field region is defined as a zone near the fault where its distance from the source rupture is less than a specific limit. Researchers have not reached to a same value for this distance that could be best suited in all applications. Some researchers consider this distance less than 50 km and some others take this distance as 15 km [26-28]. This distance in UBC97 code is defined as 15 km. Chai et al. [18] calculated the near-fault distance to Chelongpu fault, about 12 km and Li et al. [14] assumed the near-fault distance in Chinese design spectra to be 15 km. Also, it was found that rupture directivity increases the low frequency content of ground motion at distances within 20 km from the focus [29].

The results of this paper provide a simple tool to determine a new distance criterion for Iranian seismic code. The results of analysis for all studied cases in this work (Tables 13 to 15) reveal that *Na* and *Nv* give value of 1.0 at about 6.0 and 18 km from the fault rupture, respectively. It is concluded that near-fault distance criterion for Iranian seismic code can be taken as 18 km.

6. Modified Design Response Spectra for Iranian Seismic Design Code

The calculated near-fault factors for short and long periods are applied in the Iranian seismic code as follows:

$$
\begin{aligned}
&B = Na[1+S(T/T_0)] && 0 \le T \le T_0 \\
&B = Na[1+S] && T_0 \le T \le T_1 \\
&B = Nv\,(S+1)(T_S/T)^{\frac{2}{3}} && T \ge T_1
\end{aligned}
\qquad (7)
$$

With $T_1 = T_S (Na/Nv)^{\frac{3}{2}}$

Based on Iranian seismic code provisions, earthquake magnitude is not directly included in the calculation of seismic coefficients in design procedure. On the other hand, magnitude is considered as an important item to apply the near-fault effect factors. Considering the lack of sufficient information about the seismic source properties in Iran such as the failure mechanism, slip velocity, fault geometry, and potential of fault to generate strong motions, for defining the range of the magnitude in near-fault regions we need to run a seismic hazard analysis or use the previous studies carried out for different parts of Iran. Based on seismic hazard analysis of Tavakoli and Ashtiani [30], Iran has been divided into 20 seismic zones and for each seismic zone a maximum moment magnitude introduced (see Table 18 and Fig. 9). Therefore, as a possible way out, we can choose maximum expected magnitude (M_{max}) according to this map to calculate *Na* and *Nv* values from Tables 15 and 16. Modified design spectra of the Iranian seismic code for different range of magnitude and distance are presented in Figs. 10 to 21 that could be used for seismic design or performance evaluation of structures located in near-fault area in Iran.

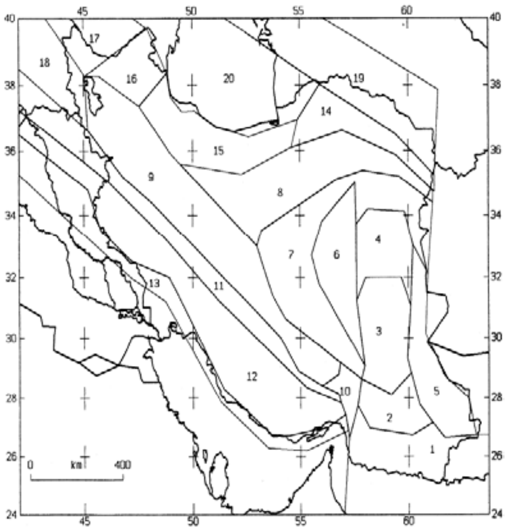

Fig. 9 Seismic zones of Iran defined based on [30]

TABLE 18. Maximum moment magnitude for different seismic zones defined by Tavakoli and Gh.Ashtiani [30]

Zone number	Maximum magnitude ($M_{\max}$)
1	8.0
15	7.7
4, 6,11, 14, 16, 18, 19	7.4
7, 17, 20	7.3
8	7.2
2, 3, 12	7
5	6.9
9	6.8
13	6.5
10	6.1

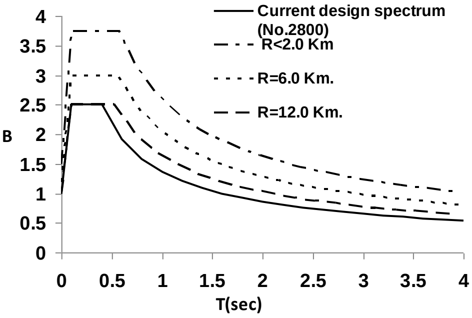

Fig. 10. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type I, *Mw*>7.0)

