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ORIGINAL ARTICLE

Empirical models for the prediction of ground motion duration for intraplate earthquakes

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Abstract Many empirical relationships for the earthquake ground motion duration were developed for interplate region, whereas only a very limited number of empirical relationships exist for intraplate region. Also, the existing relationships were developed based mostly on the scaled recorded interplate earthquakes to represent intraplate earthquakes. To the author's knowledge, none of the existing relationships for the intraplate regions were developed using only the data from intraplate regions. Therefore, an attempt is made in this study to develop empirical predictive relationships of earthquake ground motion duration (i.e., significant and bracketed) with earthquake magnitude, hypocentral distance, and site conditions (i.e., rock and soil sites) using the data compiled from intraplate regions of Canada, Australia, Peninsular India, and the central and southern parts of the USA. The compiled earthquake ground motion data consists of 600 records with moment magnitudes ranging from 3.0 to 6.5 and hypocentral distances ranging from 4 to 1000 km. The non-linear mixed-effect (NLMEs) and logistic regression techniques (to account for zero duration) were used to fit predictive models to the duration data. The bracketed duration was found to be decreased with an increase in the hypocentral distance and increased with an increase in the magnitude of the earthquake. The significant duration was found to be increased with the increase in the magnitude and hypocentral distance of the earthquake. Both significant and bracketed durations were predicted higher in rock sites than in soil sites. The predictive relationships developed herein are compared with the existing relationships for interplate and intraplate regions. The developed relationship for bracketed duration predicts lower durations for rock and soil sites. However, the developed relationship for a significant duration predicts lower durations up to a certain distance and thereafter predicts higher durations compared to the existing relationships.

Keywords Intraplate earthquakes · Bracketed duration · Significant duration · Magnitude · Distance · Predictive relationship

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1 Introduction

Earthquakes can be broadly classified as interplate and intraplate earthquakes. Interplate earthquakes occur on well-defined plate boundaries, where tectonic plates either move away from, or move towards, or slide past each other. On the other hand, intraplate earthquakes occur within the tectonic plate on fault zones. The differences between strong ground motion characteristics of interplate and intraplate earthquakes arise due to the source and path effects. In general, intraplate earthquakes have higher stress drop than interplate earthquakes. In terms of path effect, inelastic attenuation is generally assumed to be greater in the more fragmented interplate regions (Atkinson 2004). Earthquake ground motion can be characterized by various parameters (e.g., amplitude, frequency, and duration) reflecting a particular feature of the ground motion. Traditionally, the intensity of the earthquake ground motion was considered as the scaling parameter for the structural response analysis. However, intensity alone is not adequate to evaluate the damage potential of earthquake ground motions (Fajfar et al. 1990). In the current practice, earthquake ground motions are usually characterized by the amplitude of the shaking, such as peak ground acceleration and peak spectral ordinates (response spectral acceleration, velocity, and displacement). However, these parameters do not adequately consider damage or degradation due to the hysteretic behavior of the structure, which significantly depends on the duration of strong ground motion. It has been shown that duration is a meaningful predictor of performance, along with amplitude and frequency content parameters for structural or geotechnical systems whose performance is measured by the damage that accumulates during shaking (Kempton and Stewart 2006). Hence, for a complete characterization of the earthquake ground motion, duration of the strong ground motion needs to be included. However, the influence of the ground motion duration on the structural response may depend on the primary ground motion parameter used to characterize the motion. If two earthquakes of the same magnitude but different durations are compared, the earthquake with the longer duration will cause more damage to the structure than the earthquake with shorter duration (Bommer and Martinez-Pereira 1999). On the other hand, if two earthquakes with the same energy content but different durations are compared, the earthquake with the shorter duration will cause more damage than the earthquake with longer duration (Bommer and Martinez-Pereira 1999). It was observed that larger acceleration and spectral parameters caused less damage due to shorter duration of the shaking in the 1996 Parkfield earthquake (Housner 1975).

The influence of ground motion duration on the response of geotechnical structures is well established. The duration of ground motion plays an important role in soil liquefaction and slope stability. Liquefaction is a phenomenon that occurs in saturated cohesionless soil due to the generation of pore water pressure under seismic cyclic loading. The generation of pore water pressure hence depends on the amplitude and the number of cycles of the shaking or the ground motion duration. The lateral spread displacement resulting from the soil liquefaction depends on the amplitude and duration of the shaking (Rauch and Martin 2000), with displacements increasing with duration. Seismic displacement of the soil mass along the slope also depends on the duration of shaking (e.g., Bray and Rathje 1998).

The influence of ground motion duration on the structural response is more pronounced, especially for structures whose strength and stiffness degrade under earthquake ground motion (Lumantarna et al. 2010). An example of such structure is masonry structure. Moreover, the duration of earthquake ground motion has great influence on the inelastic response of structures when cumulative parameters are used to measure the damage (Hancock and Bommer 2007). Although the importance of ground motion duration for the seismic design and seismic damage assessment of structures are well documented, duration parameter has not yet been included in most of the current design codes (Victor and Federico 2013).

2 Duration definitions

Several definitions for the duration of earthquake ground motion are available in the literature. But, the most commonly used are bracketed duration and significant duration (Bommer and Martinez-Pereira 1999). Bracketed duration (D_b) is defined as the time elapsed between first and last exceedance of a specified level of acceleration. The change of threshold acceleration can significantly increase or decrease D_b. In this study, the threshold acceleration values of $0.05g$ (Bommer et al. 2009) and $0.03g$ (Ambraseys and Sarma 1967) are considered. Figure 1 shows D_b of the 2011 Virginia earthquake for the considered threshold acceleration values. It can be seen that D_b changes from 27.6 to 11.8 s with the change of threshold acceleration from 0.03 to 0.05g. It is very clear that bracketed duration parameters can be sensitive to the threshold accelerations and to small sub-events occurring towards the end of a recording (Kempton and Stewart 2006). It is because of these and other reasons, other definitions of duration are often preferred. Significant duration (D_s) is an energy-based approach. It is defined as the time interval across which a specified amount of energy is dissipated. Energy is represented by the integral of the square of ground acceleration, or velocity, or displacement. The integration of acceleration is related to the Arias intensity (AI) (Arias 1970), which is defined as

$$\mathrm{AI} = \frac{\pi}{2g}\int_0^{t_r} a^2(t)dt \tag{1}$$

where $a(t)$ is the acceleration time history, t_r is the total duration of accelerogram, and g is the acceleration due to gravity. Husid plot is used to evaluate the D_s for a

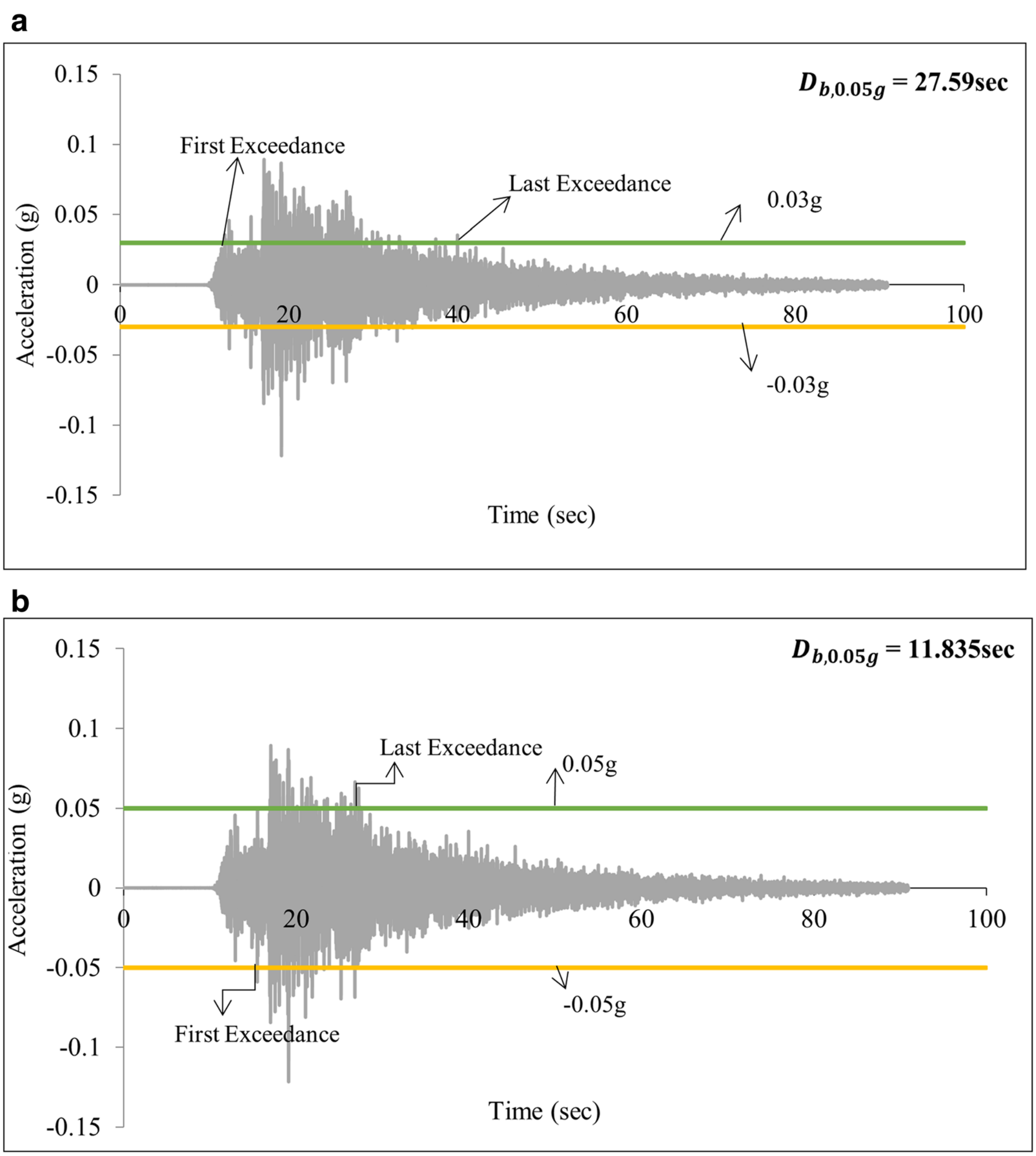


Fig. 1 Bracketed duration of the 2011 Virginia earthquake. **a** $D_{b\,,\,0.03g}$. **b** $D_{b\,,\,0.05g}$

given energy interval (Husid 1969). Two common measures of significant duration are the time intervals between 5–75 and 5–95% of AI, which are denoted as D_{s5-75} and D_{s5-95} (Bommer et al. 2009). The D_{s5-75} captures the energy from body waves, whereas the D_{s5-95} captures the energy from the full wave trains. Unlike D_b which determines the strong motion duration based on an absolute value, D_s considers the characteristics of the whole accelerogram and defines a continuous time interval in which the motion can be considered as strong. Figure 2 shows the D_s for the 2011 Virginia earthquake. The D_{s5-75} has been observed to be slightly over 40% of D_{s5-95}. It is possible to obtain non-zero D_s for low-amplitude earthquake ground motion, which might not be significant for damage analyses. However, as usual practices are, the problem can be easily overcome whenever the damage analysis takes into account both the amplitude and the duration of the ground motion.

