PREDICTIVE RELATIONS FOR SIGNIFICANT DURATIONS IN STABLE CONTINENTAL REGIONS

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ABSTRACT:
Empirical relationships relating ground motion characteristics to earthquake magnitude, site-to-source distance, tectonic setting, and site classification are commonly used in seismic hazard analyses and in seismic design. However, few such predictive relationships have been developed for stable continental regions. In this paper, ground motion parameter predictive relationships for significant durations (i.e., $D_{5\text{-}75}$ and $D_{5\text{-}95}$) are proposed for stable continental regions. The relationships were developed using an up-to-date ground motion database and non-linear mixed-effects regression techniques. The ground motion database consisted of total 620 motions: 28 recorded motions and 592 scaled motions. The latter were scaled using response spectral transfer functions based on a single-corner, point source models (e.g., McGuire et al., 2001; Boore, 1983; Silva and Lee, 1987). The predictive relations for the stable continental regions are compared to the predictive relations similarly developed for active tectonic regions. The comparison showed that the motions in stable continental regions have longer durations at rock sites than those in active seismic regions. However, for soil sites, there was relatively little difference in the significant durations between the two regions.

KEYWORDS:
Strong motion duration, significant duration, attenuation relations, predictive equation, stable continental region

1. INTRODUCTION

Strong ground motion duration is an important parameter used in seismic risk assessment because it, along with the amplitude and frequency content of the ground motions, significantly influences the response of the geotechnical and structural systems. For example, Bommer and Martinez-Pereira (1999) found that when non-linear behavior of the geotechnical and structural systems is considered, strong motion duration directly relates to damage potential of the ground motion. In this vein, various definitions of duration have been proposed for quantifying the strong motion phase of earthquake ground motions, which is the portion of the motion that is of engineering interest. Of the various definitions, significant duration is the most frequently used by engineering seismologists and earthquake engineers and is based on the normalized cumulative squared acceleration:

$$H(t) = \frac{\int_0^{t} \left[a(t)\right]^2 dt}{\int_0^{t_{dur}} \left[a(t)\right]^2 dt} \tag{1.1}$$

where: $a(t)$ is acceleration time history; and t_{dur} is the total duration of the acceleration time history. As may be surmised from this equation, the normalized cumulative squared acceleration ($H(t)$) varies from 0 to 1, or 0% to 100%. Significant duration is most often defined as the time intervals between $H(t)$ = 5% and 75% ($D_{5\text{-}75}$) or $H(t)$ = 5% and 95% ($D_{5\text{-}95}$). Figure 1 is a plot of a ground motion recorded during the 1989 Loma Prieta earthquake. Also shown in this figure is a plot of $H(t)$, known as Husid plot (Husid, 1969), and the $D_{5\text{-}75}$ and $D_{5\text{-}95}$ durations.

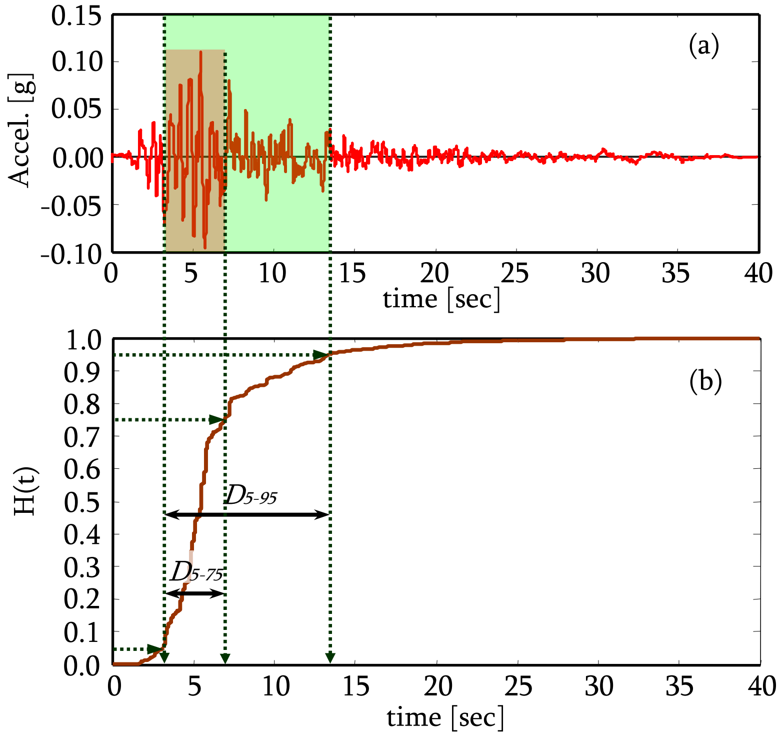

Figure 1. Significant duration determination using Husid plot: (a) acceleration time history of 1989 Loma Prieta earthquake; (b) the corresponding Husid plot

