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Keywords

iran, model, duration, prediction, motion, ground, earthquake

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A New Model for the Prediction of Earthquake Ground-motion Duration in Iran

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A New Model for the Prediction of Earthquake Ground Motion Duration in Iran

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Abstract

The paper proposes a new empirical model to estimate earthquake ground-motion duration, which significantly influences the damage potential of an earthquake. The paper is concerned with significant duration parameters that are defined as the time intervals between which specified values of Arias intensity are reached. In the proposed model, significant duration parameters have been expressed as a function of moment magnitude, closest site-source distance, and site condition. The predictive model has been developed based on a database of earthquake ground-motion records in Iran, containing 286 records up to the year 2007, and a random effect regression procedure. The result of the proposed model has been compared with that of other published models. It has been found that the proposed model can predict earthquake ground-motion duration in Iran with adequate accuracy.

Keywords: Earthquake, ground motion, significant duration, Random effect, Iran

1. Introduction

Procedures for earthquake-resistant design and seismic performance assessment of structures in major seismic design codes worldwide (e.g., IBC-2006) are typically based on peak ground motion parameters (e.g., spectral acceleration and displacement) without explicitly considering cumulative damage or degradation due to the hysteretic behavior of the structure. However, recent research investigations revealed that response of a structure in the event of an earthquake depends very strongly not only on the amplitude of the ground motion but also in some cases on the duration of the ground motion (Boomer et al. 1999 and 2009; Kempton and Stewart 2006; Reinoso and Ordaz 2001). The duration of earthquake ground motion has also been shown to have significant effects on the level of damage sustained by engineered structures during moderate to strong earthquakes (Lindt and Goh 2004a). It has been observed that studies employing damage measures related to cumulative energy usually report a positive correlation between strong-motion duration and structural damage; on the other hand, studies employing damage measures using maximum response generally report no strong correlations between duration and damage (Hancock and Bommer 2006). The apparent influence of ground-motion duration on structural damage is depended on the parameter that is used to characterize the earthquake shaking levels. However, for two earthquake ground motions of similar spectral amplitude but of different duration, the motion of longer duration would be more damaging (Boomer et al. 2009). Hence, the duration of earthquake ground motion should be considered an important parameter in addition to the maximum amplitude and frequency content for adequately characterizing the effect of earthquake ground motion on seismic damage of structures.

In order to investigate the effects of the duration of earthquake ground motion on structural responses and the associated implications in the design of earthquake-resistant structures, substantial amount of research has been carried out over the past decades (Chai et al. 1998; Iervolino et al. 2006; Lindt and Goh 2004b). To facilitate more realistic seismic structural analysis, earthquake ground-motion duration needs to be considered as an essential parameter recognizing that its effect on the damage level is dependent of the type of structure and the damage metric (Hancock and Bommer 2006). In addition, it considerably affects demand parameters such as hysteretic ductility and equivalent number of cycles (Iervolino et al. 2006) and can be used to estimate dissipated energy (Nurtug and Sucuoglu 1995), hysteretic energy (Uang and Bertero 1990), and for detailed description of damage and modeling of structural failures (Fajfar and Gaspersic 1996), as well as for generating earthquake response spectrum using random vibration theory (Reinoso et al., 1990). It is envisaged that, in the near future, the effects of earthquake ground-motion duration will be taken into account in the seismic design of new structures and the seismic assessment of existing structures.

From a geotechnical point of view, the profound effects of strong-motion duration on the behaviour of saturated soils have been acknowledged and accounted for in evaluating liquefaction potential (Youd and Idriss 2001). Also, duration of strong ground motion is essential for the built-up of pore pressure in liquefiable soils and accumulation of volumetric strain in unsaturated soils (Silver and Seed 1971). Moreover, the lateral spread displacement resulting from soil liquefaction has been known to be related to the duration of earthquake shakings (Rauch and Martin 2000). It also plays a significant role in the analysis of permanent displacement in soils.

Ground-motion prediction equation (GMPE), which is known as a key component for seismic hazard analysis, typically serves as an appropriate tool to achieve a better description of seismic actions required for earthquake-resistant design. Likewise, model for predicting ground-motion duration can be regarded as a fundamental step towards a robust seismic evaluation of important infrastructures. Accurate estimation of expected ground-motion duration at a given site from earthquakes of different distances and magnitudes could be important for a more reliable earthquake hazard assessment. Table 1 briefly presents some of the strong ground motion duration prediction equations developed for different seismotectonic regions in the world. Considerable differences have been observed between the ground motion prediction equations which might be due to different dataset used in the analyses reflecting the characteristics of different seismo-tectonic regions. Hence, their application in other regions should be subjected to significant scrutiny. In recent years, therefore, significant research efforts have been focused on the expansion of regional predictive equations or re-examination of the generality of existing well-published relationships based on the recordings of a specific region, which is the main motivation behind this study. Moreover, recently developed ground motion duration prediction equations include various source parameters such as fault style, stress drop and depth to the top of rupture that are not reported (or captured) in the available earthquake ground motion dataset in Iran. Therefore, the application of the developed ground motion prediction equations in the study area of this paper needs some gross assumptions to be made for these parameters which lead to increased uncertainty in their application.

The objective of this paper is to develop new prediction equations to estimate two common measures of significant duration which are defined as the interval between the times at which 5-95% and 5-75% of the Arias intensity are reached and are termed as $D_{a5\text{-}95\%}$ and $D_{a5\text{-}75\%}$, respectively. Apart from the moment magnitude and closest site-source distance, the effect of local site conditions is included in the proposed models. The results of this study are also compared with the results of other published models by considering the distribution of residuals against magnitude and distance.

Significant duration has been selected in this study as a more reliable predictor, as it is relatively robust with respect to the definitions of the beginning and ending thresholds (Bommer and Martinez-Pereira 1999) and well correlated to the amount of dissipated energy. In the present work, an attempt has been made to consider the issue of regional differences in the modelling of ground-motion duration for the high-seismicity region Iran, which was frequently subjected to catastrophic earthquakes in its recorded history. The proposed model, which is the first of its kind for Iran, was constructed using a random effect regression procedure and derived based on recorded strong-motion database containing 286 records up to the year 2007.

2. Significant duration of earthquake ground motion

Earthquake ground-motion duration depends on the time required to release cumulative strain energy in the rupture length of the fault as well as the transmission characteristics of seismic waves passing through from the source to the site. The major difficulty in studying the duration of strong earthquake arises as this complex phenomenon needs to be defined in a simple way. Accordingly, researchers have not reached the same definition for the earthquake ground-motion duration that is best suited for all applications and hence different definitions have been presented in the literature. The three typical definitions for the ground-motion duration are termed as the bracketed-, uniform-, and significant duration. The significant duration parameter that measured from Arias intensity (Arias 1970) has been adopted herein and is described briefly in this section. Detailed description of different definitions of earthquake ground-motion duration can be found elsewhere (Bommer et al. 2009).

Significant duration is defined as the interval between the times at which different specified values of Arias intensity are reached. The advantages of the significant duration are that it considers the characteristics of the entire accelerogram and defines a continuous time window, and it is relatively stable with respect to the definitions of beginning and end thresholds. Two generic measures of this group are used as the time intervals between 5-95% and 5-75% Arias Intensity ($D_{a5\text{-}95\%}$ and $D_{a5\text{-}75\%}$). Trifunac and Brady (1975) defined significant duration concept for the integrals of the squares of acceleration, velocity and displacement, as the time interval between which 5% and 95% of the total integral is attained. Fig. 1 indicates the significant duration $D_{a5\text{-}95\%}$ and $D_{a5\text{-}75\%}$ for 1978 Tabas, Iran earthquake at Deyhook station.

3. Strong motion database

The Iranian Plateau which is characterized by active faulting has been frequently struck by catastrophic earthquakes with high death tolls (Yaghmaei-Sabegh and Lam 2010).The strong ground motion records used in this study have been collated from the Building and Housing Research Center database (www.bhrc.com) and include all important earthquakes occurred in Iran up to the year 2007. It is worth noting that because of the limitations of good quality data and also lack of information about the soil type of recording stations, the final dataset has been limited to 286 records in this research. Uncorrected strong motion data were processed to make baseline and instrumental corrections; also, high-pass Butterworth filter has been applied. Fig. 2 shows the location of important earthquakes recorded on different geological units across Iran and used in this study.

