Kinematic Earthquake Ground-Motion Simulations on Listric Normal Faults

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Abstract Complex finite-faulting source processes have important consequences for near-source ground motions, but empirical ground-motion prediction equations still lack near-source data and hence cannot fully capture near-fault shaking effects. Using a simulation-based approach, we study the effects of specific source parameterizations on near-field ground motions where empirical data are limited.

Here, we investigate the effects of fault listricity through near-field kinematic ground-motion simulations. Listric faults are defined as curved faults in which dip decreases with depth, resulting in a concave upward profile. The listric profiles used in this article are built by applying a specific shape function and varying the initial dip and the degree of listricity. Furthermore, we consider variable rupture speed and slip distribution to generate ensembles of kinematic source models. These ensembles are then used in a generalized 3D finite-difference method to compute synthetic seismograms; the corresponding shaking levels are then compared in terms of peak ground velocities (PGVs) to quantify the effects of breaking fault planarity.

Our results show two general features: (1) as listricity increases, the PGVs decrease on the footwall and increase on the hanging wall, and (2) constructive interference of seismic waves emanated from the listric fault causes PGVs over two times higher than those observed for the planar fault. Our results are relevant for seismic hazard assessment for near-fault areas for which observations are scarce, such as in the listric Campotosto fault (Italy) located in an active seismic area under a dam.

Electronic Supplement: Movie of wave propagation for planar and listric faults.

Introduction

An integral part of probabilistic seismic hazard assessment is the prediction of expected ground motions produced by potential seismic sources near sites of interest (e.g., McGuire, 1995; Budnitz *et al.*, 1997; Bommer and Abrahamson, 2006; Beauval *et al.*, 2009). Typically, empirical ground-motion prediction equations (GMPEs) are employed to estimate ground motions over a wide range of magnitudes and distances. However, GMPEs are not perfect predictors, particularly in the near-field region where recorded data are sparse. These shortcomings were highlighted in several well-instrumented earthquakes (e.g., 1999 Chi-Chi, Taiwan; 2000 Tottori, Japan; and 2004 Parkfield, California), where the observed variability of ground-motion intensity measures in the near field was much larger than at greater distances (e.g., Shakal *et al.*, 2006; Mai, 2009).

Because GMPEs suffer from the shortage in near-field recordings and do not adequately represent the observed source effects (Dalguer and Mai, 2011), the alternative is to use numerical simulations that take into account the characteristics of the source, propagation paths, and site effects.

Early studies on near-source ground motion employed simple theoretical and numerical models to understand its first-order characteristics (e.g., Aki, 1968; Haskell, 1969; Archuleta and Frazier, 1978). More recently, scenario simulations have been performed to evaluate ground shaking for specific regions, considering a range of complexities in the earthquake source and wave propagation (e.g., Graves, 1998; Graves and Pitarka, 2004, 2010, 2016; Olsen *et al.*, 2006; Imperatori and Mai, 2012, 2013; Mena *et al.*, 2012; Vyas *et al.*, 2016). Only a few studies have systematically investigated the influence of different source parameters on the resulting near-source ground motion (e.g., Inoue and Miyatake, 1998; Aagaard *et al.*, 2001; Aagaard, Anderson, *et al.*, 2004), and even fewer attempt to rigorously quantify the uncertainty in the employed source parameters and the associated variability in ground motion (e.g., Ripperger *et al.*, 2008; Imperatori and Mai, 2012).

In addition to source and wave propagation effects, the geometric complexity of the fault and its associated rupture dynamics, and hence seismic radiation, are particularly

Figure 1. Illustration of the anatomy of a listric fault (in cross section). The steep upper part of the fault flattens downward, eventually merging with a low-angle detachment. The reverse drag of the hanging-wall block forms a rollover anticline (see [Data and Resources](#)).

important to understand ground-motion complexity. Well-studied cases focused on highly damaging reverse-faulting earthquakes, for instance, the 1994 M_w 6.7 Northridge earthquake ([Hartzell et al., 1996, 2005](#); [Pitarka and Irikura, 1996](#); [Wald et al., 1996](#); [Olsen et al., 1997](#); [Beresnev and Atkinson, 1998](#)) and the 1999 M_w 7.6 Chi-Chi event ([Dalgner et al., 2001a,b](#); [Oglesby and Day, 2001](#); [Aagaard, Hall, et al., 2004](#); [Lee et al., 2007](#)). However, little is known about rupture complexity and its associated shaking for normal-faulting earthquakes, yet the recorded acceleration time series in recent well-instrumented earthquakes, such as 2009 L'Aquila (Italy), show high variability in both amplitude and duration, highlighting the need for detailed ground-motion studies for such events ([Akinci et al., 2010](#)).