For engineering use, numerous predictive relationships have been proposed for significant durations (e.g., Trifunac and Brady, 1975; Dobry et al., 1978; McGuire and Barnhard, 1979; Kamiyama, 1984; Abrahamson and Silva, 1996; Kempton and Stewart, 2006). However, these relationships were developed for active seismic regions, and thus, do not necessarily apply to stable continental regions. In this paper, predictive relationships for significant durations (i.e., $D_{5\text{-}75}$ and $D_{5\text{-}95}$) for stable continental regions are proposed. The relationships relate the significant durations to earthquake magnitude, site-to-source distance, and local site conditions (i.e., rock vs. stiff soil). These relations were developed by performing non-linear mixed-effects regression analyses on data derived from 620 horizontal motions for stable continental regions, consisting of 28 recorded motions and 592 scaled motions. Additionally, the significant duration predictive relations proposed herein for stable continental regions are compared to those proposed by Kempton and Stewart (2006) and to relations developed by the authors for active seismic regions, where the latter relations were developed by the authors from data from 648 horizontal motion recordings from 49 earthquakes in active seismic regions.

2. STRONG GROUND MOTION DATASET

As mentioned above, 620 recorded and scaled stable continental region horizontal motions and 648 recorded active seismic region horizontal motions were used in this study to develop the predictive equations for the significant durations. The ground motions came from a database assembled by McGuire et al. (2001). Of stable continental region motions, 28 motions were recorded and 592 were "scaled" from active seismic regions. The motions were scaled using response spectral transfer functions that relate active seismic region motions to corresponding stable continental region motions (i.e., same magnitude, site-to-source distance, and local site conditions). The transfer functions were based on a single-corner, point source model (e.g., McGuire et al., 2001; Boore, 1983; Silva and Lee, 1987).

McGuire et al. (2001) grouped the motions according to the local site conditions of the recording seismograph stations. Motions recorded on profiles having an average shear wave velocity for the upper 30 m greater than 360 m/sec were classified as "rock" motions. The remaining motions (i.e., motions recorded on profiles having an average shear wave velocity for the upper 30 m less than 360 m/sec) were designated as "soil" motions. The rock and soil motions were further subdivided into ten bins according to moment magnitude (M) and the. The earthquake magnitude and site-to-source distance distributions (i.e., moment magnitude, M, vs. closest distance to the fault, R) of the strong motion dataset are shown in Figure 2.