Table 2 illustrates the list of the dataset used in this study indicating wide range of magnitude 3.7-7.7 and closest site-source distance 0.6-294 km. These data are obtained form the shallow crustal earthquakes of Iran and contain two horizontal components and one vertical component. The significant durations were calculated based on the geometric mean of the values from the two horizontal components. The distribution of the selected dataset with respect to moment magnitude (M_w) and closest site-source distance has been shown in Fig. 3.

It is noted that because of limited information about source geometry for the recorded earthquakes in Iran, the epicentral distance has been adopted as a distance metric by the studies for deriving ground motion attenuation relationship in Iran (Ghodrati Amiri et al. 2007). It is known that this distance measure do not perform adequately, especially for large earthquake events. Scherbaum et al (2004) observed that closest site-source distance (Joyner-Boore distance) is always smaller than the epicentral distance. The difference between these two distance measures depends on source size, fault dip, and site orientation. It was observed that the difference is dependent primarily on the magnitude, rather than closest site-source distance. As source size, fault dip and site orientation data are not available for all the recordings, distance conversion from epicentral distance to closest site-source distance have been carried out based on the mean difference observed in Scherbaum et al. (2004).

4. Proposed model

This section presents a brief description of the proposed model for the prediction of ground-motion duration based on a mixed effect regression analysis. The independent variables consist of the parameters that describe moment magnitude (M), closest site-source distance (R) and site condition or soil type (S). Thus, the proposed equation takes the following form similar to the ground motion prediction equations (GMPEs):

$$\log(D_a) = f_1(R) + f_2(M) + f_3(S) \qquad (1)$$

Where D_a is significant duration, and $f_1(R)$, $f_2(M)$ and $f_3(S)$ represent the distance, magnitude and soil type, respectively. Fig. 4 and 5 show the distribution of $D_{a5\text{-}95\%}$ and $D_{a5\text{-}75\%}$ with respect to the closest site-source distance. These scatter plots demonstrate the logarithmic dependency of duration with respect to distance (R), consequently the distance term is defined as:

$$f_1(R) = (a_1 + a_2 \times \log(R))^{b_1} \qquad (2)$$

Where, a_1 and a_2 are regression parameters.

Moment magnitude has been preferred as a magnitude scale in the analysis, as it corresponds to the well-defined physical property of the source and also it is known as an improved measure to avoid saturation effects for magnitudes greater than about 6 (Ozbey et al. 2004).

The magnitude dependency term ($f_2(M)$) is defined as:

$$f_2(M) = a_3 \times M^{b_2} \qquad (3)$$

The effect of different soil types in the regression analysis is simply defined as below:

$$f_3(S) = a_4 S \qquad (4)$$

The site classification criteria in the Iranian code of practice for seismic resistant design of building are adopted herein. The site classification criteria in Iranian Code are based on average shear wave velocity in the top 30 m soil layers. In the code, four different site classes are defined as a rock site, very dense soil and soft rock site, stiff soil site, and soft soil site (Table 3). The site classification system in the Iranian code of practice is compatible with site classification system proposed in 2003 NEHRP (BSSC, 2003) where soil sites are defined as site class B, C, D and E. In the regression analysis of this paper, site conditions is parameterized as S=3, 2, 1 and 0, to represent rock sites (site class B), very dense soil and soft rock (site class C), stiff soil (site class D) and soft soil (site class E), respectively.

Finally, the mathematical representation of proposed model takes the following functional form:

$$\log(D_a) = (a_1 + a_2 \times \log(R))^{b_1} + a_3 \times M^{b_2} + a_4 \times S + \eta_i + \varepsilon_{ij} \tag{5}$$

where the inter-event term η_i is the event term for the earthquake event *i* and the intra-event term ε_{ij} is residual for record *j* in event *i*. These two error terms, are assumed to be independent and normally distributed with variance τ^2 and σ^2, respectively. Accordingly, the total standard error for mixed effects is then $\sqrt{\sigma^2 + \tau^2}$. The coefficients b_1, b_2, a_1, a_2, a_3 and a_4 are determined by the regression analysis based on available data. Note that in the proposed form (Equation 5) the logarithms are in base 10.

Regression analyses utilizing equation (5) are performed using mixed-effect procedure based on the maximum likelihood (ML) method. The method is composed of fixed effect which is associated with an entire population, and random effects, which is associated with individual experimental units drawn at random from a population. As a result, the correlation of data recorded for a specific seismic event has been considered by applying a random effect model. Mixed effect models provide a flexible and powerful tool for analyzing grouped data which have been employed successfully to derive the empirical ground motion attenuation relationships by different researchers (Ozbey et al. 2004; Danciu and Tselentis 2007). The advantage of the proposed mixed effect approach is that, the contributions to overall variability may be clearly separated into two types: variability between different earthquakes (inter-events) and variability among recordings of the same earthquake (intra-event). More details about the application of the mixed effects model can be found in Pinheiro and Bates (2000). Table 4 presents results of the regression analysis of the proposed. Coefficients of the regression parameters and their standard deviations for both $D_{a5\text{-}95\%}$ and $D_{a5\text{-}75\%}$ have been shown in Table 4. It is noted that inter-event variability has been fully considered in this study. However, in earlier studies ground motion duration prediction equations have been derived using least-squared regression analysis considering equal weight to each recording and may not well correlated with the data recorded during a given event (Trifunac and Brady 1975; Bruno and Fabrice 2000; Reinoso and Ordaz 2001).

5. Comparison of proposed model with pervious studies

In this section, the proposed simple model is examined by comparing the result of this study with the result from previous studies carried out from 1975 to 2009. Special emphasis has been given for the two recently published/updated models developed in Kempton and Stewart (2006) and Bommer et al. (2009). Fig. 6 shows the predicted values of $D_{a5-95\%}$ for fixed distance of $R=30$ km on a rock site as a function of magnitude. The result of other studies (Trifunac and Brady 1975; Dobry and Idriss 1978; McGuire and Barnhard 1979; Kamiyama 1984; Abrahamson and Silva 1996; Bruno and Fabrice 2000; Kempton and Stewart 2006; Bommer et al. 2009) have also been superimposed in Figure 6. It is evident from Fig. 6 that the proposed model is in very good agreement with that from Bommer et al. (2009). This model, abbreviated herein as the *BSA09*, has been derived from the database compiled for the NGA project (Chiou et al. 2008) and its overall behaviour is similar to that proposed in this paper. Similar agreement with Kempton and Stewart (2006) and Bruno and Fabrice (2000) have been observed for low to moderate magnitude earthquake events ($M<6$) and strong earthquake events ($M>6$), respectively (Fig. 6). These two models have been abbreviated in this paper as *KS06* and *BF00*, respectively. However, large differences between the results of the proposed model with that of other models (Kamiyama 1984; Trifunac and Brady 1975; Dobry and Idriss 1978) developed in 70's and 80's have been observed (Fig. 6), which might be due to lack of correlation among the data recorded during a given event in these studies. Another possible reason might be that in these studies site conditions have not extensively investigated.

Residual analyses have been undertaken to examine the validity and fitness of the proposed model. Fig. 7 and 8 show the distribution of residuals for significant durations (D_{Obs}-D_{Pred}) in logarithmic units based on the predictive relationships for different magnitudes and distances. Similar calculations of the residual values have also been carried out for *BSA09* and *KS06* models for comparison. The residual analyses results from *BSA09* and *KS06* have been superimposed in Fig. 7 and 8.

The good quality of the relationship based on the proposed model can be represented by (i) the spread of residuals (representing the variability of individual data values) and (ii) biases of the mean of residuals. Importantly, comparable spread of the residual with *BSA09* model is observed which re-confirms the validity of this model. Generally, lower residuals are shown for these two models compared to *KS06* model with the exception of distances less than 5 km. However, this distance is not considered important in this study.

