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A study on major seismological and fault-site parameters affecting near-fault directivity ground-motion demands for strike-slip faulting for their possible inclusion in seismic design codes

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ABSTRACT

We investigate the role of major seismological (magnitude, pulse period, fault length, seismic activity, orientation of incident seismic wave with respect to fault-strike) and geometrical (fault-site geometry) parameters to understand the variations in ground-motion demands due to near-fault directivity (NFD) effects. To this end, we used a suite of probabilistic strike-slip earthquake scenarios and established the elastic spectral amplitude distributions conditioned on the above investigated parameters. The probabilistic earthquake scenarios also provided information on the sensitivity of directivity dominant near-fault (NF) ground motions to mean annual exceedance rates. We implemented different narrow-band directivity models to observe the significance of seismological modeling in the directivity dominant NF ground-motion amplitudes. The observations from these case studies suggest that each one of the above parameters have implications on the amplitude and spatial variation of directivity dominating NF ground-motion demands. The influence of each investigated parameter on NFD spectral amplitudes is dependent of the implemented directivity model. We also establish some rules to map the spatial extent of directivity dominant ground motions considering the variations in the investigated seismological parameters. The outcomes of the paper can be used to incorporate the NFD effects into design spectra representing different annual exceedance rates.

1. Introduction

When the horizontally polarized S-wave (SH-wave) radiation pattern aligns with the direction of rupture propagation and direction to the site, the ground motions are largest. This phenomenon is the major principle behind forward directivity according to Somerville et al. [68]. The forward directivity is more prominent within the ends of the strike-slip fault that suggests directivity being more significant when rupture travels longer distances [72]. The coincidence of SH-wave radiation pattern maximum and the rupture propagation toward the site produces a large displacement pulse normal to the fault strike. The minimum in the radiation pattern of vertically polarized S-wave (SV-wave) that is in the direction of seismic wave propagation produces small dynamic displacements superimposed on a larger static displacement (fling step) parallel to the fault. Instead of large pulses, the waveforms are dominated by low-amplitude and long-duration motions when the rupture propagates away from the site. This phenomenon is called as backward directivity and it is not within the scope of this paper.

The near-fault forward directivity (NFFD) ground motions have been recorded in many earthquakes during the past 50 years (e.g., Port Hueneme earthquake in 1957 [42]; Parkfield earthquake in 1966 [43]; San Fernando earthquake in 1971 [19,56]; Landers earthquake in 1992 [27]; Northridge earthquake in 1994 [69]; Kobe earthquake in 1995 [39]; Marmara earthquakes in 1999 [3]; Chi-Chi earthquake in 1999 [32]; L'Aquila earthquake in 2009 [33]; Christchurch earthquake in 2011 [23]). Their distinct features in terms of dynamic source characteristics as well as large-amplitude impulsive horizontal and vertical waveforms that increase the damage potential on structures have appealed many seismological and engineering studies. Modeling of high-slip zones and directivity e.g. [67,49,63,70,62], influence of fault mechanisms on directivity e.g. [57], and dynamic rupture modeling to characterize super shear zones e.g. [38], are among the topics investigated by seismological community to explain the physics behind the directivity-dominant ground motions. Inherently, the engineering community is interested in the damaging effects of such ground motions on different structural systems e.g. [10,16,8,9,41,61,11,5,31]. The variations in the elastic and inelastic horizontal spectral quantities under NFFD ground motions were investigated thoroughly e.g.

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[50,7,51,53,3,24,33,36,74,60,45,28,48]. The engineering studies on the definition of the response spectrum for NFFD ground motions consider the pulse period (T_p), the peak ground velocity to peak ground acceleration (PGV/PGA) and the peak ground displacement to peak ground velocity (PGD/PGV) ratios as well as the pseudo-velocity spectrum (PSV) to account for the dominant impulsive signal effect on the spectral shape. Recently, there is an increasing effort to incorporate the directivity effects within the probabilistic seismic hazard and damage assessment procedures using linear and nonlinear structural response quantities [6,14,15,34–36,46,64,65,74–76].

One of the most important contributions on the modeling of forward directivity is made by Somerville et al. (1997) [68]. The model in [68] estimates the spectral amplifications along the strike-normal and the strike-parallel components as well as their geometric average due to the rupture directivity to modify the spectral ordinates predicted by the conventional (no-directivity) ground-motion predictive models (GMPMs). The model estimations are valid for moment magnitudes $M_w > 6.5$ with a dependence on normalized rupture to fault length and the angle between the rupture propagation direction and the site. The spectral amplifications by Somerville et al. (1997) [68] increase monotonically after $T = 0.6$ s; this type of forward directivity model is referred to as broad-band model in the literature. Later, Abrahamson (2000) [1] proposed some modifications to the Somerville et al. (1997) [68] directivity model for improving the limitations in directivity scaling of large magnitude events due to the use of normalized distance.

