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Strong Ground Motion Durations of Directivity Motions

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ABSTRACT

The objective of this study is to develop an empirical strong motion duration relationship for directivity pulselike motions. Directivity effects are the near-fault effects characterized by a pronounced two-sided velocity pulse that may cause significant damages to geotechnical/structural systems. This study develops empirical strong motion duration model for directivity motions using the non-linear mixed-effects regression method and a total of 142 directivity records from the NGA-West2 strong ground motion database. The empirical models were developed for orientation-independent significant durations and durations in the strongest pulse direction as a function of earthquake magnitude, site-to-source distance, pulse period and site V_{S30}. The regression results show that the significant durations of directivity pulselike motions increase with increasing pulse periods, and are generally shorter than those of non-pulse motions especially for short pulse-period motions. In comparison with an existing empirical model, the proposed model for short pulse periods is in good agreement with the existing empirical model within near-fault distance (about 8 km).

Introduction

Directivity effects are the near-fault effects characterized by a pronounced two-sided velocity pulse that may cause significant damages to geotechnical/structural systems. For near-fault sites, directivity pulselike motions are often considered in design. For instance, Almufti et al (2013) introduced an approach for incorporating velocity pulses in design ground motions based on probabilistic seismic hazard assessment (PSHA) including directivity-effects (Shahi and Baker 2011). In developing the design ground motion time histories, their strong motion durations need to be in an adequate range for the site in addition to the other ground motion characteristics (e.g., frequency content and amplitudes). Empirical relationships are commonly used to determine suitable strong motion duration values for site considering tectonic settings, seismic hazard information and site conditions. Many empirical relationships were developed in the past two decades (e.g., Abrahamson and Silva 1997; Bommer et al. 2009; Lee 2009) but a few models explicitly considered directivity-effects (e.g., Kempton and Stewart 2006). The empirical strong motion relationships primarily based on non-directivity motions may overestimate strong motion durations for directivity pulselike motions since forward directivity effects reduces strong motion durations (Somerville et al. 1997). This study develops empirical strong motion duration relationships for directivity pulselike motions.

The strong motion durations of a horizontal ground motion can vary substantially with its orientations (Lee 2014). To incorporate the directionality of strong motion durations in the empirical model, this study considers an orientation-independent strong motion durations (Lee 2014) and the durations in the strongest pulse orientation.

Regarding the organization of this paper, the definition of significant durations is reviewed first. The orientation-independent duration and duration in the strongest pulse direction are

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presented along with the ground motion records used in this study. Then, the proposed empirical strong motion duration models are presented with the comparisons with the existing models for non-pulselike motions and directivity pulselike motions: Lee (2014) and Kempton & Stewart (2006), respectively.

Significant Durations

Significant duration is one of the most commonly used definitions by engineering seismologists and earthquake engineers. For example, U.S. Nuclear Regulatory Commission (NRC) requires ground motion time histories developed for seismic site response or structural analyses shall be checked to ensure their significant durations are consistent with the characteristics of the controlling earthquake scenarios (U.S. NRC 2007). The normalized cumulative squared acceleration, $H(t)$, is used in its definition:

$$H(t) = \frac{\int_0^t a^2(t)dt}{\int_0^{t_d} a^2(t)dt} \tag{1}$$

where $a(t)$ is the ground motion acceleration time history, and t_d is the total duration of the acceleration time history. As may be surmised from this equation, the normalized cumulative squared acceleration varies from 0 to 1 (or 0% to 100%). Significant duration is most often defined as the time interval between $H(t)$ = 5% and 75% (Somerville et al. 1997) or $H(t)$ = 5% and 95% (Trifunac and Brady 1975), denoted as $D_{5\text{-}75}$ and $D_{5\text{-}95}$, respectively. As an example, Figure 1 illustrates the determination of the $D_{5\text{-}75}$ for an acceleration time history using the $H(t)$ plot, referred to as a Husid plot (Husid 1969).