The residuals of the proposed prediction model and the residuals of the predictions by *BSA09* and *KS06* have been shown in Fig. 7 and 8. It can be seen that the proposed model shows a lower average residual (2.07 sec for $D_{a5-95\%}$ and 0.54 sec for $D_{a5-75\%}$) with the shallower slope of the linear trend line compared to *KS06* model (with corresponding average values of 6.61 and 1.43sec, respectively). The *BSA09* model is considered close to the proposed model and the observed residuals are 0.96 and 0.64 for $D_{a5-95\%}$ and $D_{a5-75\%}$, respectively.

The proposed model is able to predict significant duration of earthquake ground motion with standard deviations of 7.08 sec and 4.51 sec for $D_{a5\text{-}95\%}$ and $D_{a5\text{-}75\%}$, respectively, which are slightly larger than the corresponding values in *BSA09* Model (6.46 and 4.42 sec) and is smaller than *KS06* model values (10.28 sec and 5.17 sec). A possible reason for this difference is that the *BSA09* model has been derived based on a large dataset incorporated many records from shallow crustal earthquakes worldwide. Moreover, they include an additional variable named depth to the top of rupture, Z_{tor} (km) while it is not taken into account in the new proposed model herein because the information about aforementioned parameter in the study area is inadequate.

Further residual analyses have been carried out for different soil sites in Fig. 9 (S=3, 2, 1 and 0, representing rock sites, very dense soil and soft rock sites, stiff soil sites, and soft soil sites, respectively). Only *BSA09* model has been compared, as *KS06* model is parameterized simply for rock and soil. It can be observed from Fig. 9 that proposed model shows similar residuals to the *BSA09* model.

As a final consideration in development of the proposed model, the observed data have been compared with predicted value in Fig 10. Very good agreements have been observed with all the data within 95% confidence intervals. This signified the importance of the application of the proposed model in predicting the ground motion duration of Iranian earthquakes.

6. Conclusions

A simple and effective empirical model for the predicting of the significant duration of ground motions have been developed in this paper based on recorded earthquake events in Iran. The significant duration of earthquake ground motion has been expressed as a function of magnitude, distance and site soil conditions. The coefficients of the independent variables in this model are determined based on a mixed effects regression procedure that accounts for inter- and intra-event ground-motion variability. The method leads to better modeling of uncertainties that propagate through the regression analysis. The results of the proposed model are in very good agreement with the observed data and are considered appropriate for the estimation of significant ground-motion duration in active tectonic regions of Iran. The developed model is expected to be of use for a number of applications both in seismology and structural engineering. Comparisons with other predictions, which are not specifically developed considering the geological and seismo-tectonic settings in Iran, have also been made in this paper. The developed model for ground motion duration may be applied to other regions of similar tectonic settings. However, it is recommended to test the fitness of the developed model before adopting it for the design and assessment of structures in other regions. The analytical model developed in this study can be significantly improved if additional high quality data become available in near future, including adequate information on soil site conditions of the recording stations.

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Table 1 Summary of the prediction equations for earthquake ground motion duration available in the literature

Prediction Equation	Limited Magnitude	Limited Distance (km)	Site Conditions	Reference
$D_{br} = 0.02\exp(0.74M) + 0.3\Delta$	UN	UN	UN	Esteva & Rosenblueth (1964)
$D = 11.2M - 53$	M>5	UN	UN	Housner (1965)
$D_{a5-95} = -4.88S + 2.33M + 0.149ED$	4<M<6.5	UN	Rock, Firm, Soft soil	Trifunac & Brady (1975)
$D_{br} = 0.74\times 10^{0.23M} \times (ED)^{-0.084} \times 10^{-0.0004H} \times (1.41C_{du} + 1.31)$	4.1<M<7.9	10<ED<310	Rock	Kamiyama (1984)
$D_{a5-95} = 10^{(0.43M-1.83)}$	4.5<M<7.6	0.1<ED<130	Rock	Dobry & Idriss (1978)
$D_{br} = c_1 + c_2M + c_3S + c_5\ln R'$	UN	UN	Rock, Alluvium	McGuire & Barnhard (1979)
$\ln(SD) = \ln\left[\dfrac{\left(\dfrac{\exp(b_1 + b_2(M_W - m^*))}{10^{1.5M_W+16.05}}\right)^{-1/3}}{4.9\times 10^6 \times \beta} + Sc_1 + c_2(r_{rup} - r_c)\right] + D_{rat}, r_{rup} \geq r_c$ $\ln(SD) = \ln\left[\dfrac{\left(\dfrac{\exp(b_1 + b_2(M_W - m^*))}{10^{1.5M_W+16.05}}\right)^{-1/3}}{4.9\times 10^6 \times \beta} + Sc_1\right] + D_{rat},\ r_{rup} \prec r_c$	UN	UN	UN	Abrahamson & Silva (1996)
$\ln(D_{a5-95}) = -1.04 + 0.44Ms + 0.19\ln(R') + 0.04S$ $\ln(D_{a5-95}) = -1.04 + 0.44Ml + 0.19\ln(R') + 0.04S$	M>6 M<6	UN	Rock, Soil	Bruno &Fabrice (2000)
$D_{2.5-97.5} = 0.01e^{M} + (0.036M - 0.07)R + (4.8M - 16)(T_s - 0.5)$	5.2<M<8.1	$12 < \Delta < 520$	Rock, Firm Soil	Reinoso & Ordaz (2001)
$\ln(D_{a5-95}) = \ln\left[\dfrac{\left(\dfrac{\exp(2.79 + 0.82(M_u - 6))}{10^{1.5M_u+16.05}}\right)^{-1/3}}{4.9\times 10^6 \times 3.2} + 0.15R' - 3 - 0.0041(V_{s30}) - 0.44 + 0.0012(Z_{1.5})\right]$	5<Mu<7.6	0<D<200	Rock, Soil	Kempton & Stewart (2006) (*KS06*)
$\ln D_{a5-95} = -2.24 + 0.94M_w + (1.569 - 0.19M_w)\ln\sqrt{R'^2 + 2.5^2} - 0.348\ln V_{S30} - 0.036Z_{tor}$	4.8<Mw<7.9	R<100	Rock, Soil	Bommer & Stafford & Alarcon (2009) (*BSA 09*)

D_{br}: Bracketed duration

D: Strong motion duration

C_{du} : Duration Coefficient

Δ: Source to station distance

M: Earthquake magnitude

M_u: Magnitude (M) is taken as moment magnitude where available, and is otherwise taken as surface wave magnitude for M>6 and local magnitude for M<6.

D_{a5-95} , $D_{a2.5-97.5}$: Significant duration as function of the acceleration record

ED: Epicentral distance

T_s : Dominant site period

R, r_{rup} : Distance to the rupture area

Ml, Ms and Mw: Local magnitude, surface wave magnitude and moment magnitude, respectively

H: depth of hypocenter

V_{S30} : Shear wave velocity

$Z_{1.5}$: Deep basin parameter

Z_{tor} : Depth to the top of rupture

R' : Closest site-source distance

S: Soil Type

$\beta, b_1, b_2, m^*, c_1, c_2, c_3, c_5, D_{rat}, r_c$ are regression coefficients