In extensional regimes such as the Apennines in Italy (e.g., [Valoroso, 2016](#)), the Great Basin of Nevada, Utah (e.g., [Anderson et al., 1983](#)), or Idaho (e.g., [Harms and Price, 1992](#)), seismic hazard typically lies in nonvertical (dipping) faults ([Oglesby et al., 1998](#)). In this study, we will examine in particular fault geometries with profiles where dip decreases with depth, creating the concave upward shape of listric faults. This shape can be produced by geometric constraints, either because the faults reactivate curved thrusts, or because they must be curved to accommodate rotations ([Jackson and McKenzie, 1983](#)). Other causes include the variation of rheology with depth, because brittle failure at shallow depths produces less fault rotation than distributed creep in the lower part of the crust. Two features are considered particularly characteristic for listric faults ([Wernicke and Burchfiel, 1982](#)): (1) a steep upper part of the fault that then flattens downward, merging with a low-angle detachment, and (2) the downwarping or reverse drag ([Hamblin, 1965](#)) of the hanging-wall block, forming a rollover anticline (see Fig. 1).

There is very limited research that directly addresses the effects of listricity on near-field ground motions. [Ofoegbu and Ferrill \(1998\)](#) found that, for the Yucca Mountain region in Nevada, the curved shape has a considerable effect on the distribution of ground-motion amplitudes, such that the concentration of energy due to the fault curvature generates higher ground-motion amplitudes at distant locations than at near-fault sites. They also found that, typically, slip initiates

Figure 2. Receiver locations overlaid on the peak ground velocity (PGV) shake map for the uniform-slip planar-fault case with $H_{\text{top}} = 0.5$ km and $\delta_0 = 45^\circ$. Black receivers are used in comparing simulation results for different scenarios and against ground-motion prediction equations (GMPEs), and white numbered receivers are used in detailed seismogram comparison. The upper edge of the fault is indicated in pink.

near the base of the steep-fault segment and propagates toward the ground surface and downward and laterally along the low-angle detachment. However, ground accelerations were monitored at six locations only, and hence, the limited number of stations could lead to a sampling bias, and no reference planar-fault simulation was conducted for comparison. As we will see in the [Results](#) section, small variations in receiver position may cause large differences in ground-motion levels; therefore, by monitoring more locations we obtain more conclusive results.

To accurately reconstruct the precise fault geometry for the 2009 M_w 6.1 L'Aquila earthquakes, [Chiaraluce et al. \(2011\)](#) and [Valoroso et al. \(2013\)](#) used high-precision earthquake locations to study the anatomy of the fault system. From the seismicity profiles, the Campotosto fault exhibits a clear listric geometry. An analysis of the seismic hazard by [Walters et al. \(2009\)](#) of the area found that the 2009 L'Aquila earthquake brought the Campotosto fault closer to failure. Considering also that the fault runs underneath the dam at the northern end of the Lago di Campotosto reservoir and its vicinity to the city of L'Aquila and Campotosto, it is

Table 1
Summary of the Rupture Scenarios Developed for This Study

Section	Slip	V_{rup}	H_{top}
Listricity	Uniform	Uniform	0.125 km
Increasing H_{top}	Uniform	Uniform	Multiple
Heterogeneous rupture speed	Heterogeneous	Heterogeneous	2.5 km

Figure 3. Fault profiles used in our ground-motion simulations. For the listric profiles, the listricity coefficient (C) is fixed to 12, 8, and 4, whereas the initial dip (δ_0 in equation 1) is iteratively adjusted until the average dip equals 45° , obtaining 52° , 59° , and 82° for the respective listricity coefficients. This allows us to compare ground motions between the listric and planar simulations.

Figure 4. Examples of fault profiles with the same stochastic slip distribution mapped onto (a) listric and (b) planar faults.

imperative to include listric-faulting scenarios into a seismic hazard analysis.

To improve our understanding of seismic hazard associated with listric faulting, we aim to quantify the effects of listricity on near-field ground motion by means of kinematic simulations. Using realizations of heterogeneous on-fault slip and parameterizing the curvature of the fault that allows us to define various fault profiles under tight geometrical constraints, we construct an ensemble of simulations for which we then examine peak ground velocities (PGVs) and their variabilities at over 17,000 locations. Similar to [Ripperger et al. \(2008\)](#), rather than trying to model particular seismograms of an individual event, we are interested in the general characteristics of near-field ground motion, such as its peak amplitude and the spatial distribution and variability caused by the changes in fault geometry.