Significant Durations of Directivity Motions

Significant durations of a ground motion vary with its orientation (Lee 2014) Figure 1and Figure 2 show the $D_{5\text{-}75}$ determination for a directivity motion from the 2002 Denali Alaska (M_W7.9 R = 2.74km) in the strongest velocity pulse and in the maximum $D_{5\text{-}75}$ orientations, respectively. Figure 3 presents the variation of $D_{5\text{-}75}$ of the directivity recording in different orientations. The $D_{5\text{-}75}$ ranges from 2.8 sec to 11.1 sec and the duration in the strongest pulse direction is 4.5 sec, close to the lower end of the range. This is due to the directivity pulse with high energy in a relative short time interval; see Figure 1. Two types of durations are considered herein for $D_{5\text{-}75}$ and $D_{5\text{-}95}$ of a directivity motion:1) orientation-independent duration ($D_{5\text{-}75Rot50}$ and $D_{5\text{-}95Rot50}$); and 2) durations in the strongest pulse direction ($D_{5\text{-}75Pulse}$ and $D_{5\text{-}95Pulse}$).

Orientation-independent Duration ($D_{5\text{-}75Rot50}$ and $D_{5\text{-}95Rot50}$)

The orientation-independent duration is determined as the median (50th percentile) of durations over all orientations. For a given set of two as-recorded horizontal ground motion components, the acceleration time history, a_{Rot} of one horizontal component rotated by θ is determined by Eq. 2.

$$a_{Rot}(t,\theta) = a_1(t)\cos(\theta) - a_2(t)\sin(\theta) \tag{2}$$

where θ is the rotation angle; $a_1(t)$ and $a_2(t)$ are the as-recorded mutually-orthogonal horizontal accelerations at time, t. The significant durations ($D_{5\text{-}75}$ and $D_{5\text{-}95}$) of the rotated

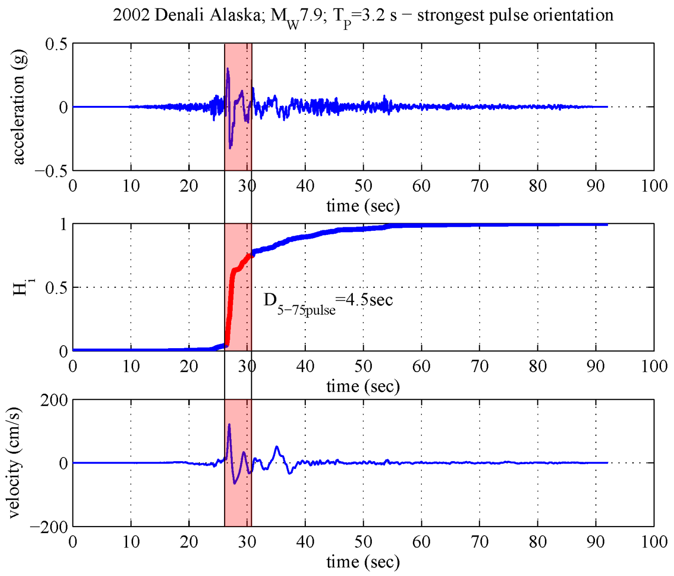

Figure 1. Significant duration, $D_{5\text{-}75}$ of a ground motion from the 2002 Denali Alaska (M_W7.9 R = 2.74km) in $D_{5\text{-}75Pulse}$ direction (rotation angle of 171°); velocity time history is not used for $D_{5\text{-}75}$ determination but shown for the corresponding strong phase in velocity.