UN: Unknown

Table 2 Summary of earthquake database in Iran: main shocks up to the year 2007

No	Earthquake Date (y:m:d)	Earthquake Time (h:m:s)	Geographical Coordinates		Mw	Number of Record	Closest Site-Source Distance Range (km)	Number of Record for Each Site Class
			E	N				
1	750307	174231	56.29	27.19	6.2	1	32.25	1SR
2	750307	70400	57.07	27.14	6.2	1	69.25	1SS
3	750313	173313	50.87	36.81	4.4	1	32.8	1SS
4	751008	81552	54.41	28.36	5.4	1	13	1HS
5	751216	74252	47.92	39.65	5.4	1	51	1SR
6	760905	164317	50.74	31.94	5.2	1	16.3	1R
7	761107	40050	59.24	33.33	6.4	1	52	1HS
8	761107	40050	59.22	33.73	6.4	1	6	1R
9	761107	40050	58.81	34.02	6.2	1	42.25	1SR
10	761124	122216	44.51	39.31	7.3	1	53	1SR
11	761109	175954	59.22	33.84	5.0	1	11	1SR
12	761109	-	59.17	33.88	5.3	1	7.5	1HS
13	761206	40604	44.38	39.06	3.9	1	4	1R
14	770321	211800	56.29	27.19	6.9	1	40	1SR
15	770321	224206	56.29	27.19	6.0	1	50	1SR
16	770323	235115	56.29	27.19	5.7	1	56	1SR
17	770401	133624	56.29	27.19	6.1	1	39.5	1SR
18	770406	133600	50.74	31.93	6.1	1	1.5	1R
19	770323	53205	51.39	29.53	4.6	1	7	1R
20	771021	145608	50.72	31.93	5.1	1	20.45	1R
21	771026	170252	50.72	31.93	5.4	1	63.1	1R
22	780520	130812	50.72	31.93	5.1	1	26.45	1R
23	780412	164824	50.98	32.1	5.1	1	35.45	1SR
24	780916	153557	57.44	33.37	7.3	1	22	1R
25	780916	163557	56.92	33.58	7.3	1	12	1R
26	780916	182547	57.07	33.79	4.7	1	27	1R
27	780916	184514	56.93	33.6	5.0	1	24.5	1R
28	780916	195021	56.93	33.6	5.1	1	20.5	1R
29	780917	73551	57.44	33.37	4.7	1	22	1R
30	780918	153507	56.93	33.6	5.2	1	15.4	1R
31	780919	11400	57.44	33.37	4.9	1	64	1R
32	780919	14919	56.93	33.6	5.3	1	62.5	1R
33	780829	141106	51.65	29.62	5.1	1	7.5	1SR
34	781609	193558	57.32	33.22	7.35	5	55.24-247	1SR+4HS
35	790116	95000	58.18	34.52	6.8	1	137	1R
36	790116	95000	58.81	34.02	6.7	1	66	1R
37	790116	95000	58.68	34.35	6.8	1	89	1SR
38	790116	95000	60.14	34.57	6.8	1	95	1SR
39	791114	22118	59.24	33.33	6.7	1	77	1HS
40	791127	171033	59.22	35.27	7.1	1	132	1HS
41	791127	171033	59.21	32.87	7.1	1	124	1R
42	791127	171033	59.24	33.33	7.3	1	73	1HS
43	801203	42615	50.3	37.13	5.2	1	15.5	1SS
44	800722	51706	50.03	37.21	5.5	1	31	1SS
45	810611	72425	57.07	30.28	6.6	1	68	1SS
46	810621	130848	57.72	29.88	4.8	1	13	1HS
47	810728	172223	55.98	30.4	7.0	1	168	1HS
48	810728	172223	57.07	30.28	7.0	1	65	1SS
49	810728	172223	57.44	29.59	7.0	1	45	1R
50	810728	172223	57.72	29.88	7.0	1	3	1HS
51	810728	203300	57.72	29.88	4.1	1	30	1HS
52	810728	215516	57.72	29.88	4.8	1	18	1HS
53	810728	223511	57.72	29.88	4.7	1	2	1HS
54	810728	172100	57.72	31.26	7.0	1	159	1HS
55	810808	41747	57.72	29.88	4.8	1	17	1HS
56	811014	91240	57.72	29.88	5.2	1	4.5	1HS
57	820225	235201	57.72	29.88	4.7	1	31	1HS
58	850819	124751	52.56	28.83	4.7	1	48	1HS
59	890315	192645	50.66	31.98	4.9	1	12.8	1HS
60	891120	41905	57.56	30.19	5.9	1	36	1R

61	900620	210011	49.22	36.09	7.7	1	71	1SS
62	900620	210011	50.28	37.13	7.4	1	75	1SS
63	900620	210011	50.03	37.21	7.7	1	52	1SS
64	900620	210011	50.88	36.81	7.7	1	107	1SS
65	900624	94601	49.39	36.76	5.2	1	14.5	1SR
66	900620	210011	51.31	36.11	7.7	1	161	1HS
67	900620	210011	48.95	36.92	7.4	1	28	1R
68	900620	210011	48.5	36.66	7.4	1	60	1R
69	900629	62552	49.4	36.8	4.5	1	48	1HS
70	900620	210011	50.9	35.44	7.7	1	174	1SS
71	900620	210011	50.37	35.72	7.7	1	120	1HS
72	900706	193454	49.39	36.76	5.0	1	20.5	1SR
73	900821	34731	49.39	36.76	4.5	1	42	1SR
74	900820	122013	49.4	36.8	4.8	1	41.8	1HS
75	900821	34731	49.4	36.8	5.0	1	34.8	1HS
76	901227	132657	49.4	36.8	4.8	1	51	1HS
77	900925	121220	49.4	36.8	4.8	1	36	1SR
78	900620	210011	49.4	36.96	7.7	12	39.4-245.3	1R+SR+4HS+6SS
79	910405	53818	51.39	29.53	5.2	1	43.5	1HS
80	911128	171958	49.4	36.8	5.4	1	10.5	1HS
81	911204	60250	49.4	36.8	4.3	1	35	1HS
82	920210	163838	57.56	30.19	4.7	1	7	1R
83	920908	3818	51.39	29.53	5.4	1	74.5	1HS
84	930114	71706	59.23	33.32	5.2	1	44.5	1HS
85	930502	175333	56.57	30.79	6.1	1	25.5	1HS
86	940330	195542	52.56	28.86	5.6	1	23	1HS
87	940618	124200	52.75	28.87	6.0	1	13.5	1SR
88	940621	41552	52.75	28.87	4.7	1	22	1SR
89	940317	80616	52.83	29.1	4.8	1	33	1R
90	940330	195548	52.83	29.1	5.6	1	13	1R
91	940403	65157	52.83	29.1	5.4	1	30	1R
92	940618	124200	52.83	29.1	5.2	1	20	1R
93	940620	90902	52.83	29.1	6.0	1	22.5	1R
94	940620	90902	52.56	28.83	6.0	1	11.5	1HS
95	940317	80616	52.68	29.2	4.8	1	31	1R
96	940620	90902	52.82	29.33	6.0	1	42.5	1R
97	940620	90902	52.07	28.87	6.0	1	50.5	1SR
98	940620	90902	53.22	28.96	6.0	1	57.5	1SR
99	940317	80616	54.62	29.07	4.8	1	16	1SR
100	940605	165412	54.62	29.07	4.8	1	65	1SR
101	940620	90902	54.62	29.07	5.2	1	10.5	1SR
102	940620	90902	54.62	29.7	6.0	1	8.5	1SR
103	940731	51539	48.25	32.68	5.6	1	20	1SS
104	940731	52210	48.25	32.68	5.4	1	24	1SS
105	940731	55257	48.25	32.68	5.0	1	29.5	1SS
106	940920	55146	48.47	32.61	5.0	1	29.5	1SR
107	940920	55146	48.31	32.45	5.2	1	38.5	1SR
108	941208	125438	52.83	29.1	5.1	1	27.5	1R
109	941208	125438	52.68	29.2	5.1	1	26.5	1R
110	941208	125438	52.57	29.03	5.1	1	6.5	1R
111	940620	90902	52.5	29.2	6.1	9	18.5-98.85	6R+3SR
112	941029	65207	55.88	27.62	5.0	1	24.5	1HS
113	941203	13551	49.12	37.37	5.0	1	32.5	1HS
114	941102	123101	49.41	36.81	5.0	1	28.5	1HS
115	941029	65207	55.88	27.62	3.9	1	41	1HS
116	950107	10919	51.93	29.28	4.8	1	31	1SR
117	951009	85449	49.39	36.76	4.6	1	32	1R
118	951109	61024	59.58	36.28	4.6	1	73	1SR
119	950322	62836	-	-	4.8	1	37	1SR
120	951015	65641	49.36	37.19	5.1	1	30.5	1HS
121	950726	124417	59.58	36.28	4.5	1	35	1R
122	951127	143144	-	-	5.1	1	16	1HS
123	950716	164223	52.85	29.09	5.0	1	30.5	1R
124	960124	60316	50.99	29.47	5.1	1	11.5	1SS
125	960124	60411	51.12	29.38	4.8	1	12	1R
126	960101	141952	50.99	29.47	3.8	1	17	1SS
127	960126	130958	51.12	29.38	5.0	1	10.5	1R
128	960316	201722	51.12	29.38	3.9	1	12	1R
129	970204	103747	57.29	37.66	6.4	4	19.9-246.5	2SR+2HS