Methodology

To study ground-motion variation caused by listricity, we use a generalized 3D finite-difference method to run a

Figure 5. Ten stochastically generated slip models with slip-dependent rupture speed. The white lines represent rupture onset times at 1 s intervals. The slip distributions are chosen to be as diverse as possible. For example, model 7 has a comparatively homogeneous slip with respect to model 9, which has a slip distribution concentrated near the bottom of the fault (compared to model 1). Note that some cases show concentrated slip near the top edge of the rupture (e.g., models 1 and 10), whereas for others slip occurs in the center of the fault plane (models 4 and 6).

multitude of fault parameterizations in which the slip distribution, rupture speed, depth of the top of the fault (H_{top}), and listricity is varied to construct a set of simulations for a scenario M_w 6.8 earthquake. Although this is not the maximum magnitude for a listric fault, it is consistent with estimates for potential future earthquakes on faults that have been recognized to be listric (e.g., the Campotosto fault north of L'Aquila has been found to have a clear listric shape; [Valoroso, 2016](#)).

Figure 6. Seismograms of fault-parallel, fault-perpendicular, and vertical components for five selected receivers shown in Figure 2, for the planar fault (black) and the listric fault (red), each with uniform slip and buried at 0.125 km. Listricity increases from left to right: (a) is for listricity factor $C = 12$, (b) $C = 8$, and (c) $C = 4$.

In this section, we explain how the synthetic seismograms are calculated and how the parameters for the kinematic faults have been chosen. Table 1 summarizes the rupture parameterization used in this study.

Computational Aspects

Because the primary scope of this study is to understand the effects of variations in fault geometry on ground motions, the faults are buried in a uniform isotropic medium, with P wavespeed $V_P = 6$ km/s, S wavespeed $V_S = 3.6$ km/s, and density $\rho = 2800$ kg/m³. This parameterization ensures that the results observed are attributable only to source effects and thus avoids any effects attributable to medium heterogeneity (e.g., waves trapped between layers having high-velocity contrast).

To generate the synthetic seismograms, we use the Support Operator Rupture Dynamics (SORD) code, which is a generalized finite-difference method (Ely *et al.*, 2008). Because the study requires a large number of simulations, we set the maximum frequency to 1 Hz, striking a balance

between computation time and resolvable details. Although engineers typically desire frequencies closer to 10 Hz, these models depend on physical parameters that vary significantly from region to region and require a thorough knowledge of the source, wavepath, and site characteristics, thus limiting their scope to a specific region. By simulating lower frequencies, our results have a broader application.

To achieve accurate wave propagation for the selected frequency, we require a minimum of 15 nodes per wavelength. This, in combination with the aforementioned medium parameters, leads to a spatial grid size of 125 m. Given the above requirement, the computational timestep is set at 0.01 s to satisfy the numerical stability criteria given by Ely *et al.* (2008).

Receivers are placed at the free surface on a uniform grid with 1-km node spacing. This results in more than 17,000 synthetic seismograms computed in a domain of dimensions $138 \times 128 \times 64$ km in the north-south, east-west, and vertical directions, which are used to generate the shake maps presented in this study. From this set, 300 locations are ran-

domly picked, and the rotated geometric mean of the horizontal components (GMRotD50; Boore *et al.*, 2006) is computed for the comparisons with an empirical GMPE (Boore and Atkinson, 2008). An additional set of five near-field sites distributed evenly around the fault is chosen for detailed waveform comparisons. Figure 2 shows the map of the receiver locations.

The simulations are run on Shaheen, a Cray XC40 supercomputer, requiring ~1800 core hours each, to obtain three-component seismograms of 30 s duration.

Fault Geometry

To estimate the effects of listricity, we use three listric profiles and one reference planar profile for quantitative ground-motion comparisons. There are several methodologies that can be used to create listric fault profiles, for example, the chevron construction (Verrall, 1981; Gibbs, 1983) or the modified chevron construction (Williams and Vann, 1987), both proposed to estimate listric fault shape from a rollover profile. Similarly, the slip-line construction (Williams and Vann, 1987) also uses the rollover profile to estimate the listric fault curvature, but instead of displacement affecting all material in vertical heave segments, it assumes that the material moves along a series of slip lines parallel to the fault profile. However, the aforementioned methods have two shortcomings: first, they require a rollover profile (usually from field observations), and second, they do not offer any means of parameterizing the final curvature.

