SIMULATED NEAR-FAULT GROUND MOTIONS FOR SPECIFIED DESIGN SCENARIO IN TABRIZ CITY USING STOCHASTIC MODEL

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ABSTRACT

In seismic performance-based engineering, the selection of input ground-motion plays a key role in outcomes of nonlinear dynamic analysis. To this end, the selected input strong-motions should represent properly the effects of earthquake source mechanism and characteristics of the site. When a site is in close distance of seismic sources, the records should exhibit the properties of near-fault ground-motions as well. In spite continuous expansion of the database of recorded earthquakes, recorded near-fault ground-motions especially those exhibiting pulse motions, remain scarce. In response to this engineering need, utilizing simulated synthetic records is one of the alternatives.

Tabriz as a major city in the northwest of Iran, is situated in the vicinity of the North Tabriz Fault, which is one of the major seismogenic faults. Due to lack of recorded near-fault ground-motions in this area, simulating near-fault ground-motions in a way that can be used in performance-based earthquake engineering is inevitable. The present study combines several existing theories to represent a non-stationary stochastic model for near-fault ground-motions to generate synthetic accelerograms for a specified design scenario of a site that is located in Tabriz city. The inputs of the stochastic model are extracted from disaggregation results of near-fault seismic hazard probabilistic analysis.

Keywords: Tabriz city; Non-stationary stochastic model; Performance-based simulation; Near-fault ground motions; rupture directivity;

1. INTRODUCTION

Structures which are built in near-fault regions are exposed to ground motions that often include a large amplitude, long period pulse in their velocity time series. This so-called phenomenon is stemmed from directivity effect and may cause considerable damage to the structures (Somerville et al. 1997; Abrahamson 2000; Mavroeidis and Papageorgiou 2002). Under these circumstances, identifying the nonlinear dynamic behavior of these structures and consequently using time history series becomes inevitable. One of these sites which is located in a near-fault region is Tabriz city. This city, in the northwest of Iran, is located in the vicinity of the North Tabriz Fault, one of major seismogenic faults in Iran. This city lacks near-fault recorded earthquakes that are corresponded to its seismic characteristics and in turn, the seismic performance of those structures which are built in this city, cannot be estimated properly.

The current design code of Iran suggests to use available recorded ground motions as inputs for time history dynamic analysis, however, each recorded motion is stemmed from particular seismic characteristics and it may not correspond to the seismic characteristics of the site of interest. As a result, these recorded motions should be adjusted to desired intensity and frequency content. However, these modifications may lead to an inaccurate representation of real ground motions (Rezaeian and Der Kiureghian 2010). In response to this engineering need, utilizing simulated synthetic records is one of the alternatives.

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Models of ground motion time series are classified into two groups: (i) Source-based models which describe the occurrence of fault ruptures and wave propagation through the ground and (ii) site-based models that describe the ground motions for a specific site by fitting to available recorded motions (Rezaeian and Der Kiureghian 2010).

One of the models used for simulating near-fault ground motions and properly represents the pulse which is caused by directivity effect, has been proposed by Mavroedis and Papageorgiou (2003). In addition to their pulse model, they used specific barrier model (Papageorgiou and Aki 1983) in order to simulate high frequency content of records and then combined them to fully represent pulse-like near-fault ground motions. The specific barrier model does not properly account for spectral non-stationarity. Additionally, this model belongs to source based models so it cannot be used in regions where seismological data are lacking. On the other hand, site-based models are more attractive to design engineers because these models only require readily available knowledge of the earthquake source and site characteristics. One of the site-based models that can properly simulate the temporal and spectral non-stationary characteristics of real ground motions, has been proposed by Rezaeian and Der Kiureghian (2008, 2010). However, this model has been originally developed to simulate far-field ground motions.

The present study is an attempt to develop a non-stationary stochastic model to simulate near-fault ground motions for various design scenarios of a site that is located in Tabriz. In this regard, we employed the model that was proposed by Rezaeian and Der Kiureghian (2008, 2010) to generate high frequency content of near-fault ground motions. However, as the model has been developed for far-field regions, the parameters of the model need to be recalibrated by using a near-fault ground motions database. Additionally, we integrated it with the proposed model by Mavroeidis and Papageorgiou to simulate directivity effect pulses. As the final step, we employed our model to simulate suites of synthetic records for various design scenarios of a site that is located in Tabriz city. In this regard, we used disaggregation results of near-fault probabilistic seismic hazard analysis (PSHA) which was provided by Yousefi and Taghikhany (2014).

