13th National Conference on
EARTHQUAKE ENGINEERING
PORTLAND, OREGON | JULY 13-17, 2026

Resilience Through Community Engagement and Technology

Exploring Rupture Directivity Effects on Significant Duration, Cumulative Absolute Velocity, and Arias Intensity

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ABSTRACT

The ground motion parameters significant duration, cumulative absolute velocity (CAV), and Arias intensity (AI) have a long history and wide range of usage in various engineering applications for describing the damage potential of ground motions. However, compared to response spectral ground motion models (GMMs), published GMMs for these parameters are rather limited. With the aim of improving upon existing published GMMs, I investigated the effects of rupture directivity on the significant duration, CAV, and AI using the Bayless et al. (2024) rupture directivity parameter for strike-slip and oblique shallow crustal earthquakes. I observed a statistically significant correlation between near-source forward directivity conditions and shorter than average significant durations in the recorded data. Median adjustment models to the Afshari and Stewart (2016) and Pinilla-Ramos et al. (2023) significant duration models are provided. These adjustment models can modify the median significant durations up to approximately ±60%. The relative impact of directivity was smaller for CAV and AI than for significant duration. This is because CAV and AI are cumulative parameters and are therefore impacted both by the duration, which is negatively correlated with the directivity parameter, and by the peak amplitudes, which are positively correlated with the directivity parameter. As a result, no CAV or AI adjustment models for directivity effects were developed.

Introduction

The definitions of AI and CAV are given by [1, 2, 3]. The significant duration (D_s), adopted here, is the most widely used duration metric in earthquake engineering applications and is defined as the time interval between reaching various percentages of AI. The significant duration intervals commonly considered are 5-75%, 5-95%, and 20-80%. In the notation, the subscript s on D_s is replaced with the corresponding duration interval percentages ($D_{5\text{-}75}$, $D_{5\text{-}95}$, and $D_{20\text{-}80}$, respectively). A Husid plot is the buildup of normalized AI with time, from which the significant durations can be calculated and visualized.

Parameters D_s, CAV, and AI have a long history and wide range of usage in various engineering applications for describing the damage potential of ground motions, yet published ground motion models (GMMs) for these parameters are relatively limited compared with response spectral GMMs. And there are even fewer models for these parameters in the literature which explicitly address rupture directivity effects. The pioneering [4] model, in addition to being the first empirical model for the modification of response spectral GMMs to account for spatial variations in near-source ground motion amplitude and duration due to the effects of rupture propagation, source radiation pattern, and the polarization of seismic waves (categorized jointly as "directivity" effects), contains a ground motion duration adjustment. But the [4] model was based on relatively limited data and utilizes an outdated directivity predictor. [6] investigated this phenomenon using the [4] directivity predictor and with the NGA-West1 database, with mixed results, and ultimately proposed a simple linear adjustment with distance to account for directivity in strike-slip earthquakes. [7] anticipated that rupture

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Bayless J. Exploring Rupture Directivity Effects on Significant Duration, Cumulative Absolute Velocity, and Arias Intensity. *Proceedings of the 13th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Portland, OR. 2026.

directivity should be incorporated into their significant duration model but were unable to find any trends in duration residuals using the isochrone directivity parameter [8]. None of these three studies utilized ground motions from simulated earthquakes nor the NGA-West2 database [9]. To my knowledge, there are no models for CAV or AI which explicitly address rupture directivity effects, nor do any existing directivity models adjust these parameters.

In this study, I used the directivity parameter from [10; Bea24 hereafter] to investigate the impact of rupture directivity effects on the significant duration, CAV, and AI, using residuals from existing GMMs, all of which are based on the NGA-West2 database. The GMMs and notations used within this paper are listed in Table 1.

Table 1. Ground motion models and descriptions.