To overcome these issues, we employ the method proposed by Wang *et al.* (2000) to approximate the M_w 7.9 Wenchuan earthquake fault curvature. The advantage of this method is that it does not require an initial rollover profile to estimate the curvature of the fault and allows a simple parameterization of the listricity using two parameters, based on the following equation:

$$\delta = \delta_0 \times \left[1 - \exp\left(-\frac{C}{h}\right) \right]. \quad (1)$$

Equation (1) includes the listricity coefficient (C) and the initial fault dip (δ_0), and can be used to estimate the depth-dependent dip (δ) for a given depth (h). By having only two coefficients to adjust, the parameter space to be investigated remains small. We apply equation (1) to generate listric faults of low, medium, and high listricity to cover a large variety of cases for analyzing the effects of listricity throughout this article. Our target average dip of 45° provides

Figure 7. Ground-motion comparisons in terms of PGV (calculated using GMRotD50) for the uniform-slip case on the planar and the three listric-fault parameterizations. We chose 300 random receivers (Fig. 1) and plotted the Boore and Atkinson (2008) GMPE for reference (dashed lines represent intraevent standard deviation). Red receivers are located on the hanging wall and blue ones on the footwall. (a)–(d) are respectively the planar and the listric cases for C factor 12, 8, and 4. As listricity increases from (a) to (d), sites on the hanging wall show an increase of PGVs, whereas sites on the footwall decrease in PGV.

the bounds for the C factor; for instance, using a value $C < 4$ requires an unphysical initial dip angle $\delta_0 > 90^\circ$. Based on this, we chose C factors equal to 4, 8, and 12 for high, medium, and low listricity. To find the initial dip angle, we iteratively create fault profile realizations until the subfault's average dip angle is within 0.1° of the target (45°). Figure 3 shows the listric profiles compared with their planar equivalents (with dip 45°) used in the simulations.

The length and width of the assumed rupture plane are 30 and 20 km, respectively, consistent with earthquake source-scaling relations (e.g., Wells and Coppersmith, 1994; Mai and Beroza, 2000) for dip-slip events of the chosen magnitude (M_w 6.8).

Distributions of Fault Slip

We use both uniform and heterogeneous slip models with mean slip $D = 89.8$ cm. The simplicity of uniform slip allows us to gain an initial understanding of the listricity effects without complexities introduced by the rupture process. Although uniform slip models offer a good starting point for analysis, their homogeneity can lead to artifacts in the observations, such as exaggerated directivity effects (Bernard and Herrero, 1994).

To overcome this, we create heterogeneous slip models using stochastically generated slip distributions following Mai and Beroza (2002). The slip-model generator calculates

a dislocation model using the spectral synthesis method in which the slip amplitude spectrum is defined through a spatial autocorrelation function or a power-law decay. Furthermore, given fault dimension, mechanism, and an autocorrelation function of choice (we use anisotropic von Karman) the correlation length or fractal dimension (i.e., spectral decay) of the autocorrelation function are computed using source-scaling relations based on the given seismic moment. From a large number of random slip distributions, we then select a subset of models that are as diverse as possible to avoid results which could be attributed to only a particular combination of source parameters. Figure 4 depicts an example of such a stochastic slip distribution, applied to a listric and the planar-fault case.

The final fault parameters for the M_w 6.8 source are as follows: 20 km width, 30 km length, 0.90 m average slip, Hurst exponent $H = 0.80 \pm 0.11$, $a_z = 6.46 \pm 0.97$ km correlation length down-dip, and $a_x = 10.39 \pm 1.08$ km correlation length along strike. Both uniform and heterogeneous models have 1 km of slip tapering toward the fault edges to minimize possible artifacts from unrealistically strong stopping phases.

The temporal evolution of slip on each point on the fault is described using a regularized Yoffe source time function (Tinti *et al.*, 2005) with rise time of 3.0 s, time to peak slip of 0.15 s, and a sample frequency of 0.01 s. The parameters for the slip-rate function were chosen to generate frequencies higher than 1 Hz, consistent with our intended simulation frequency target.

Rupture Speed

For our simulations, we used two different sets of rupture speeds (V_{rup}): (1) uniform and (2) slip dependent. In the uniform case, V_{rup} for the entire fault is set to 3.31 km/s, equal to 92% shear wavespeed. Although this provides a good starting point for initial observations, variations in V_{rup} have been noted to produce considerable effects on ground motions (e.g., Aagaard *et al.*, 2001; Graves *et al.*, 2008; Imperatori and Mai, 2012). Because our goal is to achieve a source characterization that approximately mimics the dynamics of earthquake rupture, without having to perform full dynamic simulations, we correlate V_{rup} to slip. To this end, we construct a rupture velocity distribution that reflects the spatial properties of the slip distribution but at the same time allows us to control the increase of V_{rup} with slip, the average V_{rup} , and then the maximum and minimum rupture speed that is physically plausible. The distribution of rupture velocity is computed based on the mean slip D and its standard deviation σ , using the error function parameterization as follows:

$$\varphi = 1.001 + 0.5 \times \text{erf}\left(\frac{D \times a}{\sigma \sqrt{b}}\right). \quad (2)$$

Based on careful calibration, a and b are chosen equal to $a = 0.5$ and $b = 2$ to satisfy the above conditions (e.g., ensuring subshear V_{rup}) for all heterogeneous slip models.