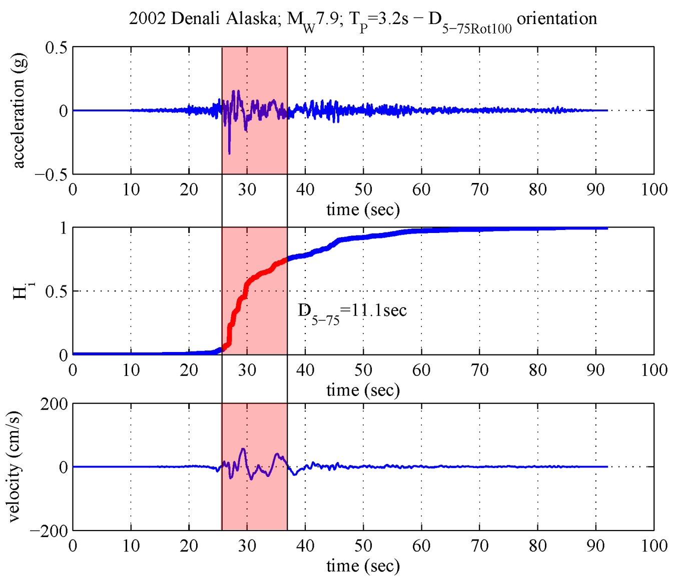

Figure 2. Significant duration, $D_{5\text{-}75}$ of a ground motion from the 2002 Denali Alaska (M_W7.9 R = 2.74km) in the maximum $D_{5\text{-}75}$ ($D_{5\text{-}75Rot100}$) orientation (rotation angle of 69°); velocity time history is not used for $D_{5\text{-}75}$ determination but shown for the corresponding strong phase in velocity.

horizontal component are computed for the non-redundant rotations. The periodicity of rotation angle is 180° because of the orthogonality of the two horizontal components. This procedure is repeated for θ range of 0° to 179° with an increment of 1°, and the significant durations are calculated at every rotation angle. Then, the 50th percentile of the significant durations is determined.

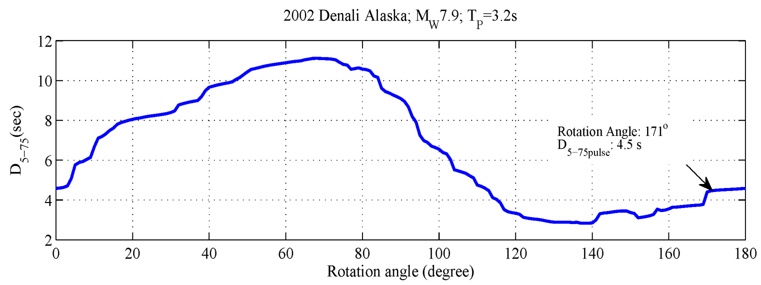

Figure 3. Variation in significant durations for non-redundant rotation angle: the 2002 Denali Alaska (M_W7.9 R = 2.74km) – the arrow indicates the strongest pulse direction.

Duration in Strongest Pulse Orientation ($D_{5-75Pulse}$ and $D_{5-95Pulse}$)

This study also determines significant durations of a directivity motion in the orientation where the velocity pulse is strongest. The strongest velocity pulse was identified by Shahi (2013) via wavelet transform. Using Equation 2, a directivity motion is rotated to the strongest pulse direction and then, the $D_{5-75Pulse}$ and $D_{5-95Pulse}$.are determined.

Directivity Motion Data

A total of 142 sets available from the PEER NGA-West2 Database (Ancheta et al. 2013) are used for developing significant duration correlations in this study. They are forward directivity motions identified by Shahi (2013) from 8611 ground motions in the PEER NGA-West2 Database. Shahi (2013) used continuous wavelet transforms to classify the ground motion as pulse-like or non-pulse-like along with the classification criteria on the followings:

- Pulse amplitude relative to the original ground motion and the peak ground velocity (PGV) of the ground motion; and
- Arrival time of directivity pulse to reject pulses arriving late in the time-history

Also Shahi (2013) manually filtered the list of pulse-like ground motions using source-to-site geometry and site conditions to check pulses most likely caused by directivity effects. It is noted that there are other sets of directivity records identified by other investigators (e.g., Hayden et al. 2014), which are however, not considered herein. Table 1 summarizes the earthquakes and the number of recordings considered in this study. Figure 4 shows the magnitude and distance distribution of the ground motions used herein. As shown in Figure 4, the magnitude ranges from 5.4 to 7.9 and the distance ranges from 0.07 km to 56 km. Also Figure 5 shows the V_{S30} values of the ground motion records used herein, ranging from 139 m/s to 2016 m/s. Note that the available recordings from V_{S30} greater than 800 m/s (only four records) and from large magnitudes greater than M_W7.5 (three events) are sparse, which inherently limits the credibility of the proposed model herein for those ranges.