2. HIGH FREQUENCY CONTENT

Having temporal and spectral non-stationary characteristics and including the variability observed in available recorded ground motions for a specific design scenario, are important factors that a good synthetic model should consist to represent realistic ground motions. Temporal non-stationarity reflects the evolving intensity over time and spectral non-stationarity refers to the time-varying frequency content of the motions. Rezaeian and Der Kiureghian (2008, 2010) used a fully non-stationary filtered white-noise process to properly account for the aforementioned factors. They formulated their model as Equation 1:

\[ x(t) = q(t, \alpha) \left( \frac{1}{\sigma(t)} \int_{-\infty}^{t} h[t-\tau, \lambda(\tau)] w(\tau) d\tau \right) \]  

(1)

In the above expression t and τ denote time, x(t) is the time history of ground motion acceleration process, w(τ) is white noise process, h[t-\tau, \lambda(\tau)] is a linear filter with time varying parameters, where \lambda denotes a set of parameters used to ‘shape’ the filter response, and q(t, \alpha) is time-modulating function with \alpha denoting a set of parameters used to control the shape and intensity of the function. \sigma(t) is standard deviation of the expression inside the square brackets.

As our aim in this paper is to simulate synthetic ground motions for a site that is located in a near-fault region, so we need to reconstruct the predictive equations for the model parameters. To this end and by following them, first, the parameters of the model should be identified by matching the evolutionary statistical characteristics of the model to a large number of recorded near-fault ground motions with known characteristics. Then, in order to develop predictive equations, these parameters will be transformed to normal space, to satisfy the normality requirements of the regression error, and finally, these values will be regressed against the earthquake and site characteristics.
2.1 Modulating function and identification of its parameters

Rezaeian and Der Kiureghian (2008, 2010) estimated $\alpha$ in a way that the Arias intensity of the motions generated by their model closely match with target accelerograms. Arias intensity of the process $x(t)$ is defined by Equation 2:

$$I_a = E\left[\frac{\pi}{2g} \int_0^{t_m} x^2(t)dt\right] = \frac{\pi}{2g} \int_0^{t_m} q^2(t,\alpha)dt$$

(2)

For $q(t,\alpha)$, they used a gamma function which is defined by Equation 3:

$$q(t,\alpha) = \begin{cases} 0 & \text{if } t \leq T_0 \\ \alpha_1 (t-T_0)^{\alpha_2 - 1} \exp[-\alpha_3 (t-T_0)] & \text{if } T_0 \leq t \end{cases}$$

(3)

Where $\alpha_1$, $\alpha_2$, and $\alpha_3$ control the intensity, shape, and duration of the motion respectively and $T_0$ denotes the start time of the process. By following them, $q^2(t,\alpha)$ is proportional to a shifted ‘gamma’ probability density function (PDF) having parameter values $a=2\alpha_3$ and $b=2\alpha_2-1$. Gamma PDF can be written as Equation 4:

$$f_T = \frac{a^b}{\Gamma(b)} t^{b-1} \exp(-at) \quad \text{if } t \geq 0$$

$$= 0 \quad \text{otherwise}$$

(4)

Where $a$ and $b$ are the parameters of the distribution and $\Gamma(b)$ is the gamma function. If $t_p$ represents the $p$-percentile variate of the gamma cumulative distribution function, then $t_p$ can be calculated in terms of the parameters $\alpha_2$ and $\alpha_3$ and the probability $p\%$. Equations 5 and 6 can be written as follow:

$$D_{5,95} = t_{95} - t_5$$

(5)

$$t_{\text{mid}} = t_{45}$$

(6)