A few predictive equations have been developed in the past to determine the strong motion duration. In most cases, the predictive equations were expressed in terms of magnitude, site to source distance/hypocentral distance, and site condition (Simon 2011; Lee and Green 2008, 2012, 2014). However, almost all of the predictive equations were developed for interplate regions (Trifunac and Brady 1975; Dobry et al. 1978; McGuire and Barnhard 1979; Kamiyama 1984; Abrahamson and Silva 1996; Kempton and Stewart 2006; Bommer et al. 2009; Abrahamson and Silva 2008), and only a few were developed for intraplate regions; moreover, these studies were based on the scaled recorded interplate earthquakes to represent intraplate earthquakes, for e.g., Lee and Green (2008, 2012, 2014). Hence, to the knowledge of the authors, none of the previous studies have developed predictive equations for the earthquake ground motion duration, considering only the recorded earthquake events in the intraplate regions.

The objective of the study presented herein is the development of empirical predictive models correlating the most common duration definitions D_b and D_s to earthquake magnitude (moment magnitude, M), hypocentral distance (R), and local site condition (S) (i.e., rock site or soil site) for intraplate earthquakes, which has not yet been adequately developed and studied. The models are developed through non-linear mixed-effect (NLME) regression analyses on data comprising 700 recorded horizontal ground motions from intraplate regions. Only the horizontal components of the ground motion records have been considered. The data were collected from 75 intraplate earthquake events. Lastly,

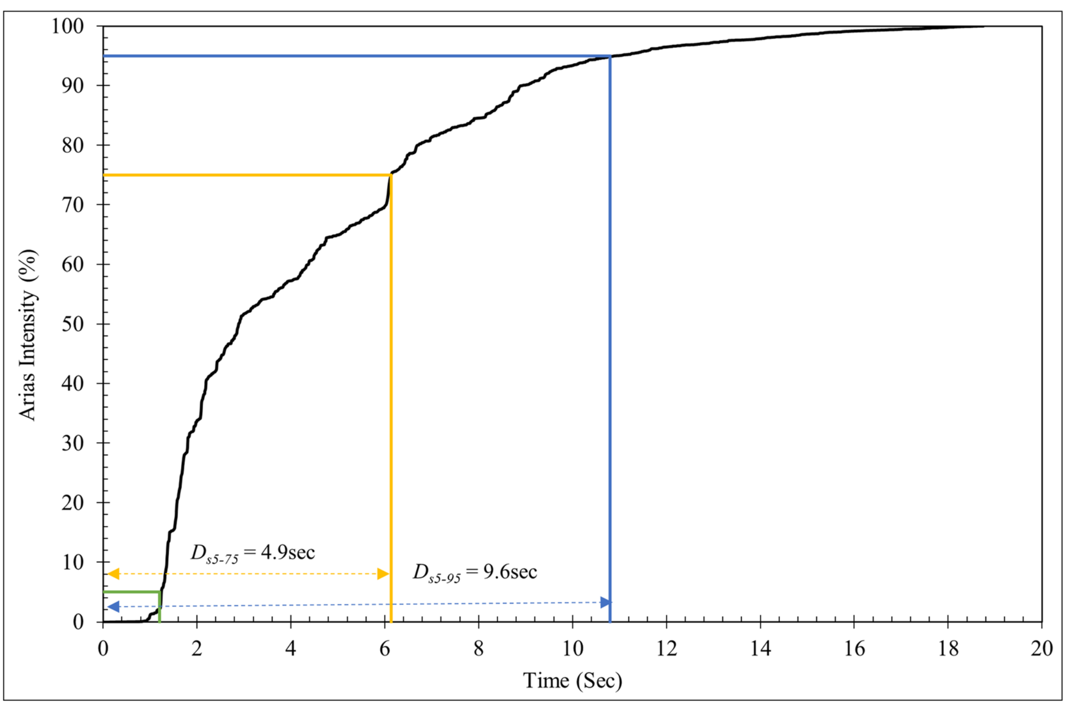


Fig. 2 Husid plot for significant duration (D_s)

the predictive durations have been compared with the previously published studies for interplate and intraplate regions.

3 Strong motion database

The recorded earthquake ground motion data were collected from the intraplate regions on the east coast of Australia, southeast of Australia, southeast of Canada, north of Canada, Peninsular India, South Atlantic region of the USA, midwestern region of the USA, southern region of the USA, and the northeastern regions of the USA. The ground motion time histories are collected from different sources, including Next Generation of Attenuation (NGA)-East database (NGA-East flat file) and engineering seismology toolbox. Most of the available ground motion time histories were processed and filtered using fourth-order Butterworth filter. The database having signal-to-noise ratio more than 4 is used for the processing. For the unprocessed time histories, fourth-order Butterworth filter and quadratic baseline correction were applied. The procedure used in processing seismic data is similar to Boore (2005). The database had records from 75 earthquakes which included 1050 ground motion records, with the 2014 Conway Springs, Kansas earthquake being the latest event included in the database.

Earthquake magnitudes in the collected database were in terms of either moment magnitude (M) or body wave magnitude (M_B) or short-period body wave magnitude (M_N). For the regression analysis, M_B and M_N were converted to M using the equations developed in Joshi and Ramancharla (2008) and Atkinson and Sonley (2005), respectively.

$$M = 0.85 \times M_B + 1.03 \quad 3.5 \leq M_B \leq 6.8 \tag{2}$$

$$M = 1.03 \times M_N - 0.61 \quad 1.0 \leq M_N \leq 6.0 \tag{3}$$

Only the horizontal components of the earthquake ground motion record were considered in developing the equations. Vertical components of the earthquake ground motion data were omitted from the 1050 ground motion records. Hence, the recorded earthquake ground motion data considered in this study were reduced to 700 records. The epicentral distance of the records varies from 4.036 to 1768.53 km. For all of the ground motion records, epicentral distances were calculated using the latitudes and longitudes of the recording station and earthquake epicenter. The focal depth of the ground motion records varies from 0.64 to 30.8 km. Figure 3a shows the distribution of M and R of the 700 recorded data points. The moment magnitudes M of the ground motion records range from 3.0 to 6.5. It can be also seen from Fig. 3a that very few recordings are available for $M > 5$ and $R < 100$. This can be improved by scaling the strong motion data from the interplate region, but this will be addressed in the future work. Figure 3b shows the distribution of database considered in this study with respect to different region. About 26% of the ground motion records are within R < 100 km and 30% are within R = 100–500 km, and only 44% are within

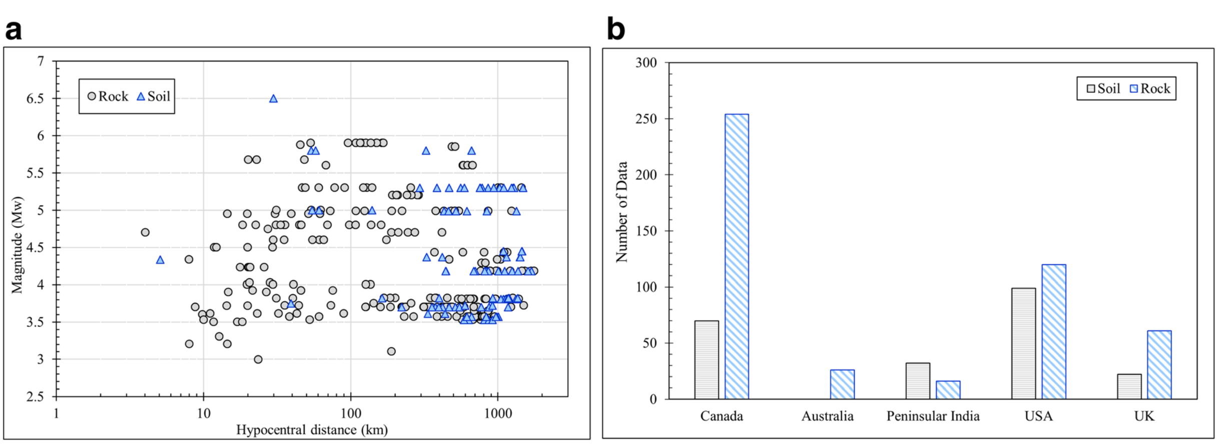


Fig. 3 **a** Moment magnitude (M) versus hypocentral distance (R) of the earthquake records used in this study. **b** Distribution of data for different region for soil and rock sites

R > 500 km. Around 14% of the database, which is recorded for R > 1000 km, is discarded as it is having insignificant peak ground acceleration. Hence, for deriving the regression coefficients, only 600 ground motion components have been used.

The ground motions were classified as either "rock" or "soil" based on the site conditions at the respective seismograph stations. The site classification scheme used for the data is adapted from McGuire et al. (2001), which are based on the third letter of the Geomatrix three-letter site classification system. Site categories A and B were considered to represent rock sites, and site categories C, D, and E were considered to represent soil sites. The respective stations were classified based on the shear wave velocity data. Only those data was considered for which proper information regarding the site class or shear wave velocity is available. Only the ground motion recorded considered in this study for which measure V_s is available; the strong motion records with calculated V_s based on proxies or other method are discarded from the study. It is noted that hypocentral distance (R) of the earthquake ground motion records was calculated based on epicentral distance and the depth of the earthquake. Among the 700 earthquake ground motion records, 509 records were on rock site and 191 records were on soil site.