Table 1. Earthquakes and the number of records considered in this study.

Earthquake Name	Year	Magnitude (M_W)	No. of Records
San Fernando	1971	6.61	1
Tabas Iran	1978	7.35	1
Coyote Lake	1979	5.74	4
Imperial Valley-06	1979	6.53	12
Montenegro Yugoslavia	1979	7.1	2
Irpinia Italy-01	1980	6.9	2
Westmorland	1981	5.9	1
Morgan Hill	1984	6.19	2
Kalamata Greece-02	1986	5.4	1
San Salvador	1986	5.8	2
Superstition Hills-02	1987	6.54	2
Loma Prieta	1989	6.93	6
Cape Mendocino	1992	7.01	3
Landers	1992	7.28	3
Northridge-01	1994	6.69	14
Kobe Japan	1995	6.9	4
Chi-Chi Taiwan	1999	7.62	36
Chi-Chi Taiwan-04	1999	6.2	1
Chi-Chi Taiwan-06	1999	6.3	2
Duzce Turkey	1999	7.14	2
Kocaeli Turkey	1999	7.51	4
Tottori Japan	2000	6.61	1
Denali Alaska	2002	7.9	1
Bam Iran	2003	6.6	1
Niigata Japan	2004	6.63	2
Parkfield-02 CA	2004	6	11
Chuetsu-oki Japan	2007	6.8	1
L'Aquila Italy	2009	6.3	3
Darfield New Zealand	2010	7	13
El Mayor-Cucapah Mexico	2010	7.2	2
Christchurch New Zealand	2011	6.2	2
		Total	142

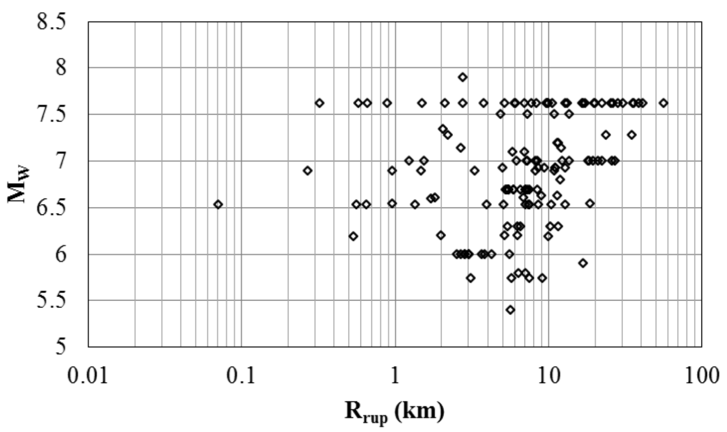

Figure 4. Magnitude and distance distribution of ground motions used in this study.

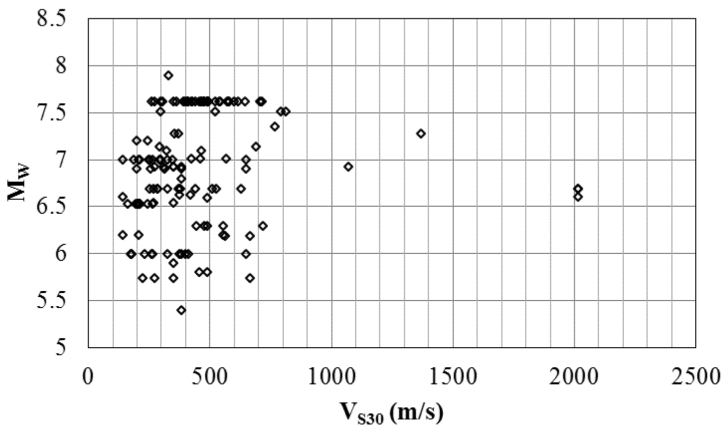

Figure 5. Magnitude and V_{S30} distribution of ground motions used in this study.