They defined $D_{5,95}$ as the time interval between the 5% and 95% of the expected Arias intensities and they considered $t_{\text{mid}}$ as the time at which 45% level of the expected Arias intensity is reached. By using a nonlinear optimization approach, parameters $\alpha_2$ and $\alpha_3$ can be calculated from distinct values of $D_{5,95}$ and $t_{\text{mid}}$, which are obtained from a target accelerogram. They also showed that $\alpha_1$ is directly related to expected Arias intensity through Equation 7:

$$\alpha_1 = \sqrt{\frac{2g}{\pi}} \frac{1}{t_3} \frac{(2\alpha_3)^{2\alpha_2 - 1}}{\Gamma(2\alpha_2 - 1)}$$

(7)

Figure 1 shows an acceleration time history of a recorded motion and its fitted gamma modulating function.
2.2 Linear filter and identification of its parameters

Rezaeian and Der Kiureghian (2008, 2010) used pseudo-acceleration response of a single-degree-of-freedom linear oscillator as their filter, formulated as Equation 8:

\[
h[t - \tau, \lambda(\tau)] = \frac{\omega_f(\tau)}{\sqrt{1 - \xi_f^2(\tau)}} \exp[-\xi_f(\tau)\omega_f(\tau)(t-\tau)] \times \sin \left[ \omega_f(\tau) \sqrt{1 - \xi_f^2(\tau)}(t-\tau) \right] ; \quad \tau \leq t \quad (8)
\]

Where \( \omega_f \) and \( \xi_f \) are natural frequency and damping ratio respectively. They adopted a linear function for the frequency of their filter as Equation 9:

\[
\omega_f(\tau) = \omega_{\text{mid}} + \omega' (t-\tau) \quad (9)
\]

Where \( \omega_{\text{mid}} \) is the filter frequency at \( t_{\text{mid}} \), and \( \omega' \) denotes the rate of change of the filter frequency with time. Following their method, to estimate \( \omega_{\text{mid}} \) and \( \omega' \), a second order polynomial should be fitted to cumulative count of zero-level up-crossings of a target accelerogram from the time at 1% to 99% level of Arias intensity. After differentiating the polynomial, the slope of this line represents \( \omega' \) and the value of the line at \( t_{\text{mid}} \) denotes \( \omega_{\text{mid}} \). Figure 2.a demonstrates this fitting process for aforementioned recorded motion.

After identifying \( \omega_{\text{mid}} \) and \( \omega' \), cumulative count of negative-maxima and positive-minima for different values of \( \xi_f \) from the time at 5% to 95% level of Arias intensity should be calculated. The curve that best matches with the curve of cumulative count of negative-maxima and positive-minima of the target accelerogram within the aforementioned time interval, represents the value of damping ratio. Figure 2.b shows application of this method to the earthquake record mentioned above. This process will be repeated to estimate the model parameters for the entire recorded motions in the database.
Figure 2. Determination of filter parameters. (a) The results of matching the cumulative number of zero-level up-crossing are $\omega_{\text{mid}}/2\pi = 3.124$ Hz and $\omega_{\text{mid}}/2\pi = 108$ Hz and (b) fitting process of cumulative count of negative-maxima and positive-minima gives $\zeta_p = 0.11$.

2.3 Regression analysis and prediction equations

In order to develop prediction equations, model parameters should be transformed to normal space. In this regard, marginal probability density functions and cumulative probability functions are assigned to each set of the model parameters. Following Rezaeian and Der Kiureghian’s notation, if $\theta_i$ denotes the $i$th parameter of the stochastic model and $F_{\theta_i}(\theta_i)$ represents the marginal cumulative distribution, corresponding to $\theta_i$, then marginal transformation is defined as Equation 10:

$$v_i = \Phi^{-1}[F_{\theta_i}(\theta_i)], \quad i = 1, \ldots, n_p$$  (10)

Where $\Phi^{-1}[\bullet]$ denotes the inverse of the standard normal cumulative distribution function and $n_p$ represents the total number of parameters. Figure 3 shows the fitted PDFs to normalized transformed parameters of the model. The fitted PDFs and their distribution types are listed in Table 1.

Figure 3. Probability density functions fitted to observed normalized parameters of the model.
To estimate prediction equations, the transformed values will be regressed against explanatory functions, including fault mechanism (F), F=0 denotes strike-slip fault and F=1 denotes a reverse fault, earthquake magnitude (M), source to site distance (Rrup), and soil effect, measured by shear-wave velocity of the top 30 meter of the site soil (Vs30).