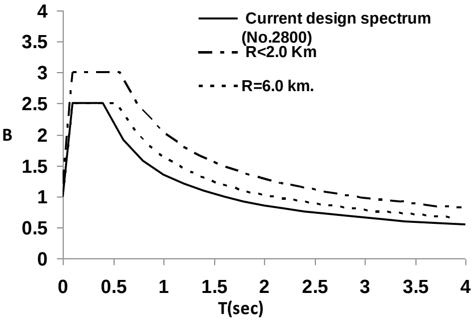

Fig. 11. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type I, 6.5< *Mw*<7.0)

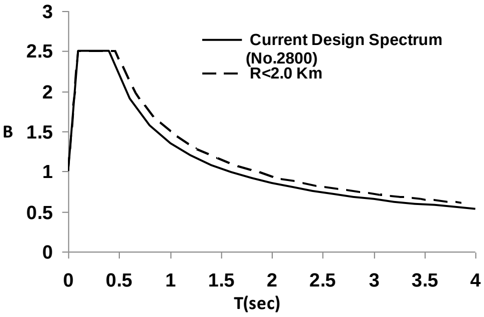

Fig. 12. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type I, *Mw*<6.5)

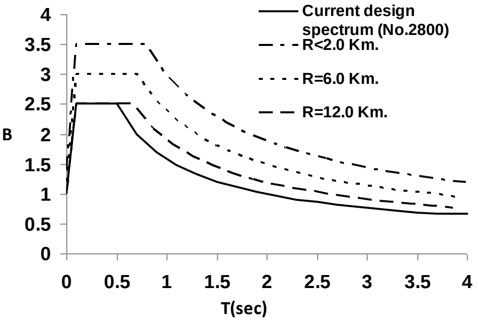

Fig. 13. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type II, M>7.0)

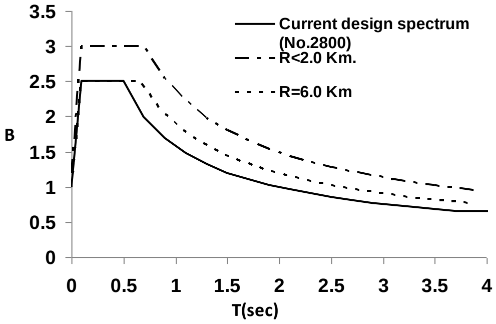

Fig. 14. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type II, 6.5< *Mw*<7.0)

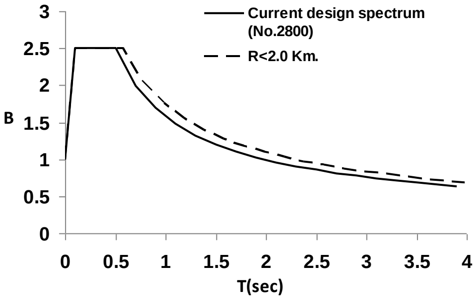

Fig. 15. Modified (dashed line) and current design spectrum of Iranian seismic design code (soil type II, *Mw*<6.5)

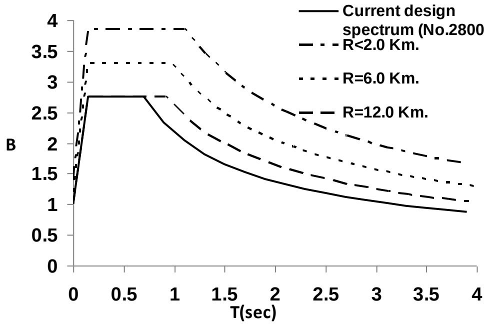

Fig. 16. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type III, *Mw*>7.0)

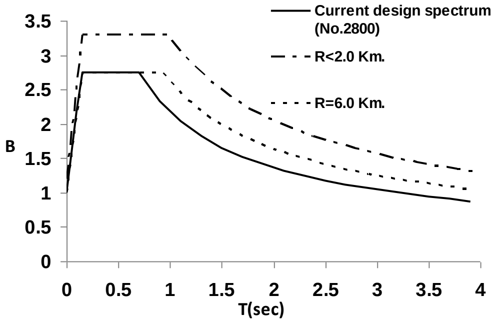

Fig. 17. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type III, 6.5< *Mw*<7.5)

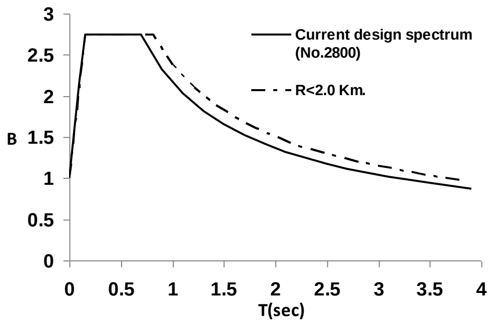

Fig. 18. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type III, *Mw*<6.5)