Empirical Significant Duration Model

This study develops empirical relationships for the 50th percentile significant durations of all orientations and the significant durations in the strongest pulse orientation. The relationships correlate the significant durations to earthquake magnitude (M_W), the closest distance to rupture (R), pulse period (T_P) and V_{S30}. The non-linear mixed-effects (NLME) regression technique was used to develop the empirical relationships in this study. NLME modeling is a maximum likelihood method based on normal (Gaussian) distribution and is primarily used for analyzing grouped data (i.e., databases comprised of subsets), allowing both inter- and intra-earthquake uncertainties to be quantified. The statistical analysis program R was used to perform the NLME regression analyses (Pinheiro and Bates 2000; Lee 2009).

The functional form used for the regression analyses is shown below:

$$lnD_{5-75Pulse} \text{ or } lnD_{5-95Pulse} = ln\left\{C_1 \exp(M_W - 6) + C_2\sqrt{R} + C_3 \ln(T_P) + S \cdot V_{S30}\right\} \quad (3)$$

where $D_{5-75Pulse}$ and $D_{5-95Pulse}$ (sec) are the D_{5-75} and D_{5-95} of the significant durations in the strongest pulse direction; M_W is the earthquake magnitude; R is the closest distance to rupture (km); T_P is the period of pulse (sec); $V_{S30}$is the average shear wave velocity of the upper 30 m (m/s); and C_1 through C_3 and S are the regression coefficients. The same functional form is used for the 50th percentile significant durations over all orientations ($D_{5-75Rot50}$ and $D_{5-95Rot50}$). The functional form is generally similar to Lee (2009) except for the pulse period term. It is observed that the durations increase with the pulse periods as shown in Figure 6. The natural logarithm of T_P is used in the model for lower standard deviations than the other functional forms.

The regression results showed no violation of normality assumptions (Pinheiro and Bates 2000; Lee 2009) on model residuals and no significant bias of the residuals, which is not presented in this paper due to the limited space. The resulting regression coefficients and the standard deviations are listed in Table 2.

Using Eq. 3 in conjunction with the coefficients listed in Table 2, D_{5-75} and D_{5-95} medians are plotted in Figure 7, as functions of site-to-source distance (R) for M_W 6.0, and M_W 7.0; T_P of 1.0 s and 5.0 s; V_{S30} of 360 m/s and 760 m/s. As shown in Figure 7, the significant durations increase with magnitude and distance. The significant durations of pulselike motions generally decrease with increasing V_{S30} (stiffer sites). These observations are consistent with those shown in the previous studies for non-pulselike motions (e.g., Abrahamson and Silva 1996; Bommer et al. 2009; Lee 2014). In addition to the common observations, the regression results show that significant durations of directivity pulselike motions increase with pulse period. Also the site effects on durations are insignificant based on the available data but more sufficient data is warranted for validating/invalidating this observation especially for stiff sites. In comparison of the median $D_{5\text{-}75Rot50}$ and $D_{5\text{-}75Pulse}$, the $D_{5\text{-}75Pulse}$ is generally smaller than $D_{5\text{-}75Rot50}$, but their difference is not considerably large especially for long pulse periods. This observation is also consistent with $D_{5\text{-}95}$.

Table 2. Regression coefficients and standard deviations.