In order to factor in uneven clustering of data, a random effect regression analysis with a linear form is employed. In random effect regression, the total error is defined as the sum of inter-event (η) and intra-event (ε) residuals. These residuals are zero mean, normally distributed with variances (τ²) and (σ²). The resulting prediction equations are given by Equations 11 and 12.

\[
\nu_i = \beta_{i,0} + \beta_{i,1}F + \beta_{i,2}\left(\frac{M}{7.0}\right) + \beta_{i,3}\left(\ln \frac{R_{rup}}{25 \text{ km}}\right) + \beta_{i,4}\left(\ln \frac{V_{s30}}{750 \text{ m/s}}\right) + \eta_i + \epsilon_i \tag{11}
\]

\[
\nu_i = \beta_{i,0} + \beta_{i,1}F + \beta_{i,2}\left(\frac{M}{7.0}\right) + \beta_{i,3}\left(\frac{R_{rup}}{25 \text{ km}}\right) + \beta_{i,4}\left(\frac{V_{s30}}{750 \text{ m/s}}\right) + \eta_i + \epsilon_i \quad i = 2,\ldots,6 \tag{12}
\]

Where \(\beta_{i,0}, \beta_{i,1}, \beta_{i,2}, \beta_{i,3}\), and \(\beta_{i,4}\) (\(i = 1,\ldots,6\)) are regression coefficients and their values in conjunction with the estimated standard deviations are listed in Table 2.

Table 1. Types of distribution assigned to the model parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fitted distribution</th>
<th>Distribution bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iₐ, s.g</td>
<td>lognormal</td>
<td>(-∞, 1)</td>
</tr>
<tr>
<td>D₅₋₉₅</td>
<td>beta</td>
<td>[1, 40]</td>
</tr>
<tr>
<td>tₘid</td>
<td>beta</td>
<td>[0.5, 30]</td>
</tr>
<tr>
<td>(\omega/2\pi)</td>
<td>gamma</td>
<td>(0, ∞)</td>
</tr>
<tr>
<td>(\omega/2\pi)</td>
<td>two-sided exponential</td>
<td>[-3, 1.5]</td>
</tr>
<tr>
<td>(\zeta_f)</td>
<td>beta</td>
<td>[0.01, 1]</td>
</tr>
</tbody>
</table>

Table 2. Estimation of regression coefficient and standard error component

<table>
<thead>
<tr>
<th>i</th>
<th>(\beta_{i,0})</th>
<th>(\beta_{i,1})</th>
<th>(\beta_{i,2})</th>
<th>(\beta_{i,3})</th>
<th>(\beta_{i,4})</th>
<th>(\tau_i)</th>
<th>(\sigma_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-4.966</td>
<td>0.428</td>
<td>4.664</td>
<td>-0.612</td>
<td>-0.428</td>
<td>0.678</td>
<td>0.805</td>
</tr>
<tr>
<td>2</td>
<td>-8.081</td>
<td>-0.628</td>
<td>8.948</td>
<td>0.636</td>
<td>-0.76</td>
<td>0.195</td>
<td>0.609</td>
</tr>
<tr>
<td>3</td>
<td>-8.555</td>
<td>-0.465</td>
<td>9.337</td>
<td>0.673</td>
<td>-0.714</td>
<td>0.102</td>
<td>0.423</td>
</tr>
<tr>
<td>4</td>
<td>1.157</td>
<td>-0.251</td>
<td>-1.767</td>
<td>-0.234</td>
<td>0.912</td>
<td>0.279</td>
<td>1.38</td>
</tr>
<tr>
<td>5</td>
<td>-2.655</td>
<td>0.179</td>
<td>2.693</td>
<td>-0.179</td>
<td>-0.064</td>
<td>0.513</td>
<td>0.687</td>
</tr>
<tr>
<td>6</td>
<td>-1.483</td>
<td>0.008</td>
<td>2.087</td>
<td>-0.532</td>
<td>-0.481</td>
<td>0.229</td>
<td>1.165</td>
</tr>
</tbody>
</table>
2.4 Database of near-fault ground motion

As mentioned earlier, Rezaeian and Der Kiureghian (2010) originally developed their model to simulate ground motions for maximum considered earthquake (MCE) event in far-field regions and the database they used and their limitation corresponded to this aim. However, as our primary goal is to develop a model that can be used for near-fault regions, we used a subset of PEER’s NGA-WEST2 (Pacific Earthquake Engineering Research Center; Next Generation Attenuation of Ground Motion) that consists of near-fault ground motions with \( R_{rup} \leq 30 \) km, \( V_{s30} \geq 360 \) m/s, and no limit is set for \( M \). The shear-wave velocity limitation is set to exclude ground motions at very soft sites (Dabaghi and Der Kiureghian 2016).