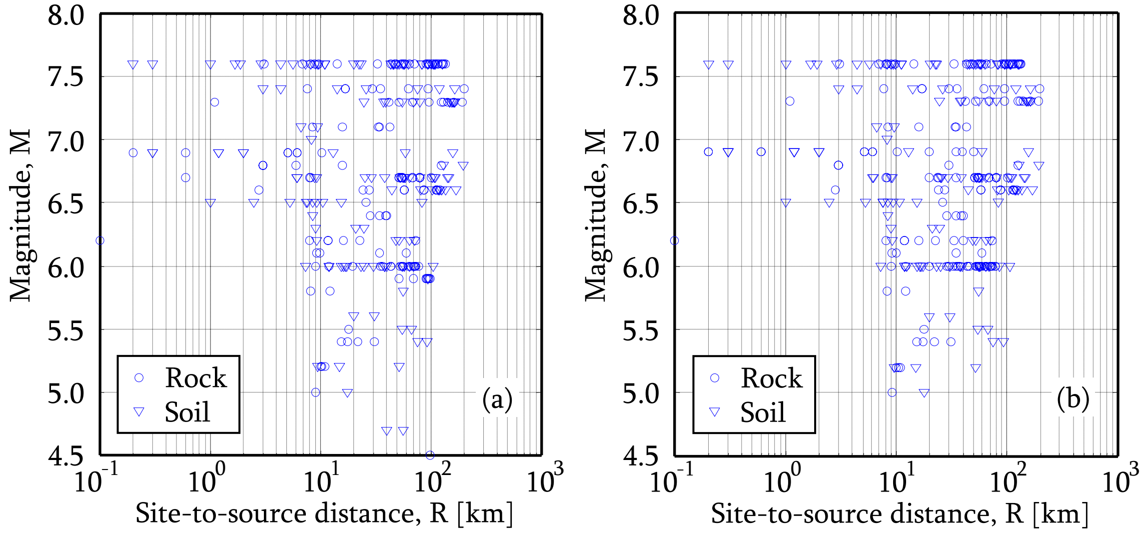

Figure 2. Earthquake magnitude and site-to-source distance distributions of strong ground motion dataset: (a) stable continental region; (b) active seismic region

3. NON-LINEAR MIXED-EFFECTS MODELING

Non-linear mixed-effects modeling is a powerful technique to regress data consisting of multiple "groups." In this study, a group of motions represents those from the same earthquake. In more traditional regression techniques (e.g., least-squares method), the entire dataset is regressed at once. However, because the dataset is composed of motions from different earthquakes, with the number of recordings from each event varying, the resulting regression is unduly influenced by the earthquake having the largest number of motions. Also, as opposed to regressing the entire dataset at once, non-linear mixed-effects regression analyses allow both inter- and intra-group uncertainty to be quantified. The inter-group (or inter-event) error is designated by η_i where the subscript i represents the i^{th} event (i.e., group) and has mean of zero and variance of τ^2. The intra-group (or intra-event) error is designated by ε_{ij} where the subscripts ij indicates the j^{th} record of the i^{th} event and has a mean of zero and variance of σ^2. The standard deviation of the total error can be determined by Eqn. 3.1.

$$\sigma_{total} = \sqrt{\tau^2 + \sigma^2} \tag{3.1}$$

where, σ_{total} is the standard deviation of total error.

There are two assumptions inherent in the non-linear mixed-effects modeling (Pinheiro and Bates, 2000):

1. The intra-event errors are independent and normally distributed, with a mean of zero and variance σ^2, and they are independent of the random effects.

2. The random effects are normally distributed, with a mean of zero and covariance matrix Ψ (not depending on the group), and they are independent for different groups.

Quantile-Quantile (Q-Q) plots, which are analogous to probability paper, are used to assess the validity of these distributional assumptions. All the nonlinear mixed-effects regression analyses were performed using the statistical data analysis program, R (version 2.5.0).

4. RESULTS

4.1. Predictive Equation

The functional form of the predictive relations used in this study was one modified from those proposed by Abrahamson and Silva (1996) and Kempton and Stewart (2006), which in turn were based on the seismic source duration relation (Hanks, 1979; McGuire and Hanks, 1980) and the seismic source model of Brune (1970, 1971). Assuming a lognormal distribution of significant duration data and considering the dependence of site-to-source distance and local site conditions, the functional form for the predictive relations for both $D_{5\text{-}75}$ and $D_{5\text{-}95}$ used in this study is:

$$\ln D_{5-75} \text{ or } \ln D_{5-95} = \ln\{C_1 + C_2 \exp(M-6) + C_3 R + (S_1 + S_2(M-6) + S_3 R)S\} \qquad (4.1)$$

where, C_1, C_2, C_3, S_1, S_2, and S_3 are regression coefficients; M is magnitude; R is the site-to source distance in km; and S is a binary parameter representing the local site condition (i.e., $S = 0$ for rock sites; $S = 1$ for stiff soil sites). It should be noted that the functional form of Eqn. 4.1 resulted in a lower standard deviation than the forms proposed by Abrahamson and Silva (1996) and Kempton and Stewart (2006), as well as several other forms used by the authors.