130	970228	125745	48.06	38.07	6.1	6	6.3-121.6	4HS+2SS
131	970510	75729	59.98	33.55	7.3	12	73.1-440	2R+6SR+4HS
132	980314	194027	57.65	30.07	6.9	3	51.52-125	1SR+2HS
133	990506	230053	52.11	26.46	6.1	12	20.5-129.5	2R+3SR+6HS
134	991031	150939	51.81	29.41	5.2	3	16.9-80.6	1SR+2HS
135	020622	25820	48.93	35.67	6.5	21	23-319	5R+8SR+8HS
136	031226	15656	58.35	29.09	6.5	13	3-279	2R+2SR+8HS+1SS
137	040528	123846	51.81	36.52	6.3	46	3.95-473.7	8R+13SR+24HS+1SS
138	051127	102223	55.89	26.78	6	4	57.5-120	2SR+1HS+1SS
139	050222	22526	56.73	30.8	6.3	8	15.1-92.67	1R+1SR+6HS
140	060331	11702	48.91	33.62	6.1	2	76.1-115.2	1R+1SR
141	070618	142949	50.86	34.52	5.5	1	155.05	1HS

Note: R: Rock, SR: Soft rock, HS: Hard (or stiff) soil, SS: Soft soil

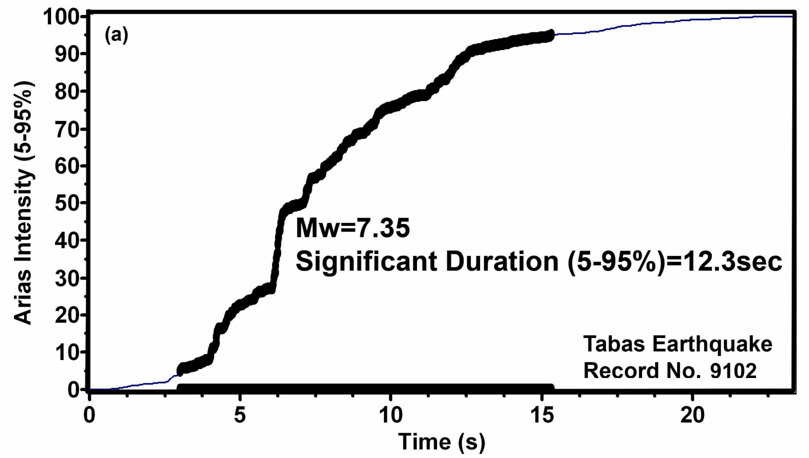
Table 3 Site classifications according to Iranian code of practice for seismic-resistant design of building

Soil Condition	Shear Wave Velocity	Site categories	Site parameter used in this study
Rock	Vs>750 m/s	I	3
Very dense soil and soft rock	350<Vs<750 m/s	II	2
Stiff soil	175<Vs<350 m/s	III	1
Soft soil	Vs<175 m/s	IV	0

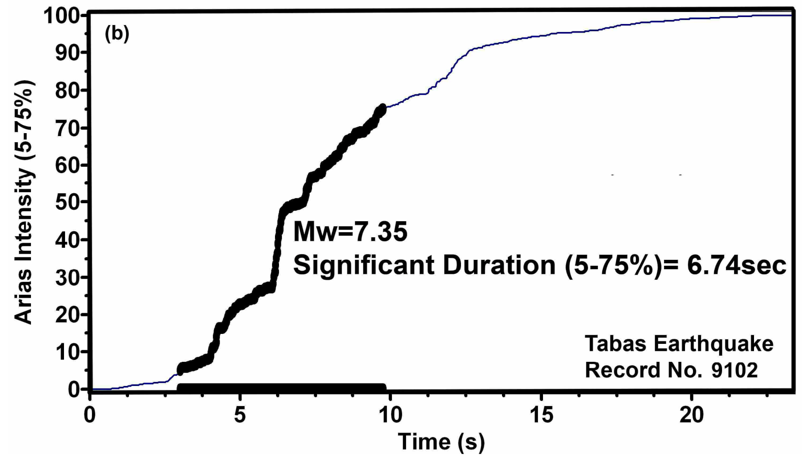
Table 4 Regression parameters for the proposed model

	a_0	a_1	a_2	a_3	a_4	b_1	b_2	τ	σ	σ_{total}
D_{a5-95}	0.271±0.12	0.07	0.236	0.16±0.01	-0.021±0.011	1.24	1.02	0.23	0.21	0.313
D_{a5-75}	0.21±0.035	-0.473	0.31	0.097±0.008	-0.052±0.016	0.2	1.2	0.3	0.316	0.438

$$\sigma_{total} = \sqrt{\sigma^2 + \tau^2}$$



(a)



(b)

Fig. 1 Representation of significant duration for 1978 Tabas event, Deyhook station (a) $D_{a5-95\%}$ (b) $D_{a5-75\%}$

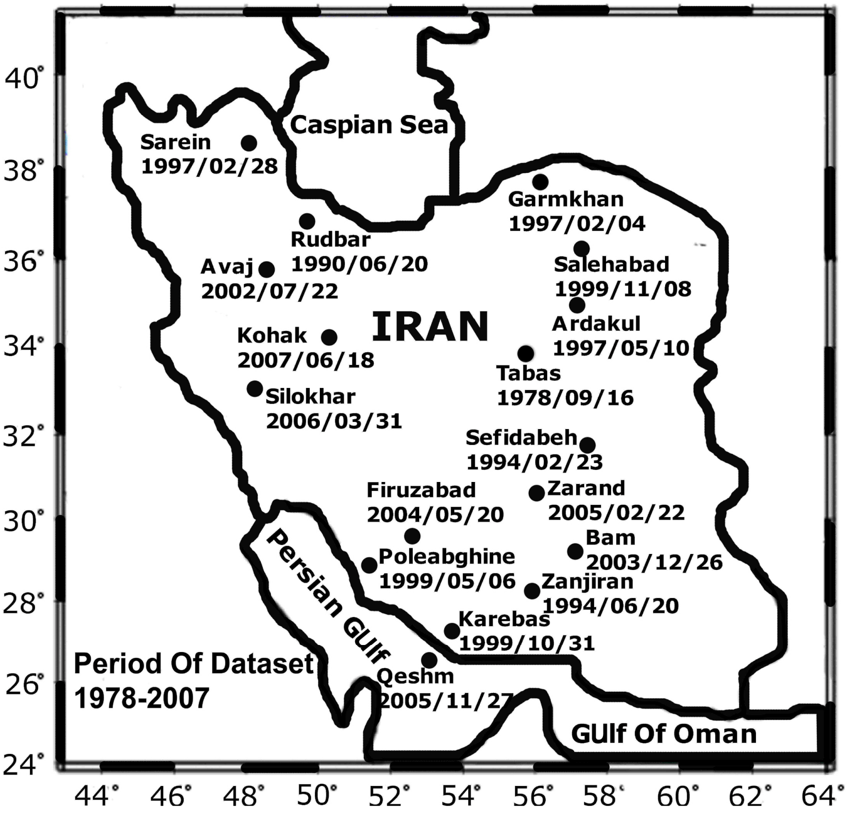


Fig. 2 Location of major earthquakes used in this study

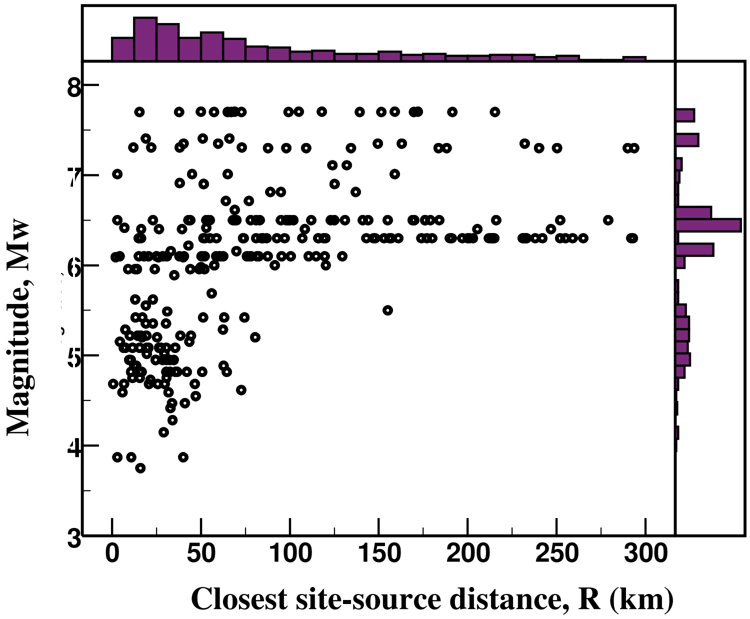


Fig. 3 Distribution of the selected dataset in terms of magnitude and closest site-source distance