2.5 Correlation analysis

In order to find dependencies among model parameters, correlation analysis should be performed. Correlation analysis contributes to accurately simulate a random sample of model parameters. Following Rezaeian and Der Kiureghian (2010), we used the correlation between the parameters \( v_i \), to estimate the correlation between the total residuals. Table 3 lists the correlation coefficients between the jointly normal variables \( v_i \).

<table>
<thead>
<tr>
<th></th>
<th>( v_1 )</th>
<th>( v_2 )</th>
<th>( v_3 )</th>
<th>( v_4 )</th>
<th>( v_5 )</th>
<th>( v_6 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( v_1 )</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_2 )</td>
<td>-0.233</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_3 )</td>
<td>0.016</td>
<td>0.539</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_4 )</td>
<td>-0.141</td>
<td>-0.025</td>
<td>-0.195</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_5 )</td>
<td>0.076</td>
<td>-0.028</td>
<td>0.005</td>
<td>-0.329</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>( v_6 )</td>
<td>-0.159</td>
<td>0.141</td>
<td>0.034</td>
<td>0.009</td>
<td>-0.062</td>
<td>1</td>
</tr>
</tbody>
</table>

2.6 Simulation of high frequency content

One important factor that should be considered in generating synthetic ground motions is the natural variability which exists among real ground motion for a specific earthquake and site characteristics. This variability can be reached through randomly simulating of jointly normal random variables \( \mathbf{v} = [v_1, \ldots, v_6] \). To this end, they have suggested that the total error terms in the prediction equations can be considered as zero mean jointly normal variables, then by using their distributions and correlation coefficients and employing Cholesky decomposition, they can be simulated and added to the prediction mean values of each \( v_i \).

3. MODEL OF PULSE

In order to simulate near-fault pulses, we needed a model that has a simple mathematical expression, though has enough flexibility to accurately represent, near source pulses. To this end, we used the proposed model by Mavroeidis and Papageorgiou (2003). They formulated velocity pulse as follow:

\[
V(t) = A_p \left[ \frac{1}{2} \left\{ 1 + \cos \left( \frac{2\pi}{T_p} (1-t_0) \right) \right\} \cos \left( \frac{2\pi}{T_p} (t-t_0) + \theta \right) \right], \quad t_0 - \frac{T_p}{2} \leq t \leq t_0 + \frac{T_p}{2},
\]

\[
= 0 \quad \text{otherwise}
\]

(13)
Parameters $A_p$ and $T_p$ control the amplitude and duration of the pulse, $\vartheta$ denotes the phase of the harmonic, and $\gamma$ defines the oscillatory character of the signal. $t_0$ is the time that the envelope reaches its peak. According to Jia et al. (2014) the prediction equations for $A_p$ and $T_p$ are formulated as Equations 14 and 15:

$$A_p = 10^{0.9(2.04 - 0.032r + \epsilon_{A_p})}$$  \hspace{1cm} (14)
$$T_p = 10^{-2.9 + 0.5M + \epsilon_{T_p}}$$  \hspace{1cm} (15)

Where $r$ is rupture distance and $M$ denotes moment magnitude. $\epsilon_{A_p}$ and $\epsilon_{T_p}$ are considered zero mean Gaussian variables with standard deviation 0.187 and 0.143, respectively. $\gamma$ and $\vartheta$ are selected as Gaussian with mean 1.8 and standard deviation 0.3 and uniform on the range $[0, \pi]$ respectively.