4 Regression analyses

As mentioned in Sect. 1, very few equations have been published, at least in recent years, for the prediction of ground motion duration. Hence, there is relatively little guidance available on suitable functional forms. It is noted that development of predictive relationships for ground motion parameters including PGA and spectral parameters for different periods at the rock and soil sites for intraplate earthquakes still remains a challenge (Anbazhagan et al. 2014, 2015). A NLME modeling is a powerful technique for the regression analysis of data consisting of multiple groups. The duration data consists of groups of ground motion representing ground motions from the same earthquake. The NLME regression modeling is a maximum likelihood method, which is based on Gaussian (normal) distribution and is mainly used for the analysis of grouped data (i.e., datasets comprising subsets) (Pinheiro and Bates 2000). The traditional regression techniques (e.g., least squares method) analyze the entire data at once. However, the dataset is composed of motions from different earthquakes, with the number of motions for each earthquake varying significantly. The resulting regression is unduly influenced by the earthquake having the largest number of ground motions. Also, NLME regression analyses quantify both interearthquake and intraearthquake uncertainties. The model produced by the NLME regression technique has unbiased fittings for each subset having a different number of duration recordings.

This regression technique inherently assumes the data and errors to be normally distributed. Therefore, quantile-quantile plot (or Q-Q plot) was used to check this assumption (i.e., if the data points plot approximately as a straight line on a normal Q-Q plot, it indicates that the data is normally distributed). The NLME regression analyses were performed using the statistical analysis program R (Program-R 2015).

The functional form of the predictive relationships in this study was adapted from those proposed in Abrahamson and Silva (1996) and Kempton and Stewart (2006), which were based on the seismic source duration relationships (Hanks 1979; McGuire and Hanks 1980) and seismic source model of Brune (1970, 1971). It is noted that although the functional form may be based upon physical reasoning, the final model is entirely empirical and care should be taken when inferring physical attributes from regression coefficients. The authors have adopted the philosophy that while it may be possible to identify more complex expressions with statistically significant terms, the resulting reduction in variance is very minor. In this study, earthquake ground motion duration is expressed as a function of M (magnitude), R (distance), and S (site condition) for both bracketed and significant durations. In order to ensure that the derived empirical models are robust, residuals were checked and the statistical significance of all the coefficients was inspected. The standard deviations for $D_{s5-95}$and D_{s5-75} were found to be smaller than those for $D_{b,0.03g}$ and $D_{b,0.05g}$. This is attributed to the fact that bracketed durations are inherently far less predictable than the significant durations (Bommer et al. 2009). Various functional forms were considered in this study, and statistical significance of the functional forms is determined based on the recorded data. The detail regarding the selection of functional form is given below.

4.1 Determination of functional form

Various authors such as Abrahamson and Silva (1996), Kempton and Stewart (2006), and Lee and Green (2012, 2014) gave different functional form for bracketed and significant durations. These functional forms were derived either based on physical reasoning or statistical significance. However, in this study, both ways are considered to determine the best suitable functional form for duration corresponding to magnitude and distance scaling. The functional form of the predictive model is developed through "trial-and-error" approach, where the model selection is based on the standard error/deviation (i.e., the smallest) and the correct representation of the underlying physics. The functional forms for ground motion duration model (GMDM) for significant duration used are

$$\log(D) = C_1 + C_2\left(M - M^*\right) + C_3\log(R) + \left\{C_4 + C_5\left(M - M^*\right) + C_6\log(R)\right\}S \quad \text{(FF 1)}$$

$$\log(D) = C_1 + C_2\exp\left(M - M^*\right) + C_3\mathrm{R} + \left\{C_4 + C_5\left(M - M^*\right) + C_6\mathrm{R}\right\}S \quad \text{(FF 2)}$$

$$\log(D) = \log\left[C_1 + C_2\exp\left(M - M^*\right) + C_3\mathrm{R} + \left\{C_4 + C_5\left(M - M^*\right) + C_6\mathrm{R}\right\}S\right] \quad \text{(FF 3)}$$

where D is the significant duration $D_{s,5-75}$ or $D_{s,5-95}$; M is the moment magnitude; M^* is the hinge magnitude; R is the hypocentral distance; S is the site condition, where $S=0$ for rock sites and $S=1$ for soil sites; and C_1, C_2, C_3, C_4, C_5, and C_6 are the regression coefficients.

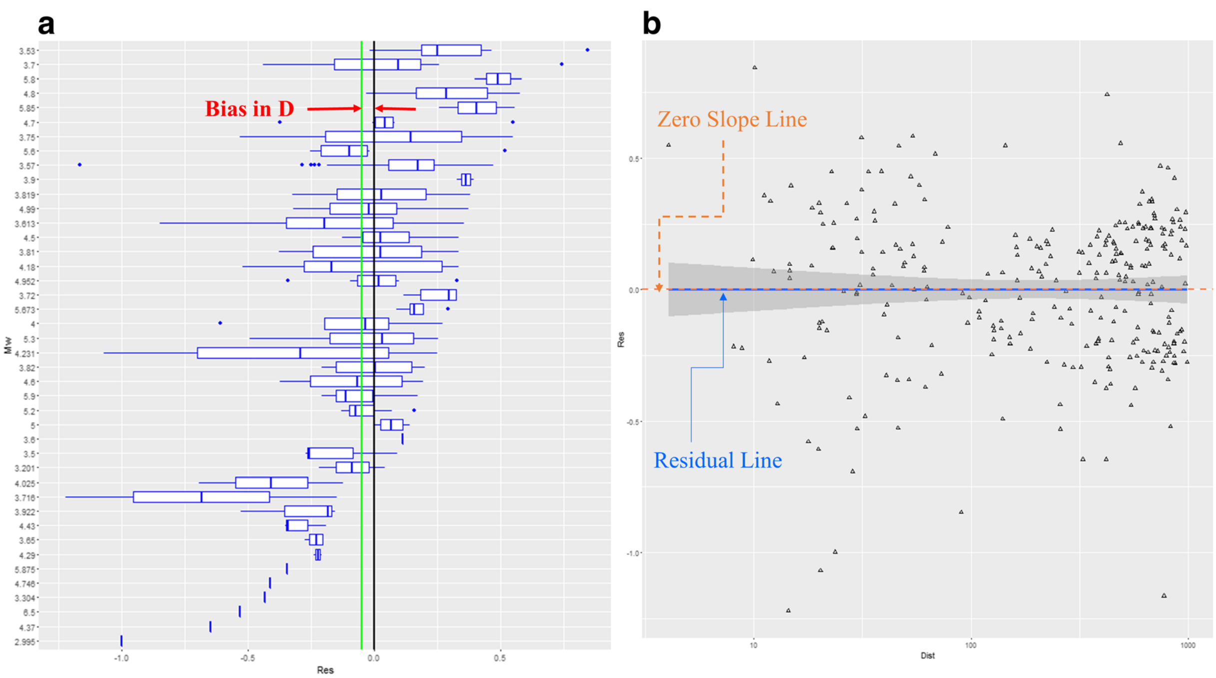


Fig. 4 Typical plot of residuals for FF1 for significant duration. **a** Interevent residuals with magnitude. **b** Intraevent residuals with logarithm of distance. Difference between the *two lines* in **a** shows the bias in the model

The regression coefficients corresponding to the above functional forms are derived, and bias for these three models is calculated. For determining the bias in each model, the residuals are divided into intraevent and interevent residuals. To accomplish that, a mixed-effect regression proposed by Abrahamson and Youngs (1992) and further extended by Jayaram and Baker (2010) is conducted by considering spatial correlation. The whole algorithm used is explained in Bajaj and Anbazhagan (2016). The following equation has been used to perform the mixed-effect regression.

$$\left(R_{i,j}\right)_k = c_k + \left(\eta_i\right)_k + \left(\epsilon_{i,j}\right)_k \tag{4}$$

where c_k is the mean offset (or bias) of the data relative to k^{th} GMDM, η_i represents the event term for event i, and $\varepsilon_{i,j}$ is the intraevent residuals for recording j in event i. The event term η_i represents the mean offset of data for event i from the prediction provided by the GMDM median after adjusting the offset c_k. In other words, the intraevent residual, $\epsilon_{i,j}$, is the residual after accounting for the interevent residual, η_i. The event term would be helpful in providing a convenient mechanism for testing the ability of a GMDM to provide the magnitude scaling of a database. Interevent (η) and intraevent (ϵ) terms are assumed to have zero mean and τ and σ, respectively, as standard deviation. Hence, τ refers to the event-to-event variability, and on the other hand, σ refers to the variability in a single event. A typical example for showing bias in a model is shown in Fig. 4. A similar study has been carried out with all the three models given as equations FF1 to FF3 for different durations. In Fig. 4, it can be seen that bias in model 1 is 0.05, and the residual line matches with the zero line. For $D_{s,5-95}$, the bias values for FF2 and FF3, respectively, are 0.1 and 0.18, and for FF3, residual line does not match with the zero line. Similar observations are seen for $D_{s,5-95}$. Hence, FF1 is further used for deriving the ground motion duration model. However, as far as bracketed duration is of concern, the functional form available in the literature is used, as this predicts less standard deviation.

A similar procedure is used for determining the reference magnitude (M^*) in case of both significant and bracketed duration. The M^* varies from 3 to 6 with an interval of 0.1, and it has been found that M^* equals to 4. The value of c_k is very less as compared to other magnitude. Hence, $M^* = 4$ is selected as a reference magnitude. The final functional

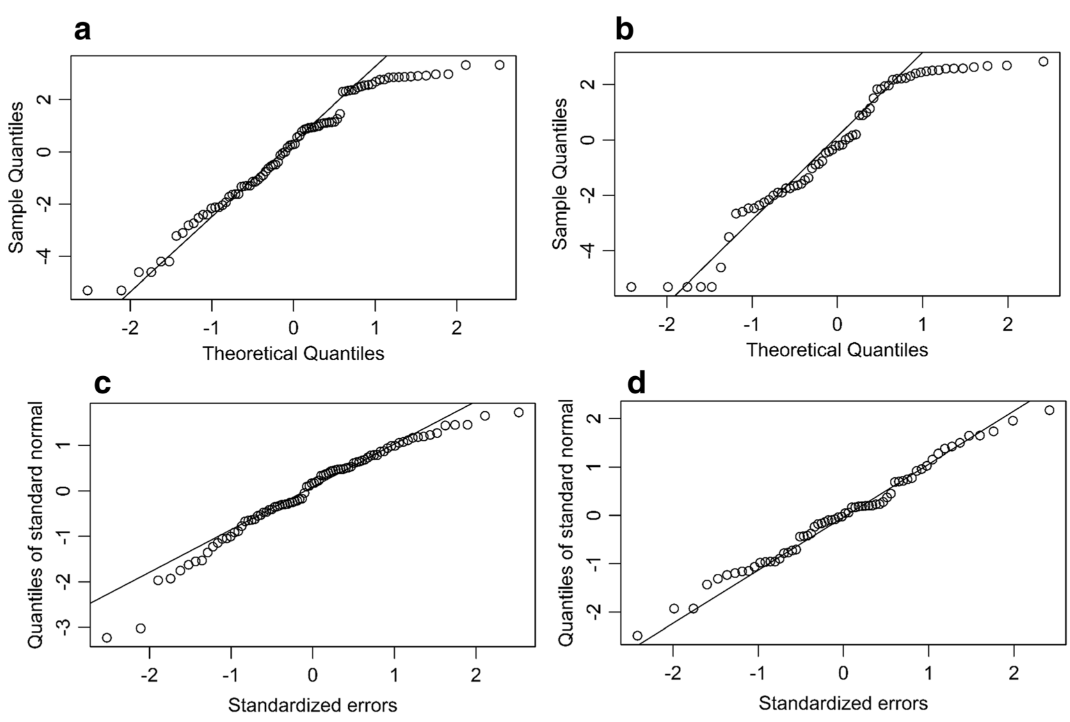


Fig. 5 *Q-Q* plots of the non-zero duration data and the resultant errors. **a** $\ln(D_{b,0.03g})$. **b** $\ln(D_{b,0.05g})$. **c** $D_{b,0.03g}$. **d** $D_{b,0.05g}$

form used in determining significant duration is as follows:

$$\log(D) = C_1 + C_2(M-4) + C_3\log(R) + \{C_4 + C_5(M-4) + C_6\log(R)\}S \quad (5)$$