Model	Notation in this study	Description
Afshari and Stewart (2016); [11]	AS16	Significant Duration Model
Pinilla-Ramos et al. (2023); [12]	Pea23	Significant Duration Model
Campbell and Bozorgnia (2019); [13]	CB19	CAV and AI Models
Bayless et al. (2024); [10]	Bea24	Rupture Directivity Adjustment Model for Response Spectra from Strike-Slip Earthquakes

Duration Modeling

Evaluation of Individual Earthquakes

Both Pea23 and AS16 used the PEER NGA-West2 database [9] in residual analyses to develop their duration models. Residuals for both $D_{5\text{-}75}$ models were acquired from the respective model developers (pers. communication). Because these models do not explicitly account for rupture directivity effects, I investigated the within-site model residuals for the earthquakes with an NGA-West2 finite-fault model that were also used in developing Bea24. Initially, I evaluated the earthquake residuals individually by mapping the rupture plane surface projections, hypocenters, GMM residuals, and values of the Bea24 directivity predictor, $f_{G'}$ at the recording locations (e.g., Fig. 1). In Fig. 1(a) the map shows the rupture surface trace in black and colored circles show values of $f_{G'}$ at the recording locations, where warm colors represent the forward directivity condition, cool colors represent the backward directivity condition, and white is a neutral directivity condition. In (b) the colored circles show the AS16 within-site residuals, δWS_{es}, where warm colors (negative residual) represent shorter than average durations, and cool colors (positive residual) represent longer than average duration. In this 1992 **M**7.28 Landers earthquake example, the backward directivity region to the south of the hypocenter has positive residuals, representing longer than average durations for this magnitude and distance. The forward directivity region to the north has negative residuals on average, corresponding to shorter than average durations. The Landers earthquake residuals appear to have a positive random effect (mean value of δWS_{es}) but this is just a bias in the spatial sampling of the stations with short distances.

Fig. 1(c) relates δWS_{es} and $f_{G'}$ for this earthquake and shows the two parameters are inversely correlated with the computed correlation coefficient (ρ = -0.76) and with p-value = 0.00. The p-value is used for testing the null hypothesis of no correlation, where the p-value is the probability of getting a correlation as large as the observed value by random chance, when the true correlation is zero.

The behavior of the Landers earthquake duration residuals is consistent with expectations as described in [4]; due to the propagation of the rupture at a velocity almost as large as the shear wave velocity, the seismic energy from the rupture arrives over a shorter than average duration when a site is in the direction of rupture propagation, and arrives over a longer than average duration when the rupture propagates away from a site. From earthquake to earthquake the statistical significance of the correlation coefficients varies; events with fewer recording stations make it more difficult to conclude a statistically significant relationship (leading to larger p-values). Overall, there is a clear observable relationship between the residuals and the directivity parameter for the strike slip and oblique earthquakes evaluated; this set of earthquakes is available in Bea24, with earthquake style of faulting classifications from [9]. Between both GMMs, 12 of the 19 earthquake evaluations have correlation p-values smaller than 0.1 (63%).

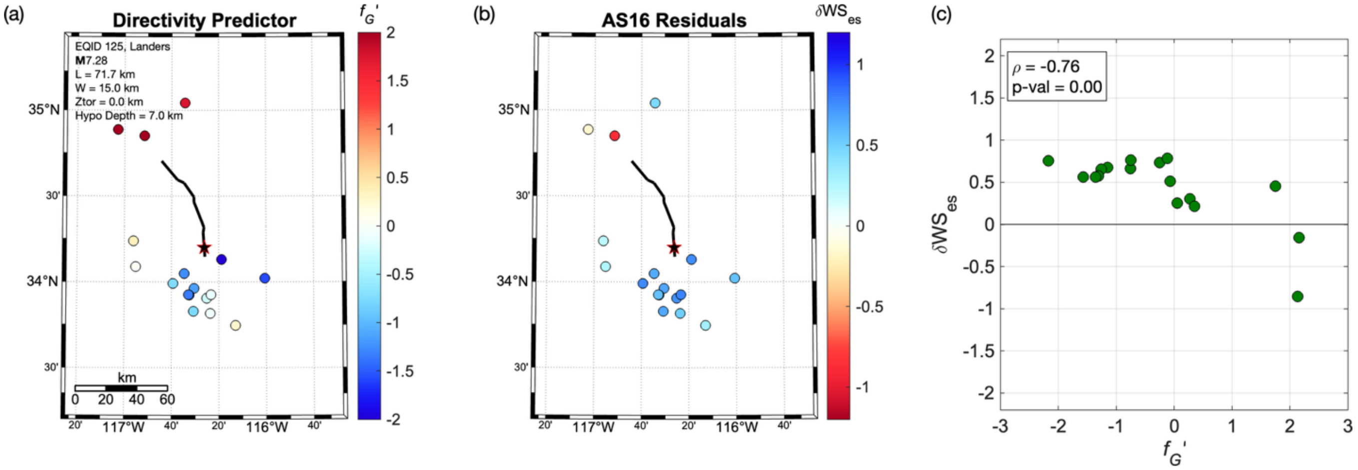

Figure 1. Evaluation of the AS16 residuals of the Landers earthquake, sites within 50 km distance.