The response spectrum amplifications due to directivity are investigated more systematically in the NGA-West1 [58] and NGA-West2 [22] projects. The directivity modelers in NGA-West1 [59,72] proposed corrections to the median predictions of the NGA-West1 no-directivity GMPMs. The implementation of these directivity models to the NGA-West1 GMPMs experienced conceptual difficulties because the median predictions of the no-directivity NGA-West1 GMPMs already included the NFFD ground motions in their datasets. Thus, the identification of reference directivity conditions corresponding to the median estimations of NGA-West1 GMPMs are unclear while implementing the corrections of the directivity models. In order to overcome this shortcoming, the NGA-West2 directivity modelers (Bayless and Somerville, Rowshandel, Shahi and Baker, Spudich and Chiou, and Chiou and Spudich – see Spudich et al., 2013 [71]) developed their models for their direct inclusion to the functional forms of the NGA-West2 GMPMs. Besides, the NGA-West2 directivity models utilize either the Joyner-Boore (R_{JB}) or the rupture (R_{rup}) distance in order to provide consistent scaling of forward directivity for the entire magnitude range of interest [73]. The NGA-West2 directivity models by Rowshandel, Shahi and Baker, Spudich and Chiou, and Chiou and Spudich are defined as narrow-band models because the spectral ordinates are amplified only within a specific period interval that is sensitive to the magnitude. The Chiou and Spudich directivity model is adopted by the NGA-West2 Chiou and Youngs (2014) [36] GMPM. The Shahi and Baker model is based on an older version of the directivity model proposed by the same authors (Shahi and Baker, 2011) [65] that makes use of the Boore and Atkinson (2008) functional form from NGA-West1 [58]. The other directivity modelers published their functional forms and regression coefficients for their implementation to either NGA-West1 or NGA-West2 GMPMs [71]. Most of the NGA-West2 forward directivity models suggest a maximum distance of 70–80 km from the ruptured fault surface for the directivity effect. Although the NGA-West2 directivity models account for the sophisticated features of directivity phenomenon, there is still some room for their further improvement. For example, except for Rowshandel, no other model can clearly distinguish the directivity effects between the reverse and normal faults. However, Oglesby et al. (2000) [57] have already shown the rupture-dynamic reasons for expecting larger amplitude near-fault motions from the reverse events rather than the normal ruptures.

The wide range of studies on the NFFD ground motions are yet to show their full implications on the seismic design codes. To the best knowledge of the authors, the 1997 version of the Uniform Building Code (UBC, 1997) [77] is the first seismic design code with a design spectrum explicitly accounting for the near-source effects. This code introduces two near-fault factors N_a and N_v to amplify the short-period and the long-period ranges in the design spectrum. Both N_a and N_v depend on the seismic activity of the fault and amplify the design spectrum for directivity effects for $R_{rup} \leq 15$ km. The Taiwanese [29,30], Chinese [37] and Iranian [80] seismic design codes use the UBC (1997) approach to include the forward directivity effects on the definition of design spectrum ordinates. The current seismic design code in China incorporates the near-source effects for base isolated structures with distance-dependent amplification factors [37]. The New Zealand seismic code [55] includes the forward directivity effects for distances up to 20 km to the ruptured fault and spectral periods $T \geq 1.5$ s, provided that the spectrum's return period is 250-year or more. The Caltrans seismic design guidelines [26] amplify the design spectrum for $T > 0.5$ s by a distance and period dependent near-fault adjustment factor. The adjustment factor increases the spectral ordinates by 20% for $R_{rup} \leq 15$ km linearly tapering to zero between the rupture distances 15 km $< R_{rup} \leq 25$ km. Caltrans (2013) [26] states the validity of above amplifications for horizontal spectral ordinates having equal probability in all orientations (e.g., GMRotI50[1] or RotD50[1] horizontal component definitions as proposed in Boore et al. (2006) [20] and Boore (2010) [21] that are used by NGA-West1 and NGA-West2 GMPMs, respectively). Upon the use of maximum direction (RotD100[1]) horizontal spectral ordinates [21] in which their occurrences are not equally probable in all orientations, Caltrans (2013) [26] suggests an additional 15–25% spectral amplification over the previously suggested amplifications for a full coverage of NFFD effects. The suggested additional spectral amplifications are in line with the findings of Huang et al. (2008) [44], Watson-Lamprey and Boore (2007) [78] and Beyer and Bommer (2006) [17] for $R_{rup} \leq 5$ km. We should note that the 2009 edition of the NEHRP provisions (BSSC, 2009) [25] as well as the 2010 edition of the ASCE 7–10 standards [12] have started the use of the maximum direction component in the definition of horizontal design spectrum since the collapse probability would reduce for structures designed against maximum direction spectral demands [25]. This horizontal component definition can also capture the strong polarization of directivity-dominant recordings [20,21].

This paper investigates the influence of the magnitude, pulse period (or magnitude-dependent period band where elastic response spectrum is amplified due to directivity), fault length, seismic activity, fault-site geometry, orientation of incident seismic wave with respect to fault-strike as well as the annual exceedance rate on the NFFD spectral amplitudes. We generated a suite of strike-slip earthquake scenarios via probabilistic seismic hazard assessment (PSHA) and implemented the narrow-band directivity models of Shahi and Baker (SHB11 [65];) and Chiou and Spudich (CHS13; Chapter 6 in Spudich et al., 2013 [71]) that is adopted by the Chiou and Youngs [36] GMPM to study the effects of the above mentioned parameters on NFFD. The use of multiple directivity models provided us an opportunity to understand the influence of different methodologies in estimating the directivity response spectral amplifications. We first explain the important features of the considered directivity models. The discussions continue by presenting the spectral amplitude distributions conditioned on the investigated seismological and geometrical parameters to assess their significance in directivity-dominated spectral amplifications. We finalize the paper by mapping the spatial influence of directivity for different probabilistic earthquake scenarios that could be of interest to the modern seismic design codes.

[1] GMRotI50 is median value of the geometric mean of the two horizontal components rotated through all non-redundant period independent angles. RotD50 is median values of response spectra of the two horizontal components projected onto all non-redundant azimuths. RotD100 (or maximum direction) is 100th percentile (the largest possible) values of response spectra of the two horizontal components projected onto all non-redundant azimuths.