4. NEAR-FAULT MODEL

Combining the two high frequency and long period components described in previous sections, by using the procedure that was proposed in (Mavroeidis and Papageorgiou 2003), leads to a stochastic near-fault model that can adequately simulate pulse-like near-fault ground motions. Finally, for assuring zero residual velocity and displacement of the motions and obtaining realistic response spectra values at long periods, we deployed the high pass filter that was proposed by Rezaeian and Der Kiureghian (2008, 2010). The rectified acceleration record, indicated by $\ddot{z}(t)$, is defined as the solution of the differential Equation 16.

$$\ddot{z}(t) + 2\omega_c \dot{z}(t) + \omega_c^2 z(t) = x(t)$$  \hspace{1cm} (16)

Where $\omega_c$ is the frequency of the filter. As they suggested, we considered $\omega_c/2\pi = 0.1$ Hz. Figure 4 illustrates the two components and the resulting pulse-like motion.

![Figure 4. Generation of high frequency content and pulse-like motion and combining them to simulate pulse-like near-fault motion](image)

5. MODEL VALIDATION

In order to develop our model, first, we needed to be sure that we could successfully replicate the original proposed model by Rezaeian and Der Kiureghian (2010) which was developed to simulate far-field ground motions. This process was useful to assure us that we could correctly implement their methodology for a new database. To this end, we compared the results of the replicated model with
those that exist in their articles. Secondly, it should be confirmed that the synthetic pulse-like near-fault ground motions generated by our proposed stochastic model can adequately represent temporal and spectral characteristics and the variability that exists among real pulse-like near-fault ground motions. In this regard, the elastic response spectra and time histories of a suite of near-fault synthetic ground motions generated for specific earthquake and site characteristics are compared to those of available near-fault recorded motions.

5.1 Validation by comparing the high frequency content results of replicated model

During the process of replicating the original proposed model by Rezaeian and Der Kiureghian (2010), we compared our results in every step to those presented in their articles. These comparisons include, obtaining model parameters from a target accelerogram and probability density functions fitted to these values, reconstruction of prediction equations after transforming data to normal space, and comparing the elastic response spectra including pseudo-acceleration and displacement spectra. Among these results we used response spectra, since it was used as one way to validate their model, to show the consistency between the replicated model and their original model.

Figure 5.a and 5.b show 5% damped pseudo-acceleration and displacement spectra of two horizontal components of an accelerogram recorded during the 1994 Northridge earthquake that corresponds to \( R_{rup}=20.3 \text{ km}, V_{s30}=1223 \text{m/s}, M=6.69 \text{ and } F=1 \) (reverse faulting) against 5% damped elastic response of 50 synthetic ground motions generated for the same earthquake and site characteristics. The following figure shows that our results are in accord with those which exist in their article.

![Figure 5](image)

Figure 5. Elastic response spectra (5% damped) of two horizontal components of the 1994 Northridge earthquake recorded at the LA-Wonderland Ave and of 50 synthetic motions: (a) pseudo-acceleration spectra and, (b) displacement spectra which are resulted from replicated model

5.2 Validation against near-fault recorded ground motions

Using spectra responses enables us to measure the variability which exists among synthetic and recorded motions quantitatively. A recorded ground motion is considered as a single realization of all the possible occurrences for a specified design scenario, while synthetic motions generated for the same earthquake and site characteristics may be regarded as other possible realizations. So it is expected that the spectra of recorded motion will lie within the range of variabilities of the spectra of the synthetic motions. Among the pulse-like near-fault recorded motions, we used horizontal component of the 2003 Bam earthquake record at the Bam station, since its seismic source and site characteristics are almost the same as Tabriz region.

Figures 6 illustrates 5% damped pseudo-acceleration and displacement spectra of the pulse-like horizontal component of the recorded motion against 5% damped elastic response of 250 synthetic
pulse-like ground motions generated for the same earthquake and site characteristics.

Figure 6. Elastic response spectra (5\% damped) of pulse-like horizontal component of the 2003 Bam earthquake recorded at the Bam station and of 250 synthetic motions: (a) pseudo-acceleration and, (b) displacement spectra.

5.3 Validation by using time histories of recorded ground motions

Comparison between time histories of pulse-like near-fault recorded motions which correspond to specific earthquake and site characteristics and pulse-like synthetic time histories that are generated for the same earthquake and site characteristics contributes to measuring the variability among the real and synthetic ground motions qualitatively. Figure 7 shows a set of one pulse-like recorded motion and four pulse-like simulated ground motions for given values of F, M, R_{rup} and V_{s30}. For each motion, the acceleration and velocity time-histories are given.