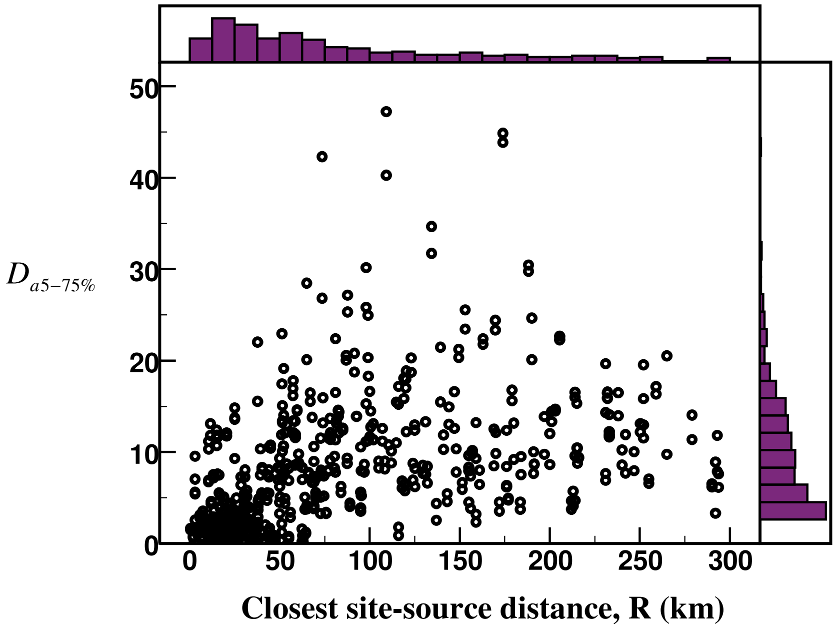


Fig. 4 Scatter plot of $D_{a5-75\%}$ vs. closest site-source distance for the dataset used in this paper

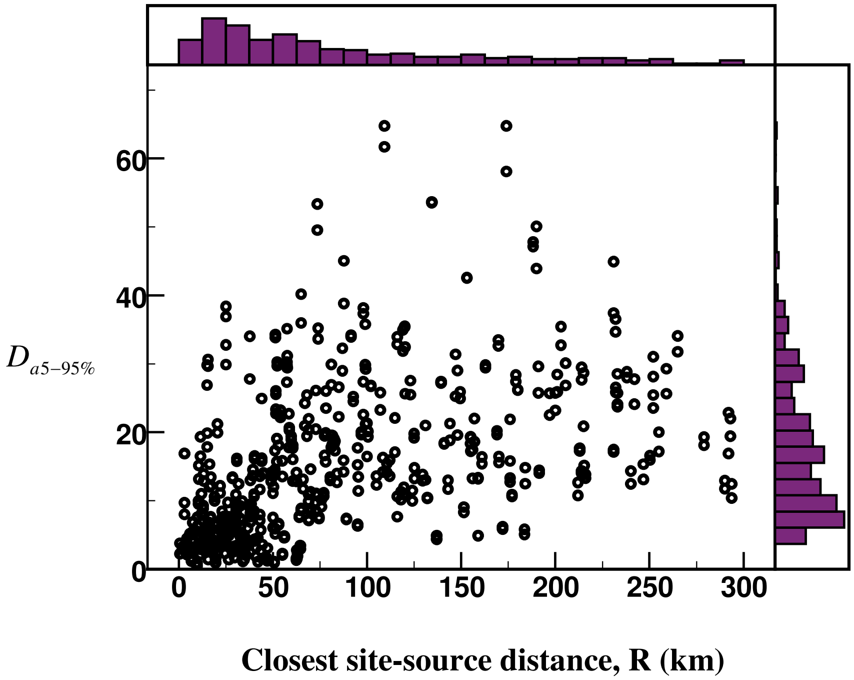


Fig. 5 Scatter plot of $D_{a5-95\%}$ vs. closest site-source distance for the dataset used in this paper