Figure 8. Seismograms of fault-parallel, fault-perpendicular, and vertical components of ground velocity in cm/s for five selected receivers (Fig. 2). In (a), we display the planar case, with H_{top} at different depths. In (b), we show the corresponding listric cases, including the planar seismogram at H_{top} 0.5 km for reference (in black). As the fault is buried deeper, the arrival times are delayed, most notably at stations 1 and 2 on the fault-perpendicular and vertical components. In contrast to an anticipated decrease in peak amplitudes as H_{top} increases, the rupture directivity for the deeper fault generates higher amplitudes for stations 1 and 2. This dominates the PGV calculations because the fault-parallel component is much smaller in comparison to the fault perpendicular.

Figure 5 shows the heterogeneous slip distributions with rupture onset times at 1 s intervals calculated using a rupture-front tracking algorithm.

Using simple relationships between kinematic and dynamic source parameters, we can build physically self-consistent kinematic models and avoid the computational expense of full dynamic simulations. This framework is referred to as pseudodynamic (e.g., Guatteri *et al.*, 2003, 2004; Song *et al.*, 2009; Schmedes *et al.*, 2010; Mena *et al.*, 2012).

Results

We analyze our ground-motion simulation results in terms of shake-map-like spatial distributions of PGV by examining a selection of three-component seismograms at designated locations and by comparing simulation data against empirical predictions from GMPEs.

For simulations with homogeneous parameters (uniform isotropic medium, with uniform slip distribution and rupture speed), we expect strongly correlated ground motions in the fault-perpendicular component. To better estimate PGV, we therefore use the GMRotD50 metric (Boore *et al.*, 2006),

Figure 9. Comparison of horizontal GMRotD50 from our simulations (symbols) with empirical predictions (lines) (Boore and Atkinson, 2008) for different values of H_{top} . (a) and (b) are for the hanging-wall planar and listric simulations, whereas (c) and (d) are for the footwall planar and listric simulations. In the distance range $0.5 < R_{\text{JB}} < 5$ km, ground velocities on the footwall of the listric fault increase as the fault is buried deeper. This is a consequence of the focusing effect due to the curvature of the fault. Ground motions on the hanging wall behave more as expected, with a general trend of decreasing PGV as H_{top} increases.

which removes the dependency from receiver orientation by computing a set of geometric means on all possible non-redundant orientation angles and by accepting the median as the best estimator. Hereafter, when referring to PGV, we are referring to the GMRotD50 estimator.

Effects of Fault Listricity on Near-Source Shaking

Let us examine how variations in the fault's listricity affect the resulting ground motions. The seismograms for the uniform-slip cases (Fig. 6) reveal that aside from the case with high listricity, the overall waveform character of the seismograms at the selected locations has not changed much: arrival time, first-motion polarity, and overall amplitudes have only small differences. Receivers 1, 2, and 5 show the largest changes, due to their close proximity to the fault and consequently higher sensitivity to the details of the source process.

Figure 10. Comparison of PGV shake maps for the planar (top row) and the listric (bottom row) fault with varying depth H_{top} (from left to right 0.5, 2.5, 5, and 10 km). In the planar case, ground motions decrease as the fault is buried, but in the listric case this is not entirely the case. There is an area (in red) where ground motions do not subside as much as in the rest of the domain, until the fault is buried 10 km deep. This is a consequence of the wave-focusing effect caused by the curvature of the fault. The listric fault produced PGVs over two times larger than the planar fault in the hanging-wall area within 20 km of the fault trace.

Figure 7 enables us to identify some trends that will carry on throughout the article: the PGV values on the footwall (in red) decrease as listricity increases, whereas the PGV values on the hanging wall (in blue) increases with listricity. Moreover, if we compare the planar fault (panel a) to the high listricity case (panel d), we see that, at distances between 8 and 12 km, the hanging-wall PGVs for the listric case do not decay as fast as in the planar case, due to a focusing effect of the seismic waves.

Effects of Increasing H_{top}

One effect we explore further is the wave focusing as the seismic waves radiate off the listric fault. For this purpose, we simulate planar and listric faults with uniform rupture parameters at four different H_{top} values: 0.5, 2.5, 5, and 10 km. We use the maximum depth of 10 km because there is evidence from high-precision foreshock and aftershock locations that listric faults may be buried down to these depths (e.g., the Campotosto fault has an H_{top} of about 6 km; [Valoroso, 2016](#)). As the fault is buried deeper, the intensity of the ground shaking is expected to diminish, due to the increased source-to-site distance. This behavior is observed in the planar case, which shows decreasing ground motions for the entire domain as H_{top} is increased (Figs. 8 and 9). However, this pattern is not observed in the listric case, which instead shows some very interesting characteristics. A few observations are particularly important in the seismograms in Figure 8; as expected, burying the faults deeper causes a delay in the first arrival, as is clearly seen at stations 1 and 2 on the fault-perpendicular and vertical components. Together with the shift in time, we also expect a decrease in peak amplitudes with increasing H_{top} . However, the area in the forward-directivity direction of rupture (stations 1 and 2) shows consistently high amplitudes. This dominates the PGV calculations because the fault-parallel component is much smaller in comparison to the fault perpendicular, due to the homogeneity of the medium. The reason for this will be discussed in the following paragraphs.