4.2. Regression Result

Non-linear mixed-effects regressions were performed using Eqn. 4.1 on the datasets for both stable continental regions and active seismic regions. The regressions of the $D_{5\text{-}75}$ data were performed in two stages. For the first stage, the data were regressed using Eqn. 4.1 as presented above. However, several regression coefficients in this equation were determined to have no statistical significance, per the p-value for the likelihood ratio test (Pinheiro and Bates, 2000). Thus, a second round of regressions was performed where the statistically insignificant regression coefficients were removed. The regressions of the $D_{5\text{-}95}$ only required one stage, as all the regression coefficients were statistically significant. The resulting regression coefficients and standard deviations are tabulated in Table 1. Note that instead of rewriting the $D_{5\text{-}75}$ regression equation with the statistically insignificant coefficients removed, these coefficients are simply listed as “zero” in Table 1. This allows one model (i.e., Eqn. 4.1) to be used for both $D_{5\text{-}75}$ and $D_{5\text{-}95}$ predictive relations. Additionally, due to the absence of the data in the regressed datasets, the regression coefficients presented in Table 1 may not be valid for $R \leq 8.2$ km in stable continental regions and for $R \leq 7.3$ km where $M \leq 6$ in active seismic regions.

Table 1 Regression coefficient values

Stable continental region									
	C_1	C_2	C_3	S_1	S_2	S_3	τ	σ	σ_{total}
$D_{5\text{-}75}$	0.00	2.23	0.10	-0.72	-0.19	-0.0145	0.46	0.35	0.58
$D_{5\text{-}95}$	2.50	4.21	0.14	-0.98	-0.45	-0.0071	0.37	0.32	0.49
Active seismic region									
	C_1	C_2	C_3	S_1	S_2	S_3	τ	σ	σ_{total}
$D_{5\text{-}75}$	0.00	1.86	0.06	0.22	0.00	0.0000	0.28	0.37	0.46
$D_{5\text{-}95}$	1.50	3.22	0.11	2.01	0.80	-0.0097	0.26	0.28	0.38

As stated above, there are inherent assumptions in non-linear mixed-effects modeling that the intra-event errors and random effects are normally distributed. To test these assumptions, Q-Q plots of the intra-event errors and the random effects were made. For example, Figure 3 shows the Q-Q plots of the intra-event errors and the random effects from the regression of the $D_{5\text{-}75}$ data for stable continental regions. As may be observed from this figure, the Q-Q plots are relatively straight lines, indicating that the distributional assumptions inherent to the mixed-effects analyses are valid. Plots of the $D_{5\text{-}75}$ data for active seismic regions and plots of the $D_{5\text{-}95}$ data for both stable continental and active seismic regions resulted in the same findings.

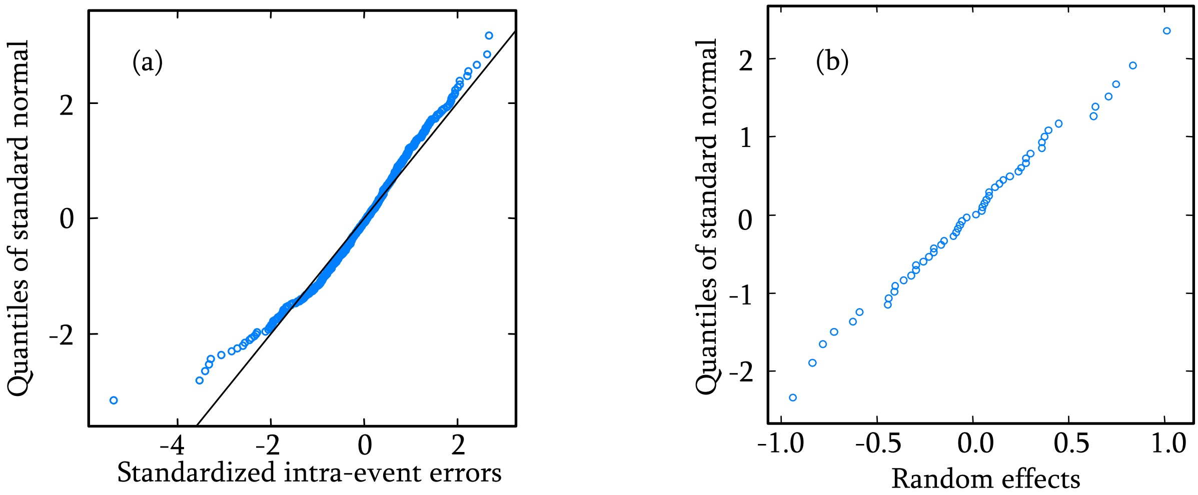

Figure 3. Q-Q plots for $D_{5\text{-}75}$ data for stable continental regions: (a) intra-event errors, and (b) random effects. Note: The standardized intra-event errors are the intra-event errors minus their mean (i.e., zero) and divided by their standard deviation (i.e., σ).