Duration Adjustment Model

The residuals from all evaluated earthquakes with five or more recording stations were combined as shown in Fig. 2 for (a) the Pea23 model and (b) the AS16 model. The combined residuals (top panels of Fig. 2) were used to fit a $D_{5\text{-}75}$ median adjustment model for directivity effects. The median duration adjustment, δ_{dir}, is of the form of Eq. 1:

$$\delta_{dir} = a_1 \left(\frac{2}{1 + \exp\,[a_2\, f_{G'}]} - 1 \right) \tag{1}$$

where a_1 and a_2 are model coefficients and $f_{G'}$ is the previously defined Bea24 directivity predictor for strike slip earthquakes. Eq. 1 is a form of the logistic function, also known as the sigmoid function, which is a family of mathematical models used to describe exponential growth with limiting upper and lower bounds. In Eq. 1, the limiting upper and lower bound is ± a_1, with inflection point at $f_{G'} = 0$. With this functional form, the median duration adjustment is limited to be $-a_1$ when $f_{G'}$ is large and positive (forward directivity) and is limited to $+a_1$ when $f_{G'}$ is negative with large absolute value (backward directivity). When the centered directivity predictor is equal to zero ($f_{G'} = 0$), the median duration adjustment is also equal to zero. The model parameter a_2 controls the slope of the relationship between $f_{G'}$ and the duration adjustment.

The fit of Eq. 1 to the data is shown by the solid blue line in the top panels of Fig. 2. I considered a linear relationship (red dashed line) but favored the sigmoid model due to the way it limits the adjustment model for large values of the directivity predictor, where the uncertainties are largest. In fitting the sigmoid functions, I set the parameter a_1 by visual inspection and determined a_2 by nonlinear least squares regression. The sample standard deviations of δWS_{es} (denoted ϕ) before and after applying the duration adjustment are shown in the upper and lower panels of Fig. 2, respectively. Table 2 lists the median duration adjustment model coefficient values.

Table 2. Model coefficients for the median adjustment to duration due to rupture directivity.

Coefficient	Adjustment to Pea23	Adjustment to AS16
a_1	1.5	0.5
a_2	1.8755	1.1636

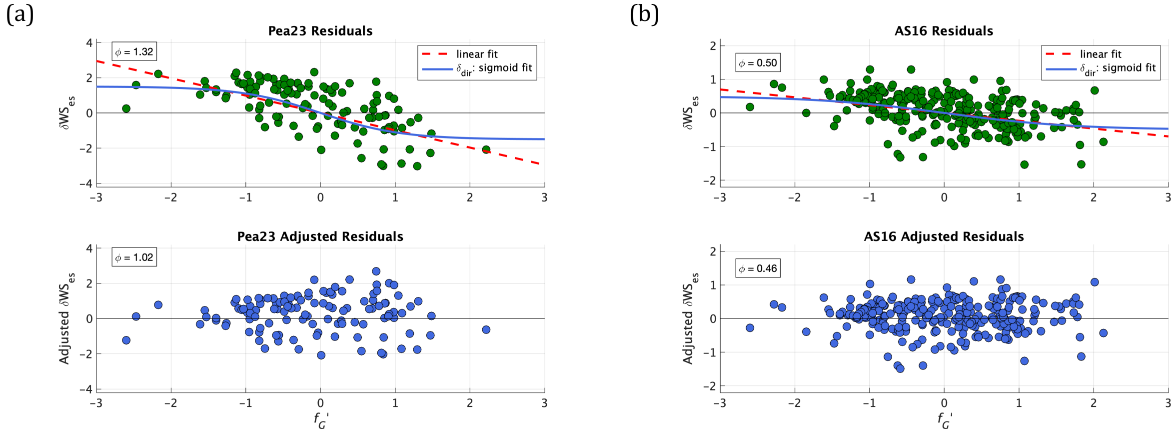

Figure 2. Duration model residuals from (a) Pea23 and (b) AS16. In both panels, the top shows residuals from all evaluated earthquakes with five or more recordings and the bottom panel shows the same residuals after adjusting for directivity effects (sigmoid fit; Eq. 1).