Duration	C_1	C_2	C_3	S	τ	σ	σ_{total}
$D_{5\text{-}75Pulse}$	1.143	0.270	1.676	-0.00008	0.268	0.394	0.477
$D_{5\text{-}75Rot50}$	1.499	0.223	1.522	-0.00011	0.251	0.357	0.437
$D_{5\text{-}95Pulse}$	3.491	0.990	2.246	-0.00034	0.190	0.318	0.370
$D_{5\text{-}95Rot50}$	3.994	1.061	1.721	-0.00038	0.199	0.312	0.370

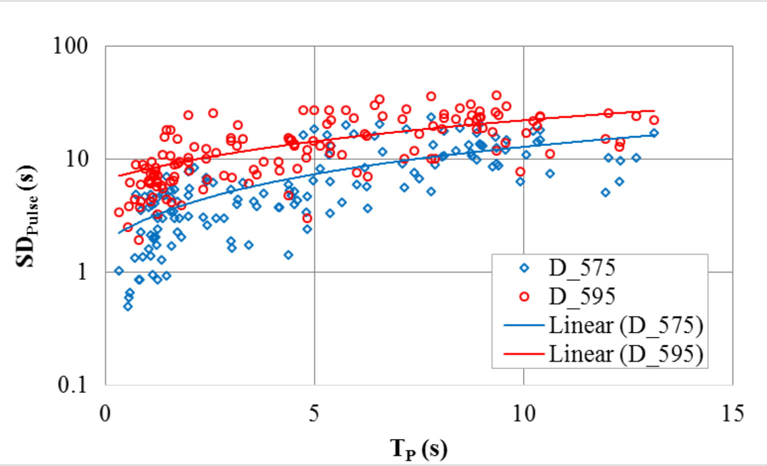

Figure 6. Distribution of $D_{5\text{-}75Pulse}$ and $D_{5\text{-}95Pulse}$ data with respect to T_P, and their linear least squares fit; a similar trend is also observed from $D_{5\text{-}75Rot50}$ and $D_{5\text{-}95Rot50}$ data.

In Figure 8, the orientation-independent significant durations ($D_{5\text{-}75Rot50}$ and $D_{5\text{-}95Rot50}$) for pulselike motions (by this study) are compared with those for non-pulselike motions by Lee (2014). As shown in Figure 8, pulselike motions tend to have shorter durations than non-pulselike motions, and their difference is substantial for pulselike motions with short pulse periods.

Figure 9 compares this study's orientation-independent significant durations with the Kempton & Stewart (2006) model for directivity motions. This study differs from Kempton & Stewart (2006) primarily in that this study considers directionality and pulse periods of directivity motions using the up-to-date database (NGA-West2). For distance within about 8 km, the significant durations per Kempton & Stewart (2006) are generally in good agreement with this study's results for short pulse periods (T_P = 1s) while for long pulse periods, Kempton and Stewart (2006) model underpredicts. For distance greater than about 20 km, Kempton & Stewart (2006) model tends to predict comparable durations to this study's for long pulse periods (T_P = 5.0 s) while for short pulse periods, Kempton and Stewart (2006) model overpredicts.