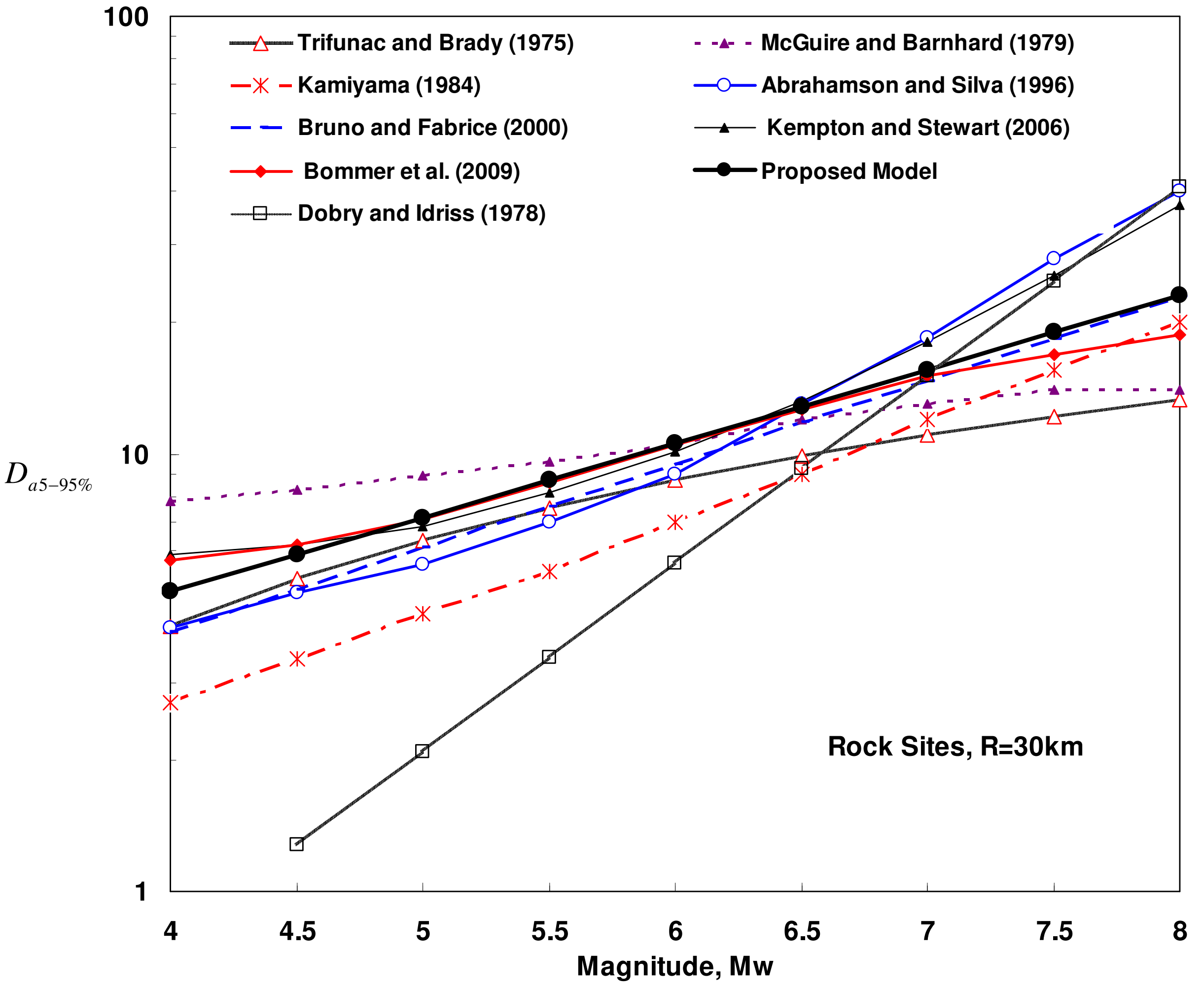
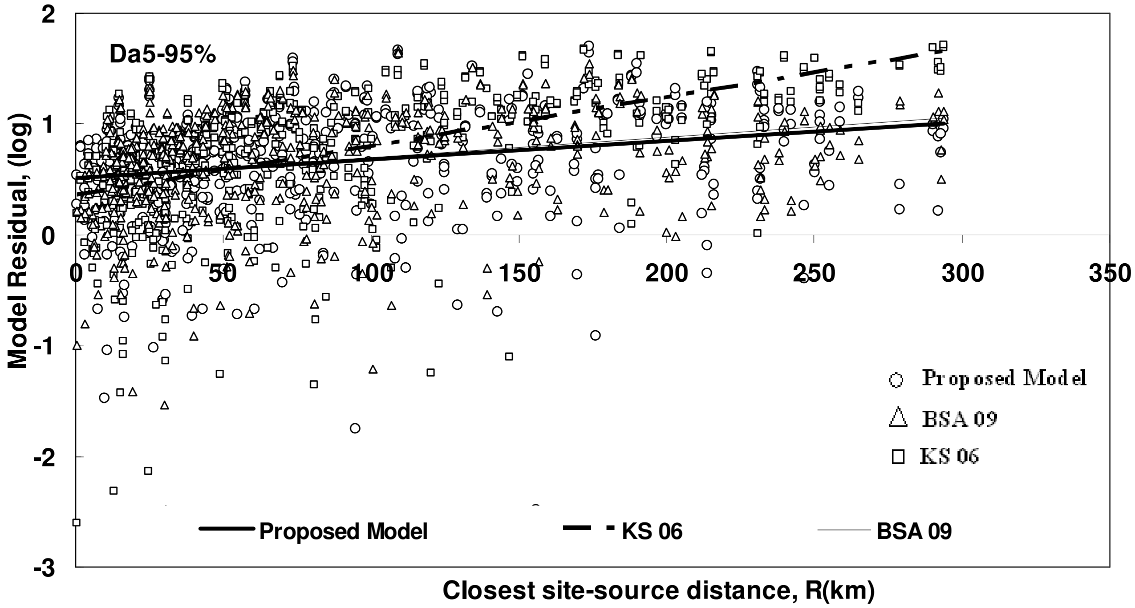
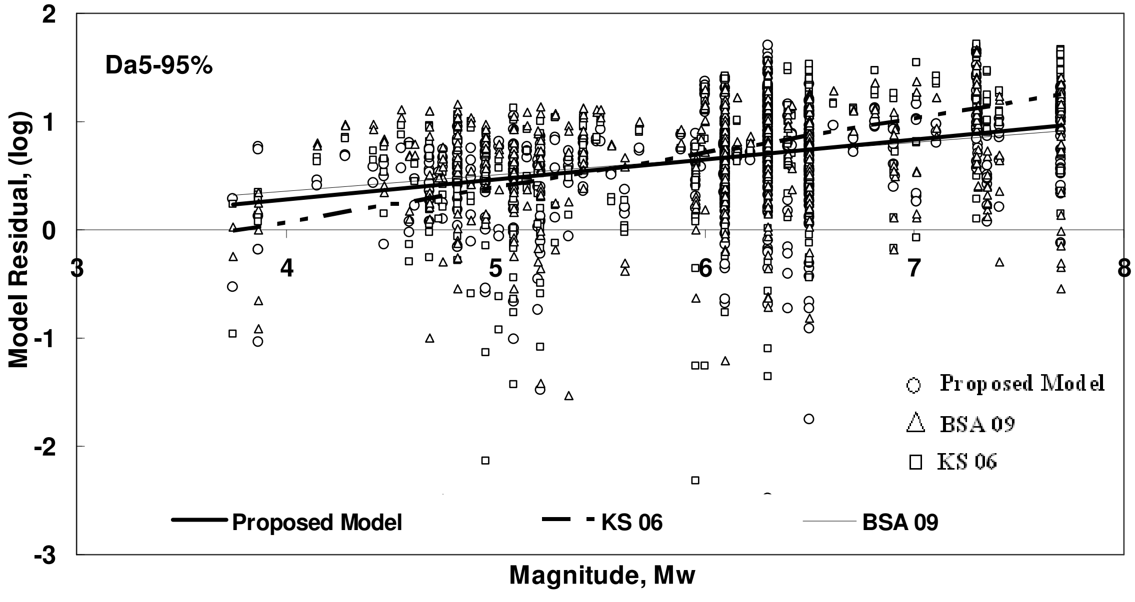


Fig. 6 Comparison of proposed model with other models for a fixed distance of R=30 km on rock sites

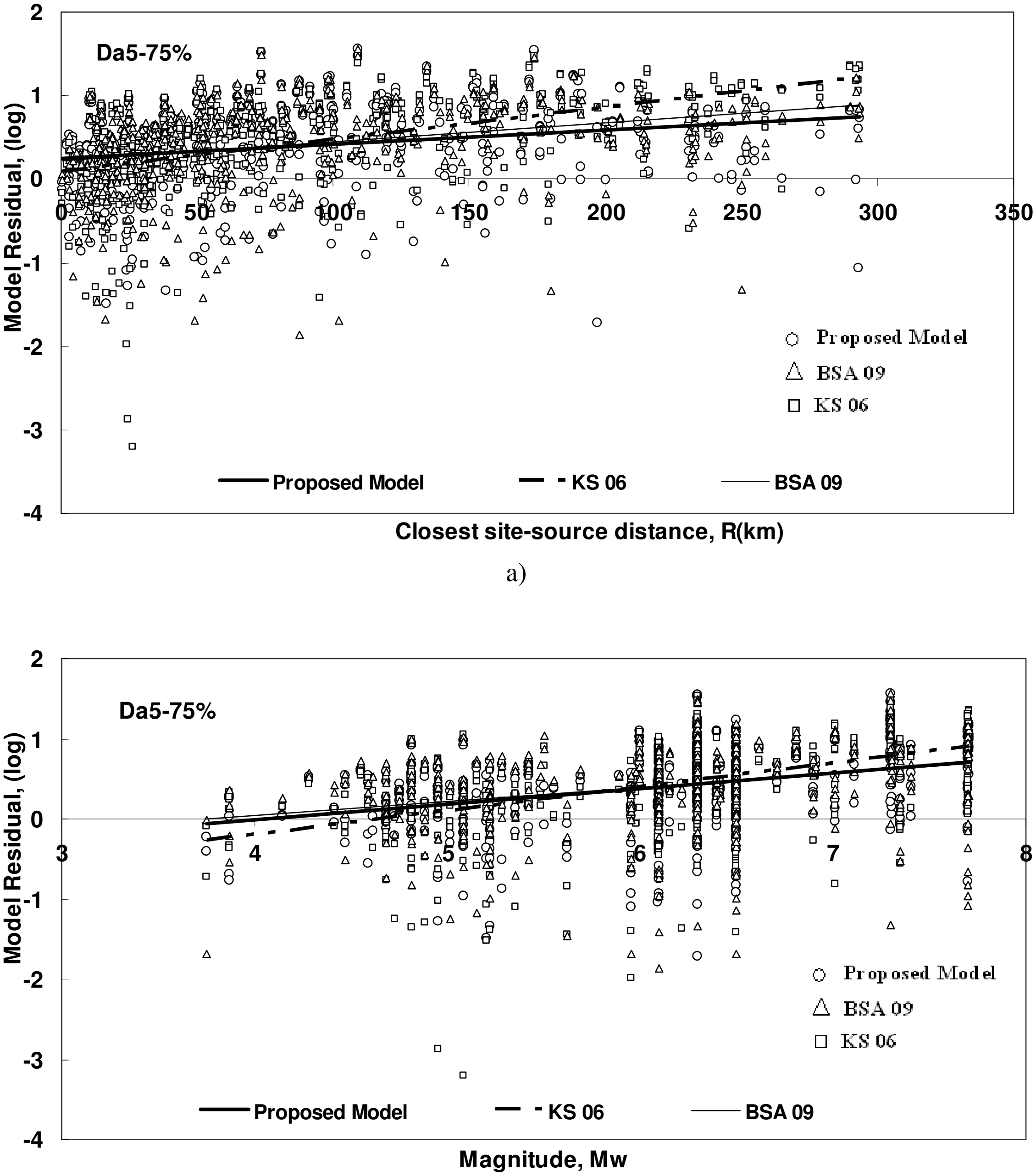


(a)