Figure 9 compares simulation-based PGV values with estimates from GMPE ([Boore and Atkinson, 2008](#)) for increasing H_{top} values. In general, both planar and listric faults are consistent with the GMPE and the notion of decreasing ground motion with increasing H_{top} . However, between Joyner–Boore distances (R_{JB}) 0.5 and 5 km, the listric fault creates larger ground motions on the footwall compared to the planar case and the GMPE.

From the shake maps (Fig. 10), we observe that ground motions in the planar case decrease over the entire region as the fault is buried, whereas for the listric case there is an area with high PGV (in red) for which ground motions do not subside as much as in the rest of the domain. Figure 11 helps explain this observation. Analyzing cross sections of the seismic wavefield at different times, we see that there is a considerable difference between the wavefronts of the listric and planar faults as they approach the free surface. The pla-

Figure 11. Snapshots of the geometric mean of the horizontal ground velocities (in m/s) for the east–west vertical profile taken at 70 km northing. The (b) listric fault is parameterized with $\delta_0 = 82^\circ$, $C = 4$, and $H_{\text{top}} = 10$ km, and (a) is the planar fault. Already after 4.04 s, differences in shaking levels begin to emerge between the (a) planar and (b) listric faults. The waves emanating from the planar fault show a symmetrical pattern. In contrast, the shape of the listric fault forces the wavefront to turn upward, due to its curvature. These wavefield cross sections illustrate the generation of the high PGV area (see also Fig. 10), with noticeable differences in how the waves interact with the free surface. The angle at which the wavefronts reach the surface is also different. In the planar case, it continues propagating very close to the surface, whereas in the listric case, it is reflected back toward depth, explaining the lower ground motions on the footwall for the listric faults with respect to the planar fault.

nar profile (left) shows a wavefront that is symmetrical and projected toward the surface at the same angle as the fault dips. The listric profile (right) has a very different shape and approaches the free surface at a different angle. In the listric case, this causes the waves to reflect off the free surface and propagate toward the bottom of the domain (this interaction is demonstrated in [Movie S1](#), available in the electronic supplement to this article). On the other hand, the waves in the planar case travel closer to the free surface for longer duration, causing the observed lower PGV values for the footwall in the listric scenario.

Figure 12. Seismograms for source models 8, 9, and 10 of fault-perpendicular (top row), fault-parallel (middle row), and vertical components (bottom row) of ground velocity (in cm/s) at the five receivers shown in Figure 2. For footwall receivers (a) R1 and (b) R2, the perpendicular components show noticeable differences between source models, with model 10 amplitudes an order of magnitude larger compared to model 9. In these locations, the planar fault clearly experienced larger ground motions, and overall PGVs are higher compared to other receivers (note the scale variations). This is attributed to directivity effects. Receivers (c) R3 and (d) R4 on the hanging wall show that model 10 with a shallow slip patch creates smaller peaks with longer periods when compared with model 9. Model 10 creates the largest velocities for receiver (e) R5, due to its vicinity to the high slip patch. As the rupture mechanism is pure dip-slip, there is very little effect on the fault-parallel components, hence all heterogeneous models share very similar waveforms on this component. The same applies for uniform slip. The vertical component shows a mixture of expected and unexpected features. The ground motions on the footwall (R1 and R2) are unexpectedly lower for model 9 with the deeper high slip patch. For the hanging-wall receivers (R3 and R4), the results are more complicated to interpret. Interestingly, model 9, with the deeper slip patch, generates higher vertical ground velocities. It is important to note that due to the vicinity to the fault and due to the rupture complexity, altering the location just by a few kilometers changes the waveforms substantially. The same can be said for receiver R5 located within the fault projection to the surface.

Slip-Dependent Rupture Speed

The random slip distributions (Fig. 5) cover a variety of cases. For example, the large slip patches are located at different azimuths with respect to the hypocenter; in some realizations, slip is concentrated in a small area, whereas in others it is more homogeneously distributed. By parameterizing rupture speed as a function of slip, we are further breaking up the coherency of the waves emanated from the fault. This rupture complexity creates a broad range of scenarios for evaluating near-source ground-motion variability.