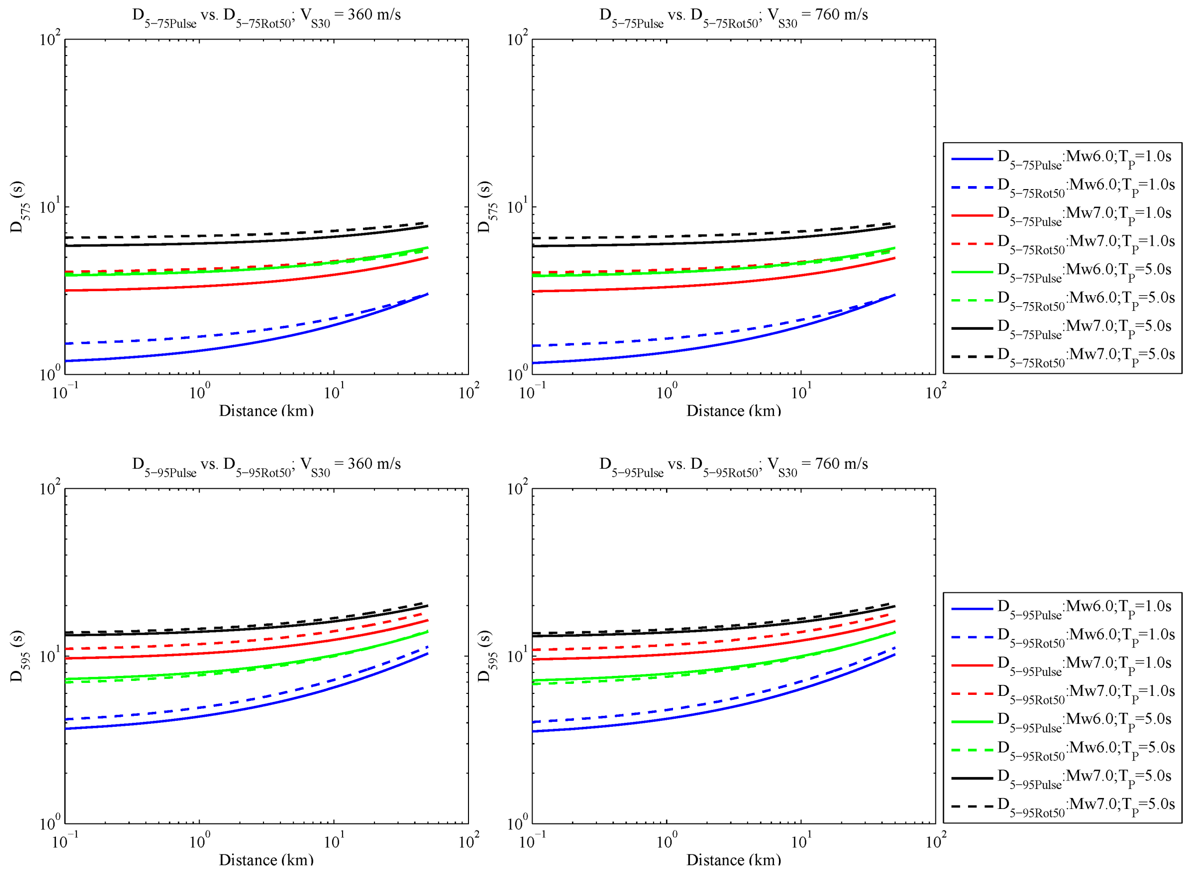

Figure 7. Model medians of $D_{5\text{-}75Pulse}$, $D_{5\text{-}75Rot50}$ (upper), $D_{5\text{-}95Pulse}$, and $D_{5\text{-}95Rot50}$ (lower) for V_{S30} of 360 m/s (left) and 760 m/s (right); and Mw6.0 and 7.0.