4.3. Result Comparison

Using Eqn. 4.1 and the regression coefficients listed in Table 1, $D_{5\text{-}75}$ and $D_{5\text{-}95}$ for stable continental regions are plotted in Figure 4 as functions of site-to-source distance for M5.5, M6.5, and M7.5 for rock sites and stiff soil sites. As found by others for active seismic regions (e.g., Abrahamson and Silva, 1996; Kempton and Stewart, 2006), it may be clearly seen in this figure that the significant durations for stable continental regions increases with increasing site-to-source distance and increasing magnitude. However, contrary to trends observed by others for active seismic regions, the significant durations for stable continental region motions for rock sites tended to be slightly longer than those for soil sites. Additional analyses are currently being performed to better understand these opposing trends.

To identify differences in $D_{5\text{-}75}$ and $D_{5\text{-}95}$ for stable continental versus active seismic regions, comparison plots of the Eqn. 4.1 using the regression coefficients listed in Table 1 for both stable continental and active seismic regions and the predictive relation proposed by Kempton and Stewart (2006) are shown in Figure 5. Comparing this study's relations, the significant durations for rock motions in stable continental regions are consistently longer than rock motions in active seismic regions. This trend is also observed for stiff soil motions where $R \geq$ ~20 km, but the differences in the durations is relatively small. Comparing the relations proposed herein for stable continental regions with that proposed by Kempton and Stewart (2006) for active seismic regions, the stiff soil motions in stable continental regions have shorter significant durations than those in active seismic regions. On the other hand, for rock sites and large magnitudes (i.e., M > ~6.5), the durations in stable continental and active seismic regions tend to be quite similar to each other. Additional analyses are currently being performed to better understand these trends.

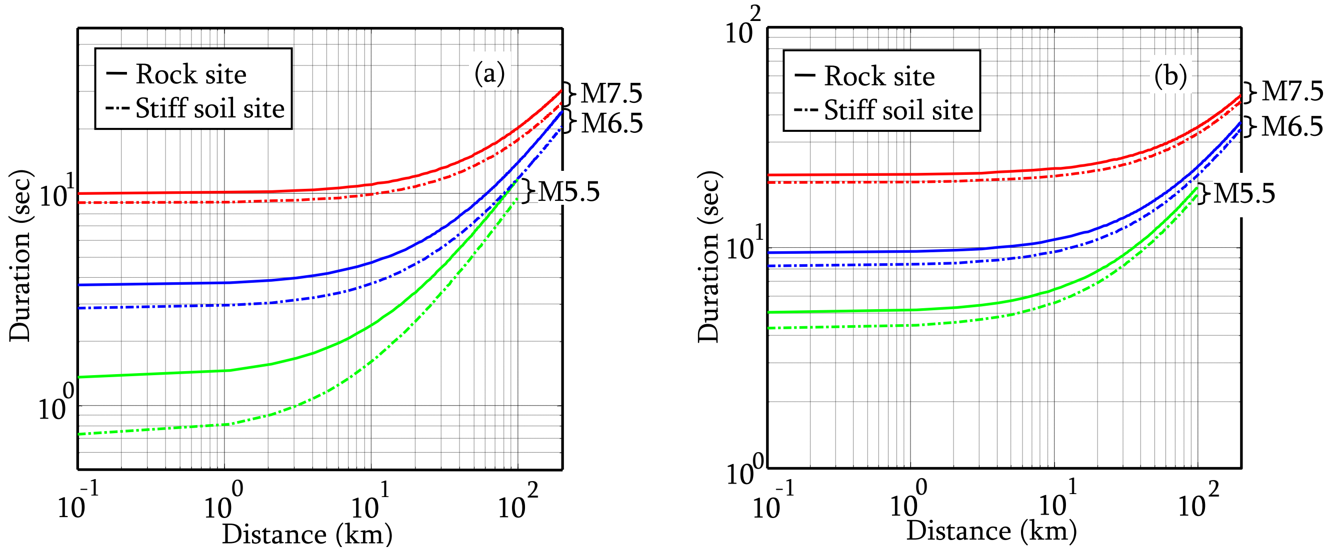

Figure 4. Predicted significant durations for stable continental regions: (a) $D_{5\text{-}75}$; (b) $D_{5\text{-}95}$