Additionally, as both the components of the ground motion are available, an attempt has been made to derive the regression coefficients using the geometric mean and maximum of both the components also by taking both the components.

4.2 Bracketed duration

The D_b has been determined from 600 ground motion records for the absolute acceleration of 0.03g ($D_{b\,,\,0.03g}$) and 0.05g ($D_{b\,,\,0.05g}$). The entire bracketed duration dataset does not follow a normal distribution. Also, the presence of zero-duration data precludes the data from being log-normally distributed (Lee and Green 2012). Moreover, the zero duration does not correlate well to the independent variables in the regression analyses. In order to bypass these issues, the zero and non-zero duration data were treated separately, with the non-zero duration data reasonably following a log-normal distribution. The zero-duration data, however, needed to be incorporated in the predictive model. Otherwise, the model would be biased towards longer durations. This becomes important for $D_{b\,,\,0.05g}$ as it has a significant number of zero-duration records.

The corresponding expected value of duration can be expressed using the total probability theorem, for a

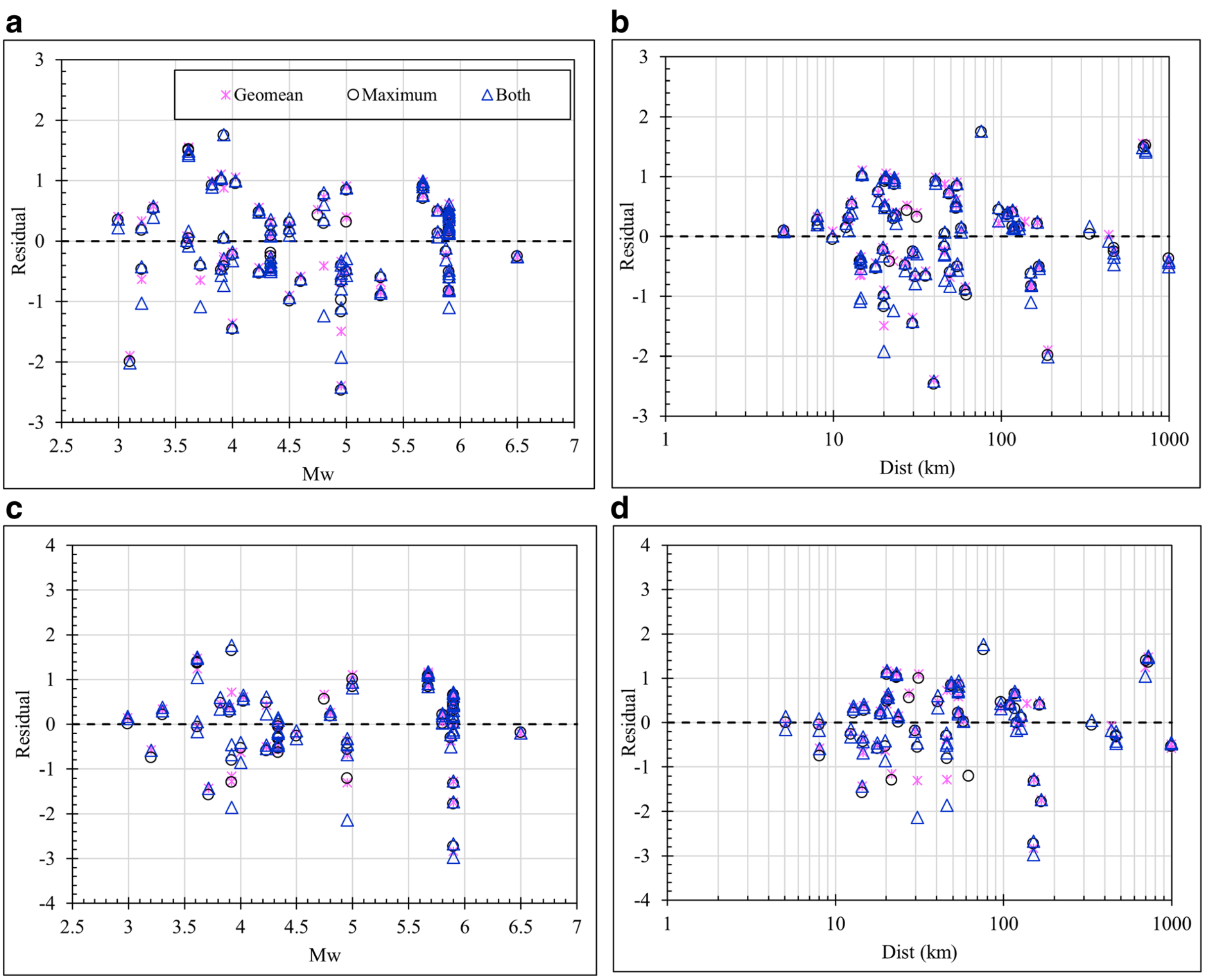


Fig. 6 Residuals for $D_{b\,,\,0.03g}$ versus **a** moment magnitude and **b** hypocentral distance. Residuals for $D_{b\,,\,0.05g}$ versus **c** moment magnitude and **d** hypocentral distance

given set of moment magnitude, local site condition, and hypocentral distance,

$$E[D] = E[D|D > 0] \times p(D > 0) + E[D|D = 0] \times p(D = 0) \quad (6)$$

where $E[\ ]$ and $p(\ )$ represent the expected value and probability, respectively. Since the value of $E[D|D=0]$ would be zero, the second term in Eq. (6) automatically becomes zero for all values of the input variables. Therefore, the expected value for D becomes equal to the quantity of the expected value for a given non-zero duration (i.e., $E[D|D>0]$) times the probability of non-zero duration occurrence (i.e., $p(D>0)$). For modeling the expected value of duration, the NLME regression technique is employed, and for modeling the probability of non-zero duration occurrence, a logistic regression method is used. The probability of non-zero duration occurrence can be easily obtained by subtracting the probability of zero duration occurrences from 1. Afterwards, this probability model is applied as a weighting function to the NLME regression result.

The entire model for bracketed duration estimation can be split into two parts, one part is the non-zero duration model that is developed through NLME regression technique (which follows log-normal distribution as shown in Fig. 5) and the other part is a weighting function that represents the probability of non-zero duration occurrence for a given earthquake magnitude, hypocentral distance, and site condition which is developed using logistic regressions.

The natural logarithm of bracketed duration is used because the bracketed duration data is assumed to be log-normally distributed. The determination of the functional was explained above; hence, based on the statistical significance in the data and the relative magnitude

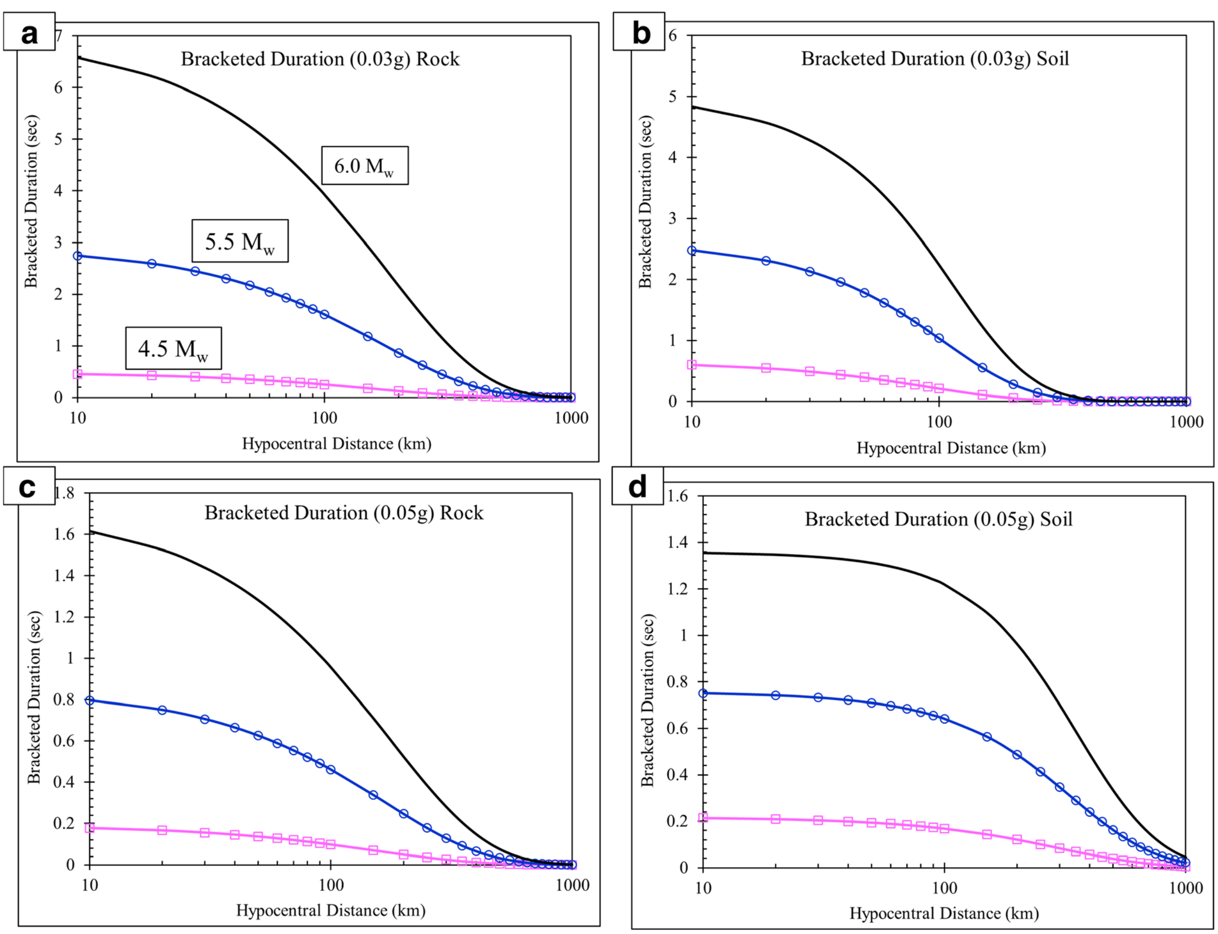


Fig. 7 Predicted bracketed duration by the combined model for $M_w = 4.5$, 5.5, and 6.0 $D_{b\ ,\ 0.03g}$ for **a** rock site and **b** soil site and $D_{b\ ,\ 0.05g}$ for **c** rock site and **d** soil site