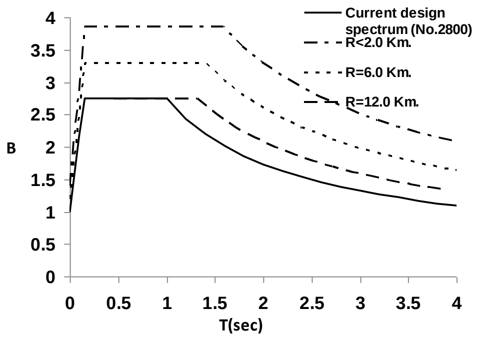

Fig. 19. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type IV, *Mw*>7.0)

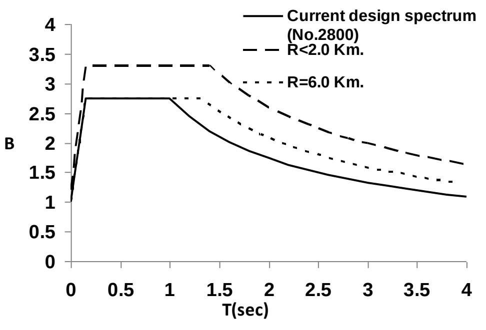

Fig. 20. Modified (dashed lines) and current design spectrum of Iranian seismic design code (soil type IV, 6.5<*Mw*<7.0)

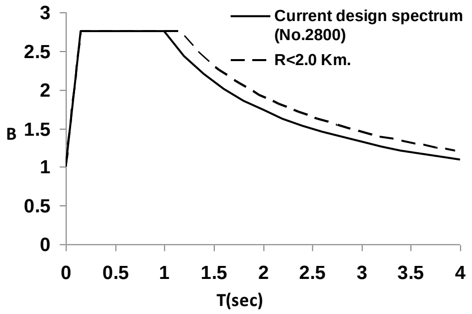

Fig. 21. Modified (dashed line) and current design spectrum of Iranian seismic design code (soil type IV, *Mw*<6.5)

7. CONCLUSION

Based on the results presented in this study, the following conclusions are drawn:

- As a significant improvement in seismic analyses and design of the structures in Iran, modified design spectra of Iranian seismic design code based on near-fault factors were presented. The results showed that near-fault ground motions are able to impose higher demand compared to those of far-field motions, particularly for flexible buildings with the natural period range larger than 1.0 second.
- The response spectrum calculated using the proposed attenuation relation for non-rotated case had a proper correspondence to those of Campbell and Bozorgnia, 2003 and Ambraseys and Douglas, 2005 relations abbreviated as CB03 and AD05, respectively.
- The values of response spectrum predicted by the proposed attenuation relation (for fault-normal case) between 0.1 to 0.6 seconds are 15 to 20 % larger than those of CB03 and AD05 in corresponding periods.
- The distance criterion that defines the near-fault region consistence with the design response spectra of Iranian seismic code was calculated as 18 km and can be used for design and performance evaluation of structures in Iran.
- The largest modification was expected for strong events (*Mw*>7) in the distance lower than 2 km from the fault rupture, which needs to be significantly increased in design demands by 1.9 times.

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Improvement of Iranian Seismic Design Code Considering the Near-Fault Effects

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چکیده

خصوصیات زلزله های نزدیک گسل می تواند بسیار متفاوت از زلزله های دور باشد که این مسئله بایستی در طراحی لرزه ای سازه ها مد نظر قرار گیرد. هدف از مطالعه حاضر اصلاح طیف های طراحی آیین نامه طراحی لرزه ای ایران (استاندارد ۲۸۰۰) با توجه به اثرات نزدیک گسل است. بدین منظور، در ابتدا رابطه کاهندگی جدیدی بر اساس مولفه نرمال زلزله های نزدیک گسل ارائه، سپس دو ضریب اصلاح برای پریودهای کوتاه و بلند محاسبه شده است. ضرائب ارائه شده در این مقاله همخوانی نسبتا خوبی با ضرائب موجود در آیین نامه هایUBC97 ، آیین نامه چین و تایوان دارد. در ضمن نتایج حاصله نشان می دهد که معیار نزدیکی گسل در ایران می تواند ۱۸ کیلومتر انتخاب شود.

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