5. CONCLUSIONS

New predictive relations for $D_{5\text{-}75}$ and $D_{5\text{-}95}$ are proposed herein for stable continental region motions. In comparison with relations developed by the authors for active seismic region motions, rock motions in stable continental regions have longer durations. A similar trend is noted for stiff soil sites for distances greater than ~20 km, but the differences in the durations is not as significant as it is for rock motions. In comparison with the durations predicted by the relations proposed by Kempton and Stewart (2006) for active seismic regions, the motions in stable continental regions have shorter significant durations at stiff soil sites, while rock motions for large magnitude events (i.e., $M \geq$ ~6.5) in stable continental and active seismic regions have similar durations.

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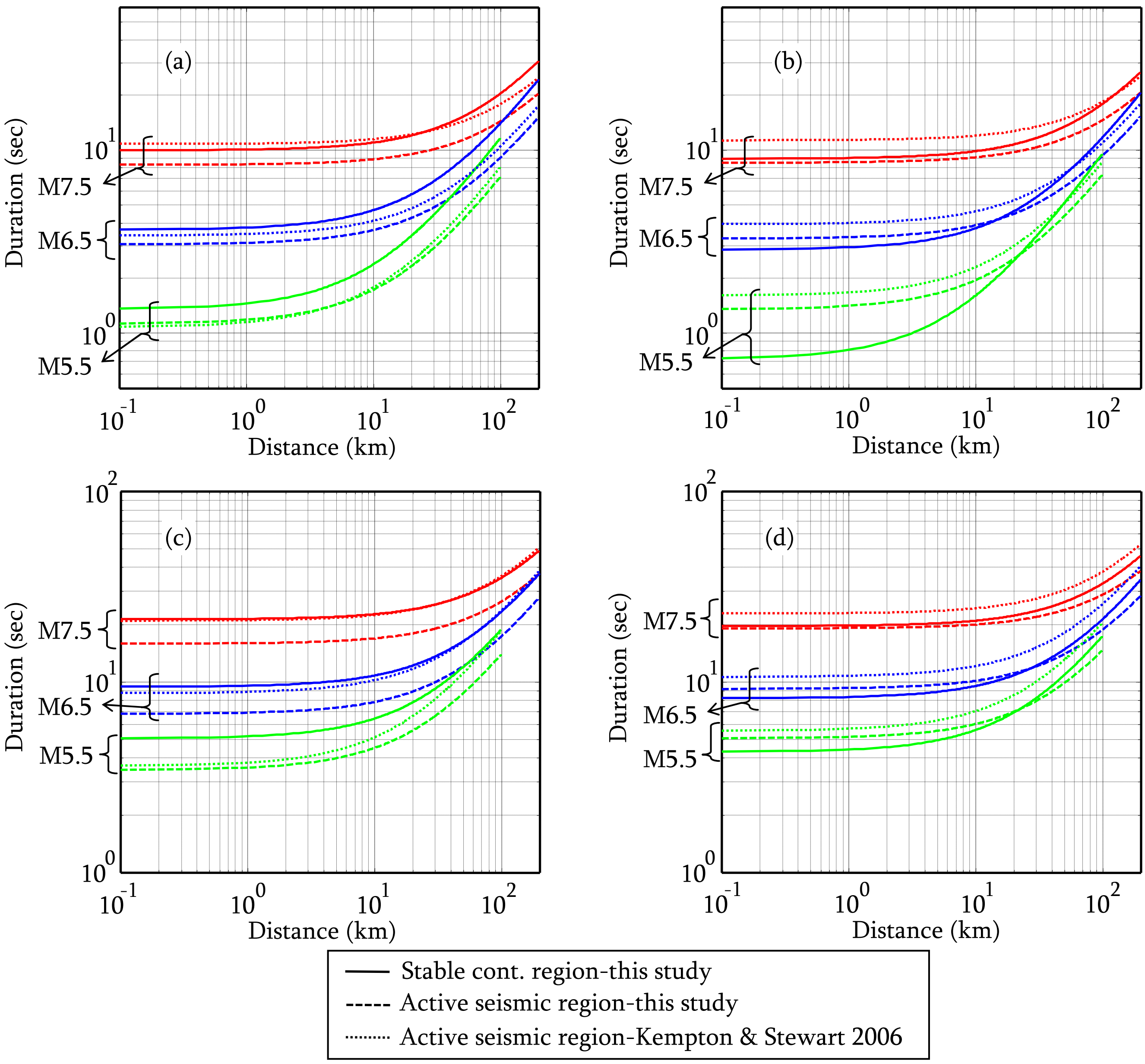