of the resulting standard deviations, the model gave the best fit of the data,

$$\ln(E[D_b|D_b > 0]) = C_1 + C_2(M-4) + C_3\log(R) + \{C_4 + C_5(M-4) + C_6\log(R)\}S \quad (7)$$

where D_b is the bracketed duration − $D_{b,0.03g}$ or $D_{b,0.05g}$; M is the moment magnitude; R is the hypocentral distance; S is the site condition, where $S=0$ for rock sites and $S=1$ for soil sites; and C_1, C_2, C_3, C_4, C_5, and C_6 are the regression coefficients.

It is noted that if duration obtained from Eq. (7) is less than zero, then zero should be used as the predicted duration. The results from the regression analysis along with the associated 95% confidence interval are reported in Table 1. The given regression coefficients are derived by taking geometric mean, maximum of both the horizontal component and by considering both the components. As it is known, there are inherent assumptions in non-linear mixed-effect modeling that the errors are normally distributed. Therefore, normal *Q-Q* plots of the errors (i.e., theoretical quantiles of the standard normal versus the standardized errors) are produced as shown in Fig. 5. As may be observed from this figure, the *Q-Q* plots are relatively straight lines, demonstrating that the distributional assumptions inherent to the regression analyses are valid. The residuals (i.e., predicted − actual value) for the recorded ground motions for intraplate are shown in Fig. 6 as a function of distance and magnitude. With the exception of only a few data points, the residuals are within model ± standard deviation range in natural log, indicating that the model predictions are in good agreement with the data. Also, the residuals do not show any trend with magnitude or distance, suggesting that the model is appropriate. In Fig. 6 and Table 1, it can be concluded that use of both the components significantly reduced the standard deviation. Hence, for comparison purpose, regression coefficient corresponding to both the components is used.

Logistic regressions were implemented separately for each site condition, as a function of M and R to estimate the probability of the occurrence of a zero-duration motion. The logistic function is defined as

$$p(D_{\text{bracketed}} = 0|M, R) = \frac{e^{\beta_1+\beta_2 M+\beta_3 R}}{1 + e^{\beta_1+\beta_2 M+\beta_3 R}} \quad (8)$$

where $p(D_{\text{bracketed}}=0|M, R)$ is the probability of zero duration for a given M and R and β_1, β_2, and β_3 are the regression coefficients determined from logistic regression and are separate for both site conditions. Then, the probability of the duration being greater

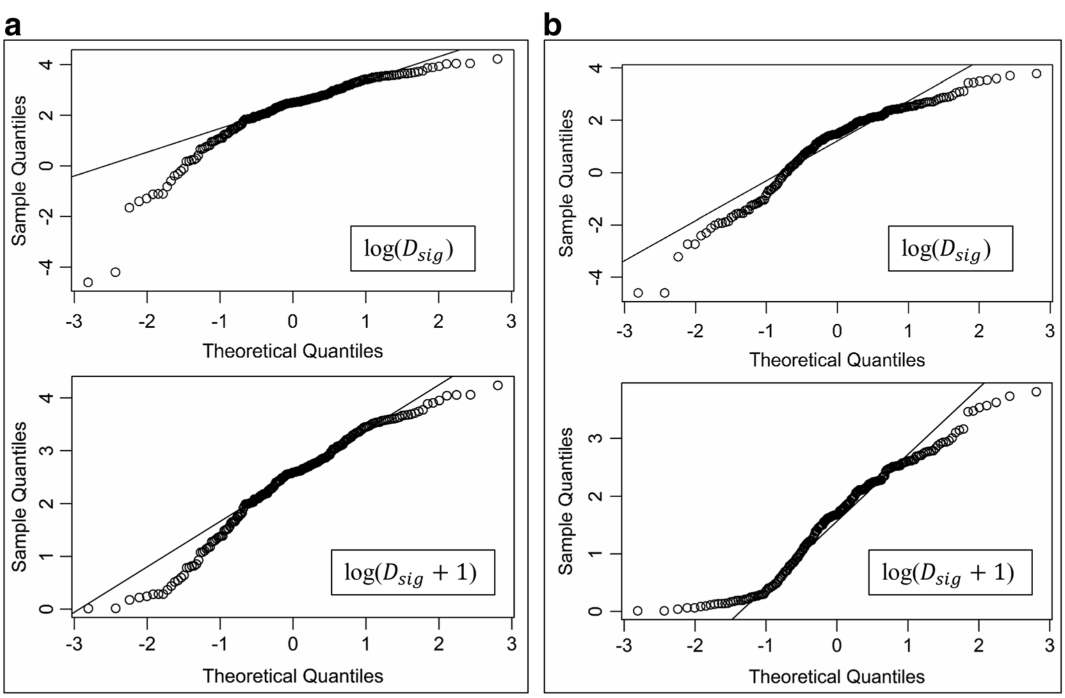


Fig. 8 Comparison of normal *Q-Q* plots for **a** D_{s5-95} and **b** D_{s5-75}

than zero is one minus the probability of that it is zero duration.

$$p(D_{\text{bracketed}} > 0|M,R) = 1 - p(D_{\text{bracketed}} = 0|M,R) = \frac{1}{1+e^{\beta_1+\beta_2 M+\beta_3 R}} \tag{9}$$

The results of the logistic regression are shown in Table 2. Equation (5) is used in conjunction with Eq. (7), which is used as a weighting function. The combined model proposed for bracketed durations that account for zero duration is given by

$$E(D_b) = \exp\{C_1 + C_2(M-4) + C_3\mathrm{R} + \{C_4 + C_5(M-4) + C_6\mathrm{R}\}S\} \times p(D_{\text{bracketed}} > 0|M,R) \geq 0 \tag{10}$$

Using Eq. (10) in conjunction with the regression coefficients mentioned in Tables 1 and 2, the bracketed durations predicted for intraplate regions are shown in Fig. 7, as functions of hypocentral distance R for $M4.5$, $M5.5$, and $M6.0$ for both rock and soil sites. It has been observed that with the increase in R, the bracketed durations decrease but increase with increasing magnitude. This trend holds true for $D_{b\,,\,0.03g}$, $D_{b\,,\,0.05g}$, and also for rock and soil sites. It is very clear from the graphs that the duration varies significantly with magnitude, particularly for distances less than around 50 km, where an increase in one magnitude unit results in a fourfold increase in duration. For rock sites, $D_{b\,,\,0.03g}$ has longer durations than $D_{b\,,\,0.05g}$, and similar trend has been observed for the soil sites. In comparing soil and rock motions, soil motions seemingly have considerably shorter durations than rock motions for both $D_{b\,,\,0.03g}$ and $D_{b\,,\,0.05g}$. However, in case of $D_{b\,,\,0.03g}$, for lower magnitude (i.e., $M_w < 4.5$) and less hypocentral distance, duration at soil sites is observed to be more as compared to the rock sites. This may be due to high upper crustal amplification for lower distances for intraplate region. In the case of $D_{b\,,\,0.05g}$, for larger hypocentral distance, and high magnitude, duration at soil sites is more as compare to rock sites. This trend may be attributed to relatively rich, high-frequency content of intraplate motions and low attenuation for larger distance. As the motions propagate up through the soil layers, high frequencies in intraplate motions filter out (Lee and Green 2012).

4.3 Significant duration

It has been determined from 600 ground motion records for two common measures, which are D_{s5-75} and D_{s5-95}. In assessing the normal distribution of the significant duration dataset, it was found that the data followed a log-normal distribution. Also, adding 1 s to the durations optimized the overall log-normality of the duration data. As shown in Fig. 8, $\log(D_{\text{sig}} + 1)$ more closely follows a normal distribution than $\log(D_{\text{sig}})$. This optimization of the normality is necessary because normal distribution of data and errors is inherently assumed in the theoretical formulation of the NLME regression. Accordingly, the NLME