(b)

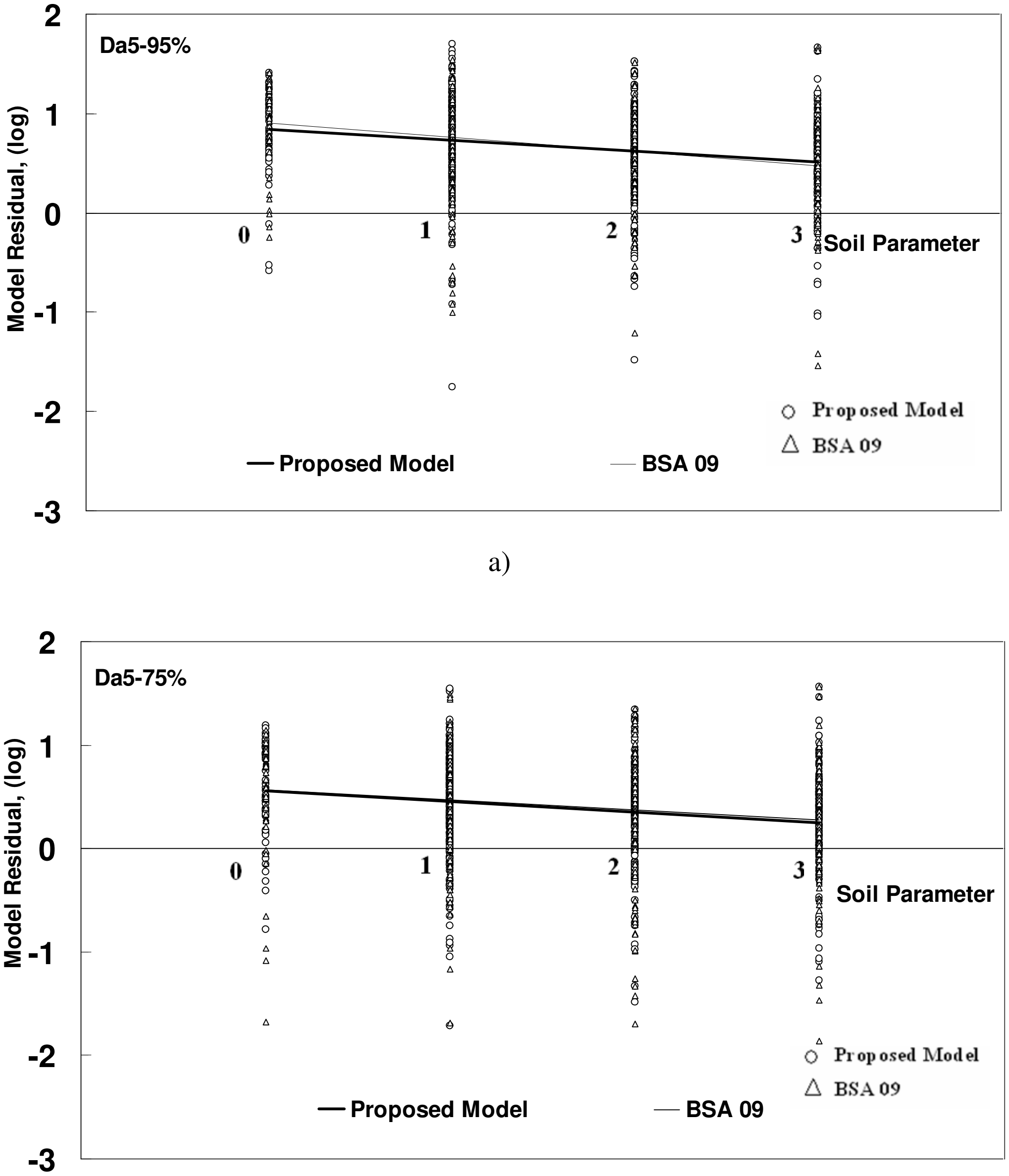
Fig. 7 The distribution of residuals between the observed and predicted significant duration ($D_{a5-95\%}$) for the proposed model along with *KS06* (Kempton and Stewart, 2006) and *BSA09* (Bommer et al., 2009) models with respect to (a) closest site-source distance and (b) magnitude.



a)

b)

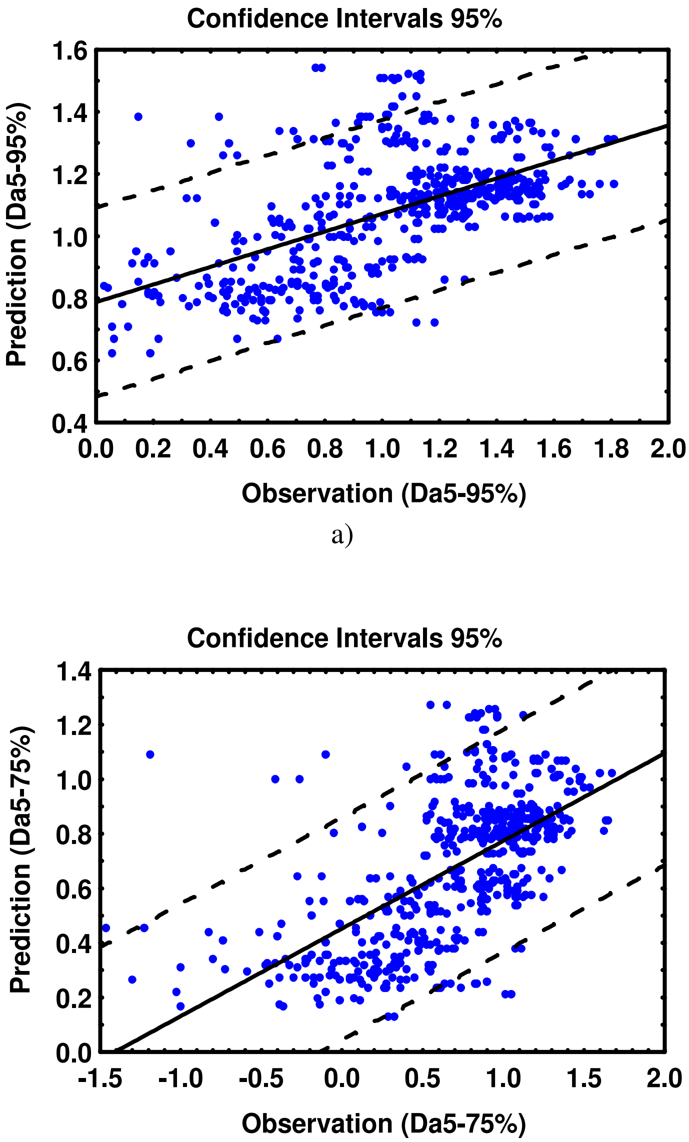
Fig. 8 The distribution of residuals between the observed and predicted significant duration ($D_{a5-75\%}$) for the proposed model along with *KS06* (Kempton and Stewart, 2006) and *BSA09* (Bommer et al., 2009) models with respect to a) closest site-source distance and b) magnitude.



a)

b)

Fig. 9 The distribution of residuals between the observed and predicted significant duration a) $D_{a5-95\%}$ b) $D_{a5-75\%}$ for the proposed model along with *BSA09* (Bommer et al., 2009) model with respect to soil parameter S=3, 2, 1 and 0, representing rock sites (site class B), very dense soil and soft rock (site class C), stiff soil (site class D) and soft soil (site class E), respectively.



a)

b)

Fig.10 Predicted versus observed significant duration of earthquake ground motion based on the model developed in this study: (a) $D_{a5-95\%}$ (b) $D_{a5-75\%}$