Figure 5. Comparison of significant durations in stable continental and active seismic regions: (a) $D_{5\text{-}75}$ – rock site; (b) $D_{5\text{-}75}$ – stiff soil site; (c) $D_{5\text{-}95}$ – rock site; and (d) $D_{5\text{-}95}$ – stiff soil site

REFERENCES

Abrahamson, N.A. and Silva, W.J. (1996). Empirical Ground Motion Models. Report, Brookhaven National Laboratory,

Bommer, J.J. and Martinez-Pereira, A. (1999). The Effective Duration of Earthquake Strong Motion. *Journal of Earthquake Engineering* **3:2**, 127-172.

Boore, D.M. (1983). Stochastic Simulation of High-Frequency Ground Motions Based on Seismological Models of the Radiated Spectra. *Bulletin of the Seismological Society of America* **73:6A**, 1865-1894.

Brune, J.N. (1970). Tectonic Stress and Spectra of Seismic Shear Waves from Earthquakes. *Journal of Geophysical Research* **75:26**, 611-614.

Brune, J.N. (1971). Correction. *Journal of Geophysical Research* **76:20**, 1441-1450.

Dobry, R., Idriss, I.M. and Ng, E. (1978). Duration Characteristics of Horizontal Components of Strong-Motion Earthquake Records. *Bulletin of the Seismological Society of America* **68:5**, 1487-1520.

Hanks, T.C. (1979). b-Values and Omega-Gamma Seismic Source Models - Implications for Tectonic Stress Variations Along Active Crustal Fault Zones and the Estimation of High-Frequency Strong Ground Motion. *Journal of Geophysical Research* **84:NB5**, 2235-2242.

Husid, L.R. (1969). Caracteristicas de Terremotos. Analisis General. *Revista del IDIEM 8*, Santiago de Chile, 21-42.

Kamiyama, M. (1984). Effects of Subsoil Conditions and Other Factors on the Duration of Earthquake Ground Shaking. *Proc. Eighth World Conference on Earthquake Engineering*, San Francisco, CA, **2**, 793-800.

Kempton, J.J. and Stewart, J.P. (2006). Prediction Equations for Significant Duration of Earthquake Ground Motions Considering Site and Near-Source Effects. *Earthquake Spectra* **22:4**, 985-1013.

McGuire, R.K. and Barnhard, T.P. (1979). The Usefulness of Ground Motion Duration in Prediction of Severity of Seismic Shaking. *Proc. Second US National Conference on Earthquake Engineering*, Stanford, CA, 713-722.

McGuire, R.K. and Hanks, T.C. (1980). RMS Accelerations and Spectral Amplitudes of Strong Ground Motion During the San Fernando, California Earthquake. *Bulletin of the Seismological Society of America* **70:5**, 1907-1919.

McGuire, R.K., Silva, W.J. and Costantino, C.J. (2001). Technical Basis for Revision of Regulatory Guidance on Design Ground Motions: Hazard-and-Risk-Consistent Ground Motion Spectra Guidelines. NUREG/CR-6728, US Nuclear Regulatory Commission, Washington, DC.

Pinheiro, J.C. and Bates, D.M. (2000). Mixed-Effects Models in S and S-PLUS, Springer, New York.

Silva, W.J. and Lee, K. (1987). WES RASCAL Code for Synthesizing Earthquake Ground Motions: State-of-the-art for Assessing Earthquake Hazards in the United States. Report 24, S-73-1, US Army Engineering Waterways Experiment Station Vicksburg, MS.

Trifunac, M.D. and Brady, A.G. (1975). Study on Duration of Strong Earthquake Ground Motion. *Bulletin of the Seismological Society of America* **65:3**, 581-626.