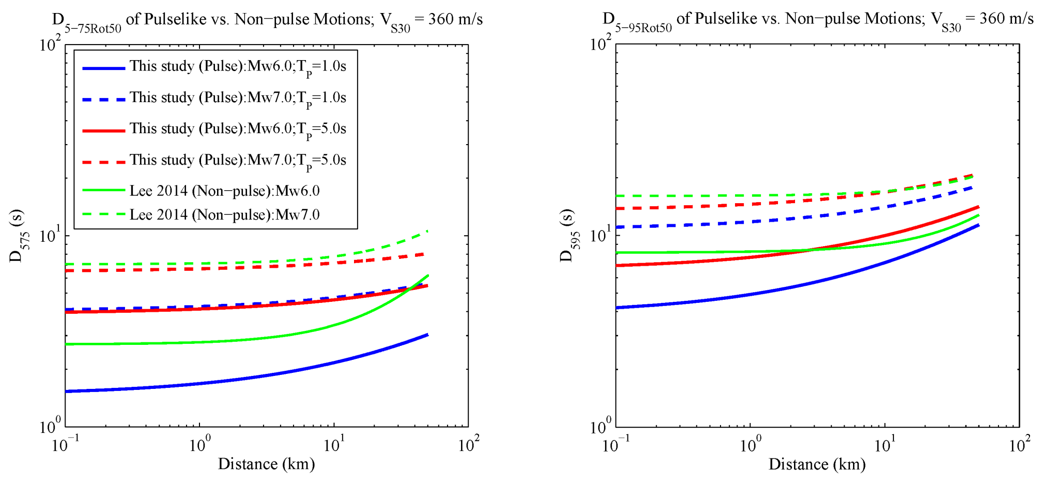

Figure 8. Orientation-independent significant durations for directivity pulselike motions (this study) and non-pulselike motions (Lee 2014); V_{S30} = 360 m/s.

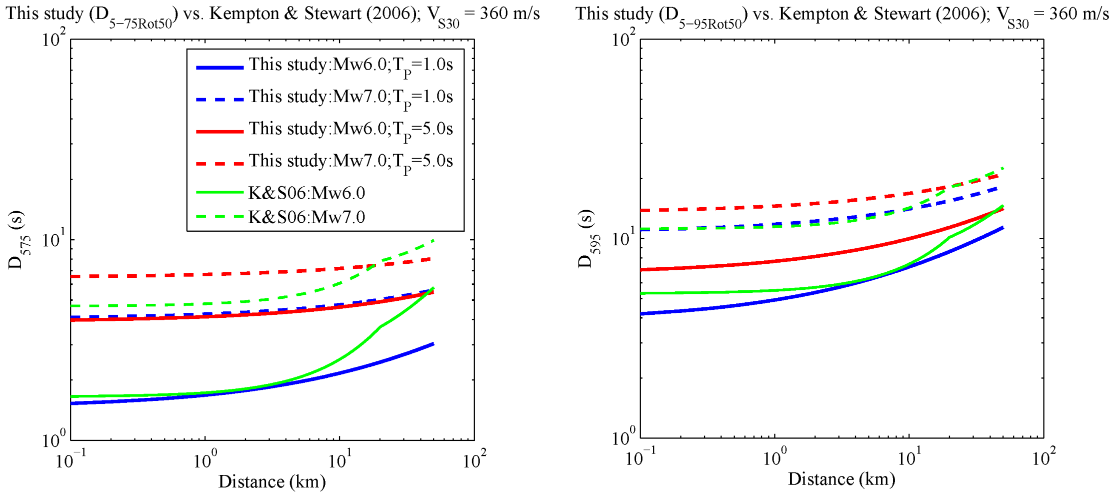

Figure 9. Orientation-independent $D_{5\text{-}75Rot50}$ and $D_{5\text{-}95Rot50}$ medians by this study versus $D_{5\text{-}75}$ and $D_{5\text{-}95}$ for directivity motions by Kempton & Stewart (2006; K&S06); V_{S30} = 360 m/s.

Conclusions

Empirical significant duration relationships for near-fault directivity motions have been developed using a total of 142 horizontal ground motion recordings from the PEER NGA-West2 Ground Motion Database and non-linear mixed-effects (NLME) regression method. The earthquake magnitude and V_{S30} ranges of the used directivity data are M_W5.4 to M_W7.9 and 139 m/s to 2016 m/s, respectively. However, the suggested applicable ranges are limited to M_W <7.5 and V_{S30} < 800 m/s due to the paucity of data. The empirical models were developed for the orientation-independent significant durations and durations in the strongest pulse direction as a function of earthquake magnitude, site-to-source distance, pulse period and site V_{S30}. The significant durations of directivity pulselike motions increase with increasing pulse periods, and are generally shorter than those of non-pulse motions especially for short pulse-period motions. In comparison with an existing model (Kempton & Stewart 2006), the existing model independent of pulse periods is relatively in good agreement with this study's model for short pulse periods within distance of about 8 km.

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