We start by examining seismograms from models 8, 9, and 10 (Fig. 12). Model 8 has a fairly evenly distributed slip pattern; therefore, we expect the waveforms to be similar to

the one of the models with uniform slip distribution. Model 9 has the high slip patch located down-dip from the hypocenter, in an area of the fault that is close to horizontal. This may potentially generate lower vertical motions compared to model 10, which has a high slip patch located up-dip from the hypocenter and closer to the free surface on a part of the fault with high dip angle. Figure 12 clearly demonstrates the strong effects of these slip-model variations on the near-fault seismic wavefield. The footwall receivers 1 and 2 (R1, R2) on the fault-perpendicular component show noticeable differences between source models, with amplitudes of model 10 an order of magnitude larger compared to model 9. In these locations, the planar fault clearly experienced larger ground motions, in line with our previous observations.

Figure 13. Maps of PGV ratios, in which positive values represent higher PGVs for the listric fault, whereas negative values represent higher PGVs on the planar fault. A PGV ratio of unity means that the listric fault experiences ground motions 100% higher than the planar fault. Two general observations can be made from these ratios: first, the listric fault produces higher ground motions on the hanging wall (right part in each map) but lower ground motions on the footwall. This is consistent with our previous observation for the case of uniform slip (e.g., Fig. 6). Second, there is an area of high PGV for the listric fault near the fault trace, with PGV ratios in the 1.5–2 range, indicating ground-motion amplifications of up to a factor of 3 (ratio = 2). This area generally is located near high-slip patches close to the top of the fault. A secondary focusing effect can be observed on the hanging wall (between 70 and 100 km easting), which appears more pronounced in models that have a high-slip patch in the lower half of the fault (e.g., models 1 and 9), as opposed to models with a high-slip patch at a shallower depth (e.g., 1 and 10). In some cases, these focusing effects lead to PGV ratios of 2, equivalent to a 200% PGV increase for the listric fault.

The overall PGVs are also higher at R1 and R2 compared to other receivers (note the scale variations), due to directivity effects. Receiver 3 and 4 (R3 and R4) on the hanging wall show that model 10 with a shallow slip patch creates smaller peaks with longer periods compared to model 9. Model 10 creates the largest velocities for receiver 5, due to the vicinity of R5 to the high-slip patch. As the rupture direction is pure dip-slip, there is very little effect on the fault-parallel components, so even heterogeneous slip models have very similar fault-parallel waveforms. Finally, the vertical motions on the footwall (R1 and R2) are lower for model 9 with the deeper high-slip patch. For the hanging-wall receivers (R3 and R4), the results are more complicated to interpret. At these locations, model 9 generates larger vertical ground velocities. Obviously, because of rupture complexity, changing the location just by a few kilometers in the near-source region has profound effect on changes to the waveforms.

Figure 13 shows PGV ratios, computed as the PGV values of the listric case over the planar fault for 10 different slip models. An overall trend is clearly visible: the listric fault creates larger ground motions on the hanging wall, whereas the opposite is true for the footwall. On closer inspection, two other features can also be noted: first, we observe a region with PGV values 1.5–2 times higher in the listric case near the fault trace, generally associated with the

location of high slip patches in the upper part of the fault; and second, focusing is also observed on the hanging wall between 70 and 100 km easting. This focusing is generally more pronounced for models with high-slip patches in the lower half of the fault (e.g., models 1 and 9) as opposed to models with high-slip patches at shallower depth (e.g., models 1 and 10). This focusing effect causes PGVs over two times higher in the listric simulation.

As the scope of the article is to describe general observations regarding the effects of fault listricity on near-fault ground motions, Figure 14 shows average PGVs for the planar and listric case, considering the 10 slip-model realizations used in this study (Fig. 5). Although the overall spatial patterns of the two shake maps are similar, differences can be seen near the fault due to heterogeneous slip. The previously noted differences for the hanging wall and footwall are not well developed in this comparison. However, by examining the averaged PGV ratios (Fig. 15 and the random receiver PGV comparison in Fig. 16), these differences are much better visible. The region with higher ground motions for the listric case, near the fault trace, is clearly visible, and the secondary focusing on the hanging wall (between 80 and 95 km easting) becomes much more evident, showing PGV values that are over 1.5 times larger for the listric fault than for the planar one.

Figure 14. The average shake map from 10 PGV maps (shown in Fig. 13) summarizes the overall listricity effect on ground-shaking levels. First, the different distribution of high values near the fault trace is noticeable, with the listric fault having a pocket of very high PGV values (with differences above 20 cm/s, i.e., two times higher in the saturated areas in the directivity region on the footwall). Second, the listric fault overall produces higher PGVs on the hanging wall compared to the planar. Figure 15 shows this in more detail.