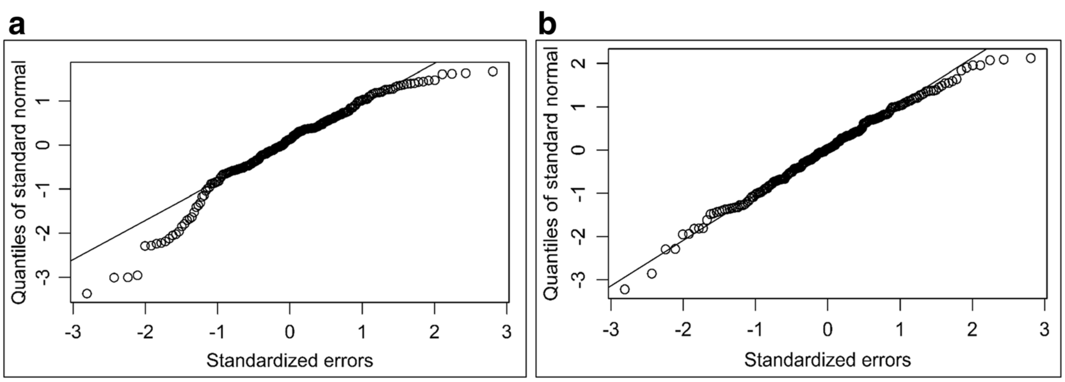


Fig. 9 *Q-Q* plot of the standard errors. **a** D_{s5-95}. **b** D_{s5-75}

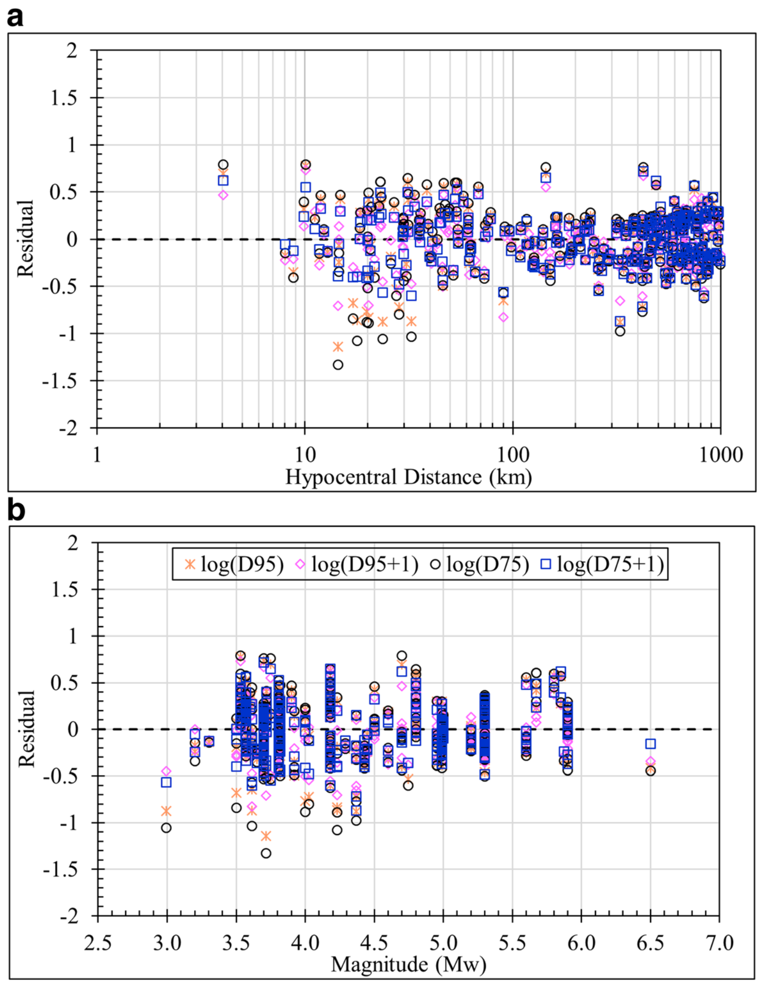


Fig. 10 Residuals for D_{s5-95} and D_{s5-75} with respect to **a** hypocentral distance and **b** magnitude

regression analyses were performed on log(D_{sig}+1) and log(D_{sig}). Both the equations will be statistically tested, and the coefficient that corresponds to both is given in Table 1. Numerous regression analyses were performed using various functional forms for the predictive relationships. The model gave the best fit for the data (i.e., smallest standard deviation) as explained above.

$$\log\left(D_{sig}\right) = \left[C_1 + C_2(M-4) + C_3\log(R) + \{C_4 + C_5(M-4) + C_6\log(R)\}S\right] \tag{11}$$

where D_{sig} is the significant duration – D_{s5-75} or D_{s5-95}; M is the moment magnitude; R is the hypocentral distance; S is the site condition, where $S=0$ for rock sites and $S=1$ for soil sites; and C_1, C_2, C_3, C_4, C_5, and C_6 are the regression coefficients.

For determining the coefficients corresponding to log(D_{sig}+1), the proposed model given by Eq. (11) was rewritten from its original form by taking the exponential and subtracting 1 from both sides of the original equation, i.e., $D_{sig} = 10^{\left[\log\left(D_{sig}+1\right)\right]}-1$. The results from the NLME regression analyses of the significant duration dataset for both log(D_{sig}+1) and log(D_{sig}) are given in Table 1. The regressions of both the D_{s5-75} and D_{s5-95} data were performed in two stages. For the first stage, the significant duration data were regressed using Eq. (11) as mentioned above. However, several regression coefficients were determined to have no statistical significance, as per the p value for the likelihood ratio test (Pinheiro and Bates 2000). Therefore, a second round of regressions was performed, in which the statistically insignificant regression coefficients were removed. The statistically insignificant coefficients are simply listed as "zero" in Table 1, instead of rewriting the regression equation for both D_{s5-75} and D_{s5-95}. This allows only one model to be used for both D_{s5-75} and D_{s5-95} predictive relationships. Figure 9 shows the Q-Q plots of the standard errors from the regression analyses. As shown in the figure, the errors follow normal distributions, consistent with the assumptions inherent to NLME modeling. Similarly, the residuals for the recorded ground motions for intraplate are shown in Fig. 10 as a function of distance and magnitude. It is evident from Fig. 10 that barring a few data points, the residuals are within model ± one standard deviation range in natural log, representing that the model predictions are in general in accordance with the data. In addition, the residuals do not form a trend either with magnitude and or with distance, which is suggestive of the model being fit. However, it can also be observed from Fig. 10 that residual for log(D_{sig}+1) is less as compared to log (D_{sig}); hence, it is recommended that coefficients corresponding to log (D_{sig}+1) need to be used for calculating the duration for intraplate region.

Using Eq. (11) and the regression coefficients listed in Table 1, D_{s5-75} and D_{s5-95} for intraplate regions are plotted in Fig. 11 as functions of hypocentral distance for M4.5, M5.5, and M6.5 for rock and soil sites. The significant durations for intraplate region increase with increasing hypocentral distance and increasing magnitude, which is in harmony with the findings of Abrahamson and Silva (1996) and Kempton and Stewart (2006) for interplate regions

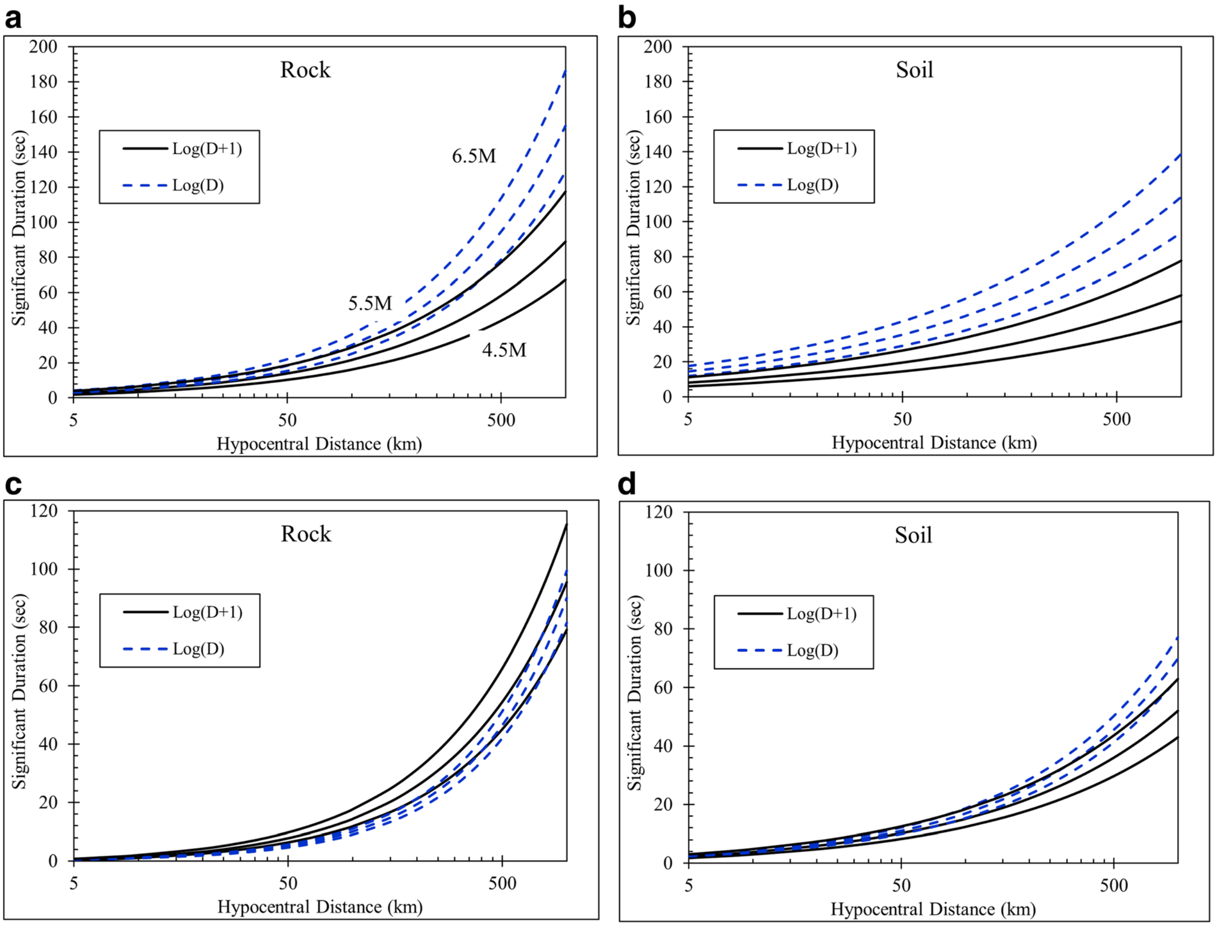


Fig. 11 D_{s5-95} for **a** rock site and **b** soil site and D_{s5-75} for **c** rock site and **d** soil site

and also with Lee and Green (2014) for intraplate regions. Dissimilar to the trends observed for interplate regions, the significant durations for intraplate regions for rock sites tend to be a little longer than those for soil sites, except for the small earthquake magnitude (i.e., $M4.5$) and D_{s5-75} measure of significant duration. Another observation from Fig. 11 is that the soil sites have a higher duration for shorter distance compared to the wreck sites. This could be because of high-frequency content for intraplate region being significantly filter out as the ground motions propagate though the soil stratum. The same trend was observed for bracketed durations as well. The reason may be the same as mentioned earlier in the paper. The durations for rock sites for D_{s5-95} are consistently longer than rock durations forD_{s5-75}. Similar observation is also noticed for the soil sites.