Model Application

The rupture directivity adjustment model for significant duration is applicable for shallow crustal strike-slip earthquakes in active tectonic regions. The model should be used for sites with rupture distances less than 25 km. The median $D_{5\text{-}75}$ adjustment model for the AS16 GMM can be applied using Eq. 2:

$$\ln(D_{5\text{-}75,dir}) = \ln\left(D_{5\text{-}75,med}\right) + \delta_{dir} \qquad (2)$$

where $D_{5\text{-}75,med}$ is the median $D_{5\text{-}75}$ duration from AS16 and $D_{5\text{-}75,dir}$ is the significant duration adjusted for rupture directivity effects and with δ_{dir} from Eq. 1. Because AS16 is a multiplicative model, the AS16 δWS_{es} are in natural log units and the quantity $\exp(\delta_{dir})$ is the factor by which the median duration model (in seconds) is multiplied to account for rupture directivity. As shown in Fig. 2, the AS16 δ_{dir} values range between -0.5 to 0.5, and exp(0.5) is approximately a factor of 1.6.

The median $D_{5\text{-}75}$ adjustment model for the Pea23 GMM can be applied using Eq. 3:

$$D_{5\text{-}75,dir} = \left[\left(D_{5\text{-}75,med}\right)^{0.7} + \delta_{dir}\right]^{\left(\frac{1}{0.7}\right)} \qquad (3)$$

where $D_{5\text{-}75,med}$ is the median duration from Pea23 and $D_{5\text{-}75,dir}$ is the duration adjusted for rupture directivity effects. Pea23 is an additive model, and their regression processes used a Bayesian statistical analysis, in which the δWS_{es} is power-normal distributed with exponent $n_1 = 0.7$. As a result, the units of Pea23 δWS_{es} and δ_{dir} are seconds$^{0.7}$.

Conclusions

I found a statistically significant relationship between the [10] rupture directivity parameter for strike-slip and oblique earthquakes, $f_{G'}$, and the significant duration, $D_{5\text{-}75}$, in the near-field. Consistent with expectations from [4], the forward directivity condition is correlated with shorter than average significant durations. Median duration adjustment models for two existing duration GMMs are provided: [11] and [12]. These models can be used in forward application to account for the effects of rupture directivity on the median predicted $D_{5\text{-}75}$. The models apply to shallow crustal earthquakes in active tectonic regions and to sites with rupture distances smaller than 25 km.

A similar analysis was performed for the intensity measures CAV and AI using the [13] GMM residuals. CAV and AI are cumulative (duration-sensitive) parameters, as opposed to spectral acceleration, which is a peak response parameter. As regions of forward directivity typically have shorter than average durations and higher than average amplitudes, and these two phenomena appeared to counteract each other in determining the cumulative parameters CAV and AI. Regions of backward directivity have longer than average durations but lower peak amplitudes which also offset each other. Therefore, based on this study using the Bea24 directivity model for strike-slip and oblique earthquakes, the relative impact directivity has on CAV and AI appears to be smaller than on peak response parameters like spectral acceleration and on the duration itself.

The conclusions of this paper are based upon the [10] rupture directivity model for strike-slip and oblique earthquakes. In the future, similar studies should be performed using other rupture directivity models or datasets. The conclusions of this paper would be strengthened by studying the durations of ground motions from additional strike-slip and oblique earthquakes as they become available.

Acknowledgments

I gratefully acknowledge the financial support for this work by the USGS under award number G23AP00377. Thanks to Camilo Pinilla-Ramos, Norman Abrahamson, Jonathan Stewart, Yousef Bozorgnia, and Ken Campbell for sharing their GMM residuals. Additional thanks to Yousef Bozorgnia and Ken Campbell for their support and collaboration which led to the idea behind this study.

Project Data

The NGA-West2 significant duration data and the Bayless et al. (2024) rupture directivity parameters used in this study are available at doi.org/10.17603/ds2-gw4r-cm44. This research uses publicly available data from the Pacific Earthquake Engineering Research Center (https://peer.berkeley.edu). The CAV (CB19), AI (CB19), and duration (Pea23 and AS16) model residuals were obtained via personal correspondence with the model authors. All other data and codes are available upon request.

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