Figure 15. Average PGV ratios of 10 maps shown in Figure 13. Positive values represent higher PGVs for the listric fault, whereas negative values represent higher PGVs on the planar fault. This graph corroborates our previous observation that the listric fault produces higher ground motions on the hanging wall and lower on the footwall. Note the region of high PGVs for the listric fault near the fault trace (with listricity creating values 1.5–2 higher than the planar) and a secondary wave-focusing effect on the hanging wall between 70 and 100 km easting.

As an additional analysis, we examine the final surface displacements by integrating the surface seismograms in time. The final displacements are also compared with Okada static displacement models (Okada, 1992), yielding an identical result. The curvature of the listric fault creates the premise for a region of uplift on the hanging wall. Figure 17 shows that, between 70 and 100 km, the observed final static displacement in the listric case is over four times larger than

Figure 16. PGV comparison with respect to the Boore and Atkinson (2008) GMPEs (dashed line represent intraevent standard deviation) at 300 random receiver locations for the average shake maps in Figure 15. (a) is for the footwall and (b) for the hanging wall. Red and blue receivers represent the listric and planar geometries, respectively. This figure illustrates that at short R_{JB} distances the footwall experiences higher PGV values in the listric scenario but lower PGV beyond distances of 10 km. The hanging wall in general has higher PGVs in the listric case, with a peak at an R_{JB} distance of around 15 km (similar to what can be seen in the PGV ratios map in Fig. 15).

in the planar case to accommodate the curvature of the fault plane.

Discussion

At least four general observations can be made about the effects of listricity on near-field ground motions: (1) as listricity increases, the hanging wall shows an increase of PGVs and the footwall a decrease with respect to the planar case; (2) an increase of H_{top} affects the planar and listric fault very differently; in the former, we clearly see ground motions decreasing as the fault is buried, whereas in the latter, this is not entirely the case. This can be seen in Figure 10, where the area adjacent to the fault trace continues to experience high ground motions until the fault is buried 10 km deep; (3) by averaging the computed PGV shake maps for the heterogeneous slip models and computing PGV ratios (Fig. 15), we discover a secondary focusing effect on the hanging wall, in which, at R_{JB} distances of 10–15 km, PGV values were over 1.5 times higher in the listric case. Most likely, the location of this focusing depends on the average dip, but further simulations are necessary to test this conjecture; and (4) the curvature of the listric fault creates the premise for a region of uplift on the hanging wall, where the final displacements are over five times larger than in the planar-fault case.

Our results have strong implications for seismic hazard assessment in case listric faults are located in the proximity of important structures. For example, in the Campotosto area in Italy, where parts of the fault are running under the Campotosto dam, very strong ground motion variability may be expected, and the potential for differential vertical near-fault displacement cannot be ruled out. At these distances (less than 1 km), the listric faults simulations predict twice larger PGV values than for the comparable planar fault, as

Figure 17. Comparison of final surface displacements for the (a) fault perpendicular, (b) fault parallel, and (c) fault vertical. The plots are computed by integrating the surface seismograms in time. The curvature of the listric fault creates the premise for a region of uplift on the hanging wall. Between 70 and 100 km easting, the observed final static displacement in the listric case is above four times larger than in the planar case to accommodate the curvature of the fault plane.

well as for a GMPE-based estimation. These findings should be considered when updating the seismic hazard assessment at this (and similar) locations, because it may affect the structural design criteria.

Conclusion

Numerical simulations show that ground-motion amplitudes are affected by listricity in an intricate manner. At least three general observations illustrate the effects of listricity on near-field ground motions:

- with increasing listricity, PGVs reduce on the footwall and increase on the hanging wall;
- burying the fault generates strong wavefront-focusing effects and creates areas close to the fault trace, with peak ground motions that are 2.5 times higher than for the planar case; and
- secondary wavefield focusing effects for hanging-wall sites at R_{JB} distances of 10–15 km cause PGV values over 1.5 times higher than for the planar case.

In the example of the Campotosto fault (Italy), the listric fault simulations for the region of the Campotosto dam predict twice larger PGV values than for the comparable planar fault or for the GMPE-based estimation. The implications of ignoring source effects of listricity in the near-field region could have serious consequences for such man-made structures. In conclusion, listricity causes systematic changes in ground motions, making it an important factor when

estimating seismic hazard in the near-field region, where the effect of fault geometry enhanced by the rupture process are most influential.

Data and Resources

Figure 1 adapted from <https://www.studyblue.com/notes/n/exam-iii/deck/1495069> (last accessed August 2017). Stochastic slip distributions in this study were created using the RUPGEN tool located at <http://equake-rc.info/CERS-software/rupgen/> (last accessed August 2017).

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