5 Comparison with existing relationships

The bracketed duration relation proposed herein is compared with the relationships proposed by Koutrakis et al. (2002) and Lee and Green (2012). Koutrakis et al. (2002) derived their relation using Greek strong motion data, which comprised of 93 seismic events and 141 accelerograms covering magnitudes between 4.5 to 6.9 and distances from 1 to 128 km. They used multi-linear regression analysis technique (i.e., least squares method) as their regression methodology. The distance considered by them is epicentral distance, since, for most of the cases, fault rupture was not adequately determined. Moreover, due to the uncertainty in the focal depth determination, the application of the hypocentral distance was avoided. Also, they did not consider the soil condition parameter at the recording site as one of the independent variables. In contrast to Koutrakis et al.

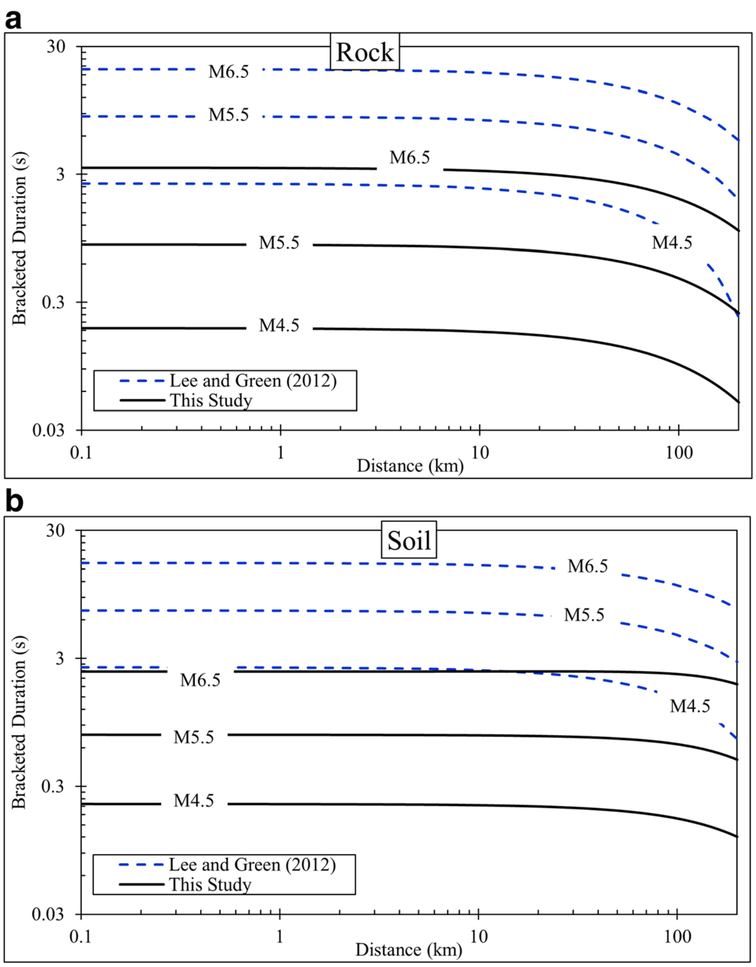
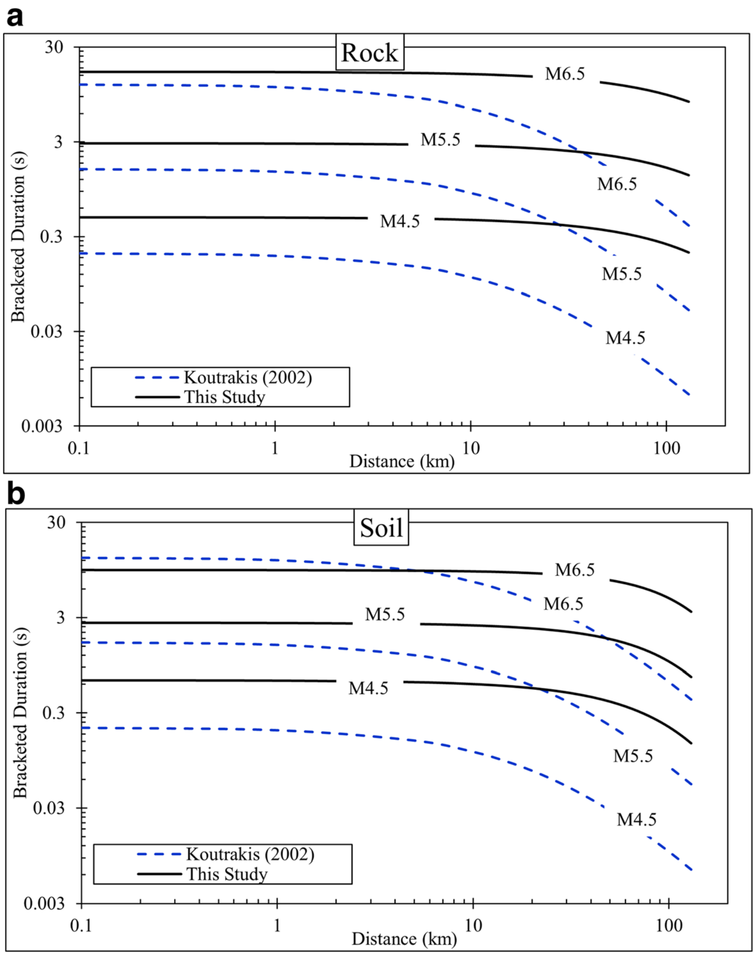


Fig. 12 Comparison of $D_{b,\,0.05g}$ between this study and Lee and Green (2012) model for intraplate regions for **a** rock site and **b** soil site

Fig. 13 Comparison of $D_{b,0.05g}$ between this study and Koutrakis et al. (2002) model for Greece for **a** rock site and **b** soil site. The distance on x axis is the epicentral distance from the fault and varies from 0.1 to 128 km. The depth of the rupture for M4.5 is 10.37 km, for M5.5 is 16.72 km, and for M6.5 is 27 km



(2002), the Lee and Green (2012) relationship was developed for stable continental regions of North America using the NLME regression method on the data from the NGA database. The dataset considered by them comprised of 28 recorded motions and 592 scaled motions. Zero duration was also considered by conducting logistic regression to model the probability of its occurrence. However, their relation is only applicable for a threshold acceleration of 0.05g. This limits the comparison of Lee and Green's (2012) relation to be made only to the $D_{b,0.05g}$ measure of bracketed duration of the present study. On the other hand, $D_{b,0.03g}$ measure of bracketed duration has been compared with the relationship proposed by Koutrakis et al. (2002). The comparisons are hampered by the use of different parameter definitions in the model proposed by Koutrakis et al. (2002); therefore, adjustments are made for magnitude scales using the conversion of Ambraseys and Free (1997) (for converting M_S values to M_w). Figures 11 and 12 show the comparison of bracketed duration relationships. Considerable differences exist between the predictions from this study and from Lee and Green (2012) and Koutrakis et al. (2002). This is likely due to Koutrakis et al. (2002) not considering the difference between the rock and soil sites in their analysis; not fully accounting for zero-duration motions; and using least squares method for regression analysis, wherein the results are disproportionately influenced by the number of records in an earthquake event. This conclusion is further supported by the fact that similar were reported in Bommer et al. (2009). Bommer et al. (2009) compared the empirical relationships for strong motion duration with those in Koutrakis et al. (2002). Also, the dissimilarity might be because of differences in the database used by Lee and Green (2012) and this study. Lee and Green (2012) database have almost all the records scaled from active crustal regions. The present study used only the recorded ground motion data

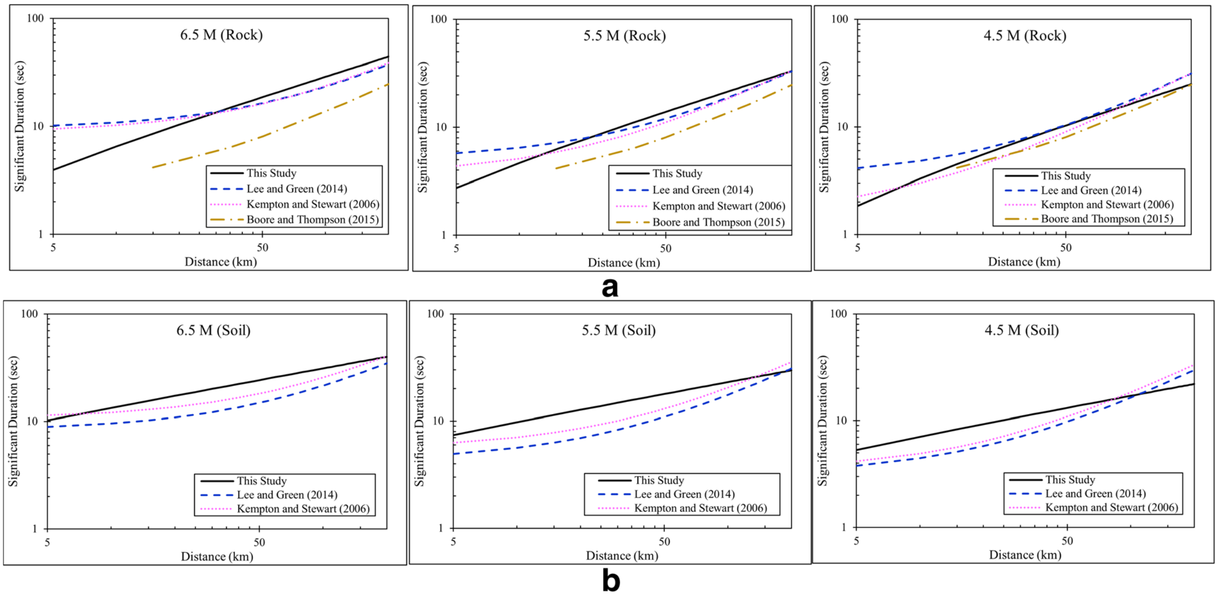


Fig. 14 Comparison of D_{s5-95} between this study and Kempton and Stewart (2006) and Lee and Green (2014) for **a** rock site and **b** soil site

from intraplate region. Overall, Lee and Green (2012) relationship predict significantly higher bracketed durations than the model developed in this study. It is also noted that $D_{b,0.03g}$ of this study and Koutrakis et al. (2002) prediction for M6.5 and M5.5 for rock site are relatively close (Fig. 13).