Figure 7. Recorded and synthetic motions corresponding to F=0 (strike-slip faulting), V_{s30}=487.4 m/s, R_{rup}=1.7 km, M=6.6. The near-fault recorded motion is the pulse-like horizontal component of the 2003 Bam earthquake recorded at the Bam station.
6. EXAMPLE APPLICATION

As a case study, we employed our model to simulate suites of pulse-like near-fault synthetic records for two different design scenarios of a site that is located in Tabriz city and then we compared our results with the current design code of Iran. In order to select M and R parameters of our model that have the most probable of occurrences (higher contributions among others), we used disaggregation results of near-fault PSHA for location (38.10, 4630) at the north of Tabriz, available in (Yousefi and Taghi Khany 2014). These values are (M=6.6, R=4.9) and (M=7.4, R=4.4) for return period of 475 years and spectral periods of 1 second and 3 seconds respectively. We considered F=0, as earthquake focal mechanism indicates that the region faults are mainly strike-slip (Jackson 1992). Finally, according to the downhole data of shear-wave velocity profile in (Poormirzaee and Moghadam 2014), we assumed V₃₀=440 m/s.

For each design scenario, 100 synthetic pulse-like ground motions were generated and their pseudo-acceleration spectra were calculated, then their means were compared with the design spectrum that is proposed by current design code of Iran for Tabriz city. Figure 8.a corresponds to a magnitude of 6.6 and distance of 4.9 km, which were stemmed from disaggregation results for spectral period 1 second, while Figure 8.b corresponds to a magnitude of 7.2 and distance of 4.4 km, for spectral period of 3 seconds. Figures 8.a and 8.b represent that the mean values of pseudo-acceleration spectra of synthetic motions, generated for the longer spectral period, have greater values in comparison with those generated for shorter one since with the presence of a pulse, contributions of close distances and major magnitudes for long spectral periods increase. This result indicates that in near-field regions, high rise structures with primary long periods are more exposed to danger than other structures with shorter periods. Furthermore, Figure 8.a indicates that the values of mean spectra of simulated records more closely follow the design spectrum in comparison with those that are depicted in Figure 8.b. According to this observation, it can be inferred that the current design code of Iran is more suitable for structures with short periods than high rise structures.

![Figure 8](image_url)

Figure 8. Comparison between the values of mean spectra of pulse-like near-fault simulated records with design spectra. (a) pseudo-acceleration spectra of pulse-like near-fault synthetic motions and their mean values corresponding to F=0, M=6.6, R=4.9, and V₃₀=440 m/s and (b) pseudo-acceleration spectra of pulse-like near-fault synthetic motions and their mean values corresponding to F=0, M=7.2, R=4.4, and V₃₀=440 m/s.

7. CONCLUSION

This paper is an attempt for developing a stochastic model that can be used for generating synthetic pulse-like near-fault ground motions according to the earthquake and site characteristics and deploying this model for a site that is located in Tabriz city due to lack of near-fault ground motion records. In this regard, two available models were employed. One model for simulating near-fault pulses that
are caused by directivity effect and another one for simulating high frequency content of motions. In order to obviate the limitation of the later model, the parameters were adjusted so that it could be used in near-fault regions. To this end, first, the parameters of the model were identified by matching to the evolutionary characteristics of the recorded near-fault ground motions. Then, in order to develop prediction equations, these parameters were transformed to the normal space according to their marginal probability distribution functions and regressed against earthquake and site characteristics of the recorded motions. Correlation analysis was performed to determine the correlations among the transformed model parameters. By utilizing the empirical prediction equations and the correlations, sets of realizations of the model parameters were generated for specified characteristics. Finally, the model was employed for generating 100 pulse-like synthetic motions for two different design scenarios for a site that is located in Tabriz city. The pseudo-acceleration spectra of these motions were calculated and their mean values were compared to the spectrum which is suggested by current design code of Iran. The comparison indicated that the code provisions are more suitable for low rise structures.

8. REFERENCES