Significant duration relationships proposed herein for two measures (D_{s5-75} and D_{s5-95}) are compared with relationships proposed by Kempton and Stewart (2006) and Lee and Green (2014). Both of these relationships were developed using NLME regression analyses. The relationship proposed by Kempton and Stewart (2006) is for active crustal regions (e.g., western North America (WNA)), whereas the relationship proposed by Lee and Green (2014) is for stable continental regions. Kempton and Stewart's "base" model was developed using data from 1557 recordings from 73 shallow

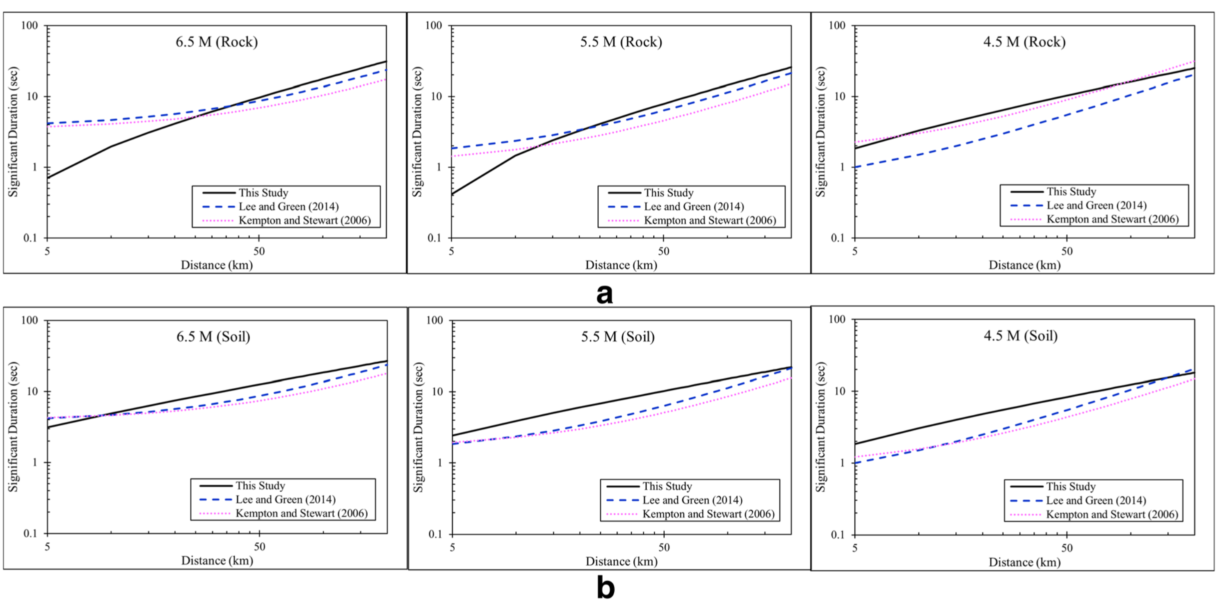


Fig. 15 Comparison of D_{s5-75} between this study and Kempton and Stewart (2006) and Lee and Green (2014) for **a** rock site and **b** soil site

Table 1 Coefficients of the predictive durations developed in this study

		C_1	C_2	C_3	C_4	C_5	C_6	τ	σ	σ_{total}
$D_{b,0.03g}$	Geo-mean	−1.43 ± 0.52	1.54 ± 0.12	−0.005 ± 0.0008	1.27 ± 1.41	−0.64 ± 0.37	0.007 ± 0.008	0.62	0.52	0.81
	Maximum	−1.26 ± 0.44	1.56 ± 0.12	−0.005 ± 0.0008	1.02 ± 1.30	−0.63 ± 0.37	0.008 ± 0.012	0.61	0.48	0.78
	Both	−1.14 ± 0.33	1.62 ± 0.09	−0.005 ± 0.0008	1.36 ± 0.88	−0.67 ± 0.25	0.009 ± 0.004	0.51	0.44	0.68
$D_{b,0.05g}$	Geo-mean	−1.43 ± 0.67	1.44 ± 0.15	−0.005 ± 0.0008	1.36 ± 1.64	−0.66 ± 0.43	0.007 ± 0.006	0.73	0.56	0.92
	Maximum	−1.25 ± 0.57	1.37 ± 0.15	−0.005 ± 0.0008	1.03 ± 1.48	−0.49 ± 0.42	0.011 ± 0.012	0.72	0.54	0.90
	Both	−1.60 ± 0.43	1.21 ± 0.11	−0.005 ± 0.0008	1.15 ± 1.03	−0.44 ± 0.29	0.009 ± 0.006	0.68	0.51	0.85
D_{s5-95}	Geo-mean	−0.176 ± 0.11	0.04 ± 0.02	0.724 ± 0.032	0.78 ± .32	0.007 ± 0.05	−0.29 ± 0.11	0.15	0.28	0.32
	Maximum	−0.110 ± 0.13	0.03 ± 0.03	0.694 ± 0.042	0.05 ± .36	0.005 ± 0.07	−0.013 ± 0.12	0.24	0.32	0.40
	Both	−0.061 ± 0.08	0.08 ± 0.02	0.712 ± 0.032	0.82 ± .32	0.005 ± 0.05	−0.32 ± 0.11	0.17	0.22	0.28
$D_{s5-95}+1$	Geo-mean	0.001 ± 0.09	0.052 ± 0.02	0.662 ± 0.02	0.71 ± 0.29	0.008 ± 0.05	−0.26 ± 0.11	0.13	0.27	0.30
	Maximum	−0.036 ± 0.11	0.098 ± 0.02	0.692 ± 0.03	0.52 ± 0.29	0.004 ± 0.05	−0.21 ± 0.11	0.13	0.29	0.32
	Both	−0.026 ± 0.11	0.121 ± 0.02	0.601 ± 0.03	0.56 ± 0.29	0.005 ± 0.05	−0.25 ± 0.11	0.16	0.19	0.25
D_{s5-75}	Geo-mean	−1.146 ± 0.12	0.006 ± 0.02	0.982 ± 0.03	1.06 ± 0.29	0.00 ± 0.00	−0.38 ± 0.09	0.24	0.30	0.39
	Maximum	−1.001 ± 0.11	0.033 ± 0.02	0.966 ± 0.03	0.51 ± 0.31	0.00 ± 0.00	−0.21 ± 0.11	0.20	0.26	0.34
	Both	−0.975 ± 0.11	0.043 ± 0.02	0.955 ± 0.03	0.91 ± 0.29	0.00 ± 0.00	−0.34 ± 0.09	0.19	0.26	0.33
$D_{s5-75}+1$	Geo-mean	−1.146 ± 0.12	0.006 ± 0.02	0.982 ± 0.03	1.06 ± 0.29	0.00 ± 0.00	−0.38 ± 0.09	0.24	0.30	0.39
	Maximum	−0.516 ± 0.11	0.075 ± 0.02	0.791 ± 0.03	0.57 ± 0.31	0.00 ± 0.00	−0.23 ± 0.11	0.17	0.19	0.26
	Both	−0.528 ± 0.08	0.081 ± 0.02	0.797 ± 0.03	0.58 ± 0.29	0.00 ± 0.00	−0.28 ± 0.11	0.19	0.19	0.27

The plus and minus values define the 95% confidence interval for each parameter

Table 2 Coefficients of the logistic regression for weighting functions

	Site	β_1	β_2	β_3
$D_{b,0.03g}$	Rock	2.45	−0.70	0.004
	Soil	3.12	−0.69	0.018
$D_{b,0.05g}$	Rock	4.27	−0.72	0.003
	Soil	4.25	−0.68	0.008

crustal earthquakes, which covered a magnitude range of ≈5–7.6 and closest hypocentral distance range of ≈0–200 km. They expanded their base model by adding several terms that incorporate near-fault directivity and deep basin effects. The local site conditions were represented via the average shear wave velocity in the upper 30 m (V_{s30}) of a profile, instead of using site classification. On the other hand, Lee and Green (2014) developed their relation from 620 horizontal motions for stable continental regions (e.g., central and eastern North America (CENA)), which comprised of 28 recorded motions and 592 scaled WNA motions for CENA conditions. The moment magnitude for these motions range from 4.5 to 7.6, and hypocentral distances range from 0.1 to 199.1 km. In Figs. 14 and 15, the new model for significant durations is shown for various combinations of magnitude and distance and compared with those from Kempton and Stewart (2006), Lee and Green (2014), and Boore and Thompson (2015). The predictions of this study are lower until a certain hypocentral distance and after the predictions become higher compared to the previous studies. This is true for all the magnitudes of earthquake considered in the study for rock sites and is clearly evident in the case of small-magnitude earthquake event (M6.5). However, for the case of small-magnitude earthquake event (M4.5), this trend is not visibly distinct and one could argue that the prediction is roughly similar. However, in case of soil sites for small-magnitude earthquake event (M4.5), reverse can be seen from Figs. 14 and 15. Figure 14a shows the comparison of estimated significant duration from proposed predictive relation with Boore and Thompson (2015) path duration for rock and very hard rock sites of stable continental regions. It is seen in Fig. 14a that for rock sites, predicted durations are slightly higher than Boore and Thompson (2015). This difference may be due to type of duration, Boore and Thompson (2015) given path duration, which is effective duration $\left(D'_{95}\right)$ minus source duration. Hence, path duration given by Boore and Thompson (2015) is lower than significant duration proposed in this study.

6 Conclusions

In this study, new predictive equations for the bracketed duration ($D_{b,0.03g}$ and $D_{b,0.05g}$) and significant duration (D_{s5-75} and D_{s5-95}) have been developed for the intraplate regions based on the recorded intraplate earthquake ground motions. None of the existing relationships for ground motion duration, to the best of the author's knowledge, were developed using only recorded intraplate motions. The best functional form is developed based on dividing the residual into intraevent and interevent residuals. The models presented in this study are based on mixed-effect regression on the residuals determined from the functional forms available in the literature. The models include magnitude, hypocentral distance, and site condition. The database used consists of 75 recorded intraplate earthquakes, 600 horizontal ground motion records with moment magnitudes ranging from 3.0 to 6.5 and hypocentral distance from 4 to 1000 km. Similar to the findings of previous studies, the bracketed durations were predicted to decrease with increasing distance but predicted to increase significantly with increasing magnitude. When compared with the existing relationships, the new models predicted noticeably lower bracketed durations for both rock and soil sites. Again, the significant durations were also predicted to follow trends proposed by previous studies; i.e., significant durations increase with increasing hypocentral distance and magnitude. In contrast to trends observed for interplate regions, the significant durations for intraplate regions for rock sites were found to be a little higher than those for soil sites, except for the small earthquake magnitude (i.e., M4.5) and D_{s5-75} measure of significant duration. While comparing significant duration relation proposed herein with the existing relations, the models presented in this study predicted lower durations for both rock and soil sites initially, but after a certain hypocentral distance predicted higher durations. Quantitatively, the relationships proposed herein and the ones published previously differ significantly, while qualitatively, they are similar in some respects.

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