The Near-Fault Ground Motion Characteristics of Sustained and Unsustained Free Surface-Induced Supershear Rupture on Strike-Slip Faults

Feng Hu1, David D. Oglesby2, and Xiaofei Chen3

1School of Earth and Space Sciences, University of Science and Technology of China, Hefei, China, 2Department of Earth and Planetary Science, University of California, Riverside, CA, USA, 3Department of Earth and Space Sciences, Southern University of Science and Technology, Shenzhen, China

Abstract The free surface is shown to be one of the key factors that may promote supershear rupture propagation on strike-slip faults even if its initial shear stress is not larger enough as predicted by the Burridge-Andrews mechanism. However, previous study has shown the free surface-induced supershear rupture may be unsustained, which turns to sub-Rayleigh rupture itself as the rupture propagates. We study the near-field ground motion of sustained and unsustained supershear ruptures using the finite difference method based on the dynamic rupture processes of three vertical strike-slip faults with the same initial stresses and different hypocenter depths. Both the unsustained supershear ruptures with shallower hypocenter depths show the sub-Rayleigh characteristics in the peak ground velocity distribution, that is, strong amplitude is noticed beyond the end of the fault without any observed Mach cone. We observe that the arrival time differences between the maximum fault-perpendicular and fault-parallel velocity reveal the Mach cone clearly for the sustained supershear rupture. A distinct supershear phase in the high-frequency seismograms is observed. We also compare the 70° dip strike-slip case in which unsustained supershear rupture may still present sub-Rayleigh characteristics in the near-field ground motion, and the break of symmetry perturbs the normal stress as rupture propagates, which has a key influence in the rupture propagation and ground motion. Our work provides a new insight to understand the supershear rupture in nature earthquakes and the relationship between the ground motion and the rupture process on the fault.

Plain Language Summary The free surface-induced supershear rupture on strike-slip faults could turn to sub-Rayleigh rupture before it reaches the end of the fault under certain conditions. Sometimes the area that rupture propagates at supershear speed could be tens of kilometers long for the unsustained supershear ruptures. By comparing the vertical strike-slip faults with the same initial stress and different hypocenter depths, our study shows that such unsustained supershear rupture still may not trigger the observable Mach cone on the free surface, and its peak ground velocity also presents sub-Rayleigh rupture characteristics. The arrival time differences between the maximum fault-perpendicular and fault-parallel velocity reveal the Mach cone clearly for the sustained supershear rupture. We also compare the 70° dip strike-slip case which also supports that unsustained supershear cannot trigger observable Mach cone in the free surface, and the normal stress unclamping ahead of the right-lateral rupture front may facilitate the slip on the free surface, which helps to generate the sustained supershear rupture there. The Mach cone of the sustained supershear ruptures mainly distributes in the hanging wall direction. Our work helps to understand the relationship between the supershear ground motion characteristics and the rupture process.

1. Introduction

Supershear rupture (the propagation of a rupture front at a speed faster than the S wave speed) has been predicted by theoretical and numerical studies (e.g., Andrews, 1976b; Burridge, 1973; Day, 1982). It also has been observed directly and indirectly via ground motion measurements in a number of strike-slip earthquakes, including the M6.5 1979 Imperial Valley (Archuleta, 1984; Olson & Apsel, 1982), 2001 M8.1 Kunlunshan (Bouchon & Vallée, 2003), 2002 M7.9 Denali Fault (Dunham & Archuleta, 2004), and 2018 M7.5 Palu (Bao et al., 2019; Socquet et al., 2019) events, as well as aftershocks of the 2013 M8.3 Sea of
Okhotsk (Zhan et al., 2014) event. Because supershear rupture can propagate stably only in the Mode II direction, it is most commonly seen in long strike-slip faults such as the examples above. Supershear rupture has also been reproduced on the small scale in laboratory analogs of earthquakes (Lu et al., 2009; Passelegue et al., 2013; Rosakis et al., 1999; Wu et al., 1972; Xia et al., 2004). The presence of supershear rupture can shed light into the physical state of the fault, for example, implying that the fault is relatively close to failure (Andrews, 1976b; Day, 1982) and/or the energy release rate is high compared to the fracture energy (Madariaga & Olsen, 2000), and/or a high-strength barrier is encountered during rupture propagation process (Dunham et al., 2003). The implications of supershear ground motion are important from a practical as well as theoretical consideration, as a supershear crack produces a seismic radiation field that is qualitatively different from that of a subshear crack, with the formation of a Mach cone of $S_0$ waves, a reduction of the effects of directivity, and the presence of higher ground motion in the fault-parallel (instead of fault perpendicular) component of seismic recordings (Aagaard & Heaton, 2004; Dunham & Archuleta, 2004; Ellsworth et al., 2004; Mello et al., 2016). Near-source records are of key importance to identifying supershear earthquakes, such as Pump Station 10 (3 km from fault) in the 2002 Denali fault event (Dunham & Archuleta, 2004). In addition to an $S$ wave Mach front, a Rayleigh Mach wave front is also noticed in elastic media in dynamic rupture simulations with fixed rupture velocities (Dunham & Bhat, 2008). This additional Mach cone has been utilized to identify supershear earthquakes using far-field surface waves, such as the 2001 Kunlunshan earthquake (Vallée & Dunham, 2012) and the 2018 Palu earthquake (Bao et al., 2019). Thus, for a variety of reasons, it is important to understand the physical mechanisms by which rupture may propagate at speeds faster than the $S$ wave speed.

Perhaps, the most cited mechanism for supershear rupture propagation is the Burridge-Andrews effect (Andrews, 1976b; Burridge, 1973). In this mechanism, the $S$ wave radiation ahead of a sub-Rayleigh speed crack gradually builds in strength until the stress level in the wave exceeds the static frictional strength of the fault; at this time, a daughter crack forms ahead of the sub-Rayleigh crack. This daughter crack can then accelerate up to the $P$ wave speed. After some time, the parent sub-Rayleigh crack slowly dies out (due to the daughter crack relieving a gradually increasing proportion of the elastic stress), leaving only the supershear crack to propagate forward. In a homogeneous model, the ability of rupture to make this sort of transition hinges on how close the fault is to failure, as well as the amplitude of its stress drop. These factors are combined into a relative fault strength ratio $S$ (Andrews, 1976b; Das & Aki, 1977):

$$S = \frac{\tau_y - \tau_0}{\tau_0 - \tau_f},$$

where $\tau_y$ is the yield stress on the fault (typically the static frictional coefficient $\mu_s$ times the normal stress $\tau_n$), $\tau_0$ is the initial shear stress on the fault, and $\tau_f$ is the final frictional stress on the fault (typically assumed to be the sliding frictional coefficient $\mu_f$ times the normal stress $\tau_n$). In 3-D, the maximum value of $S$ for the Burridge-Andrews supershear transition to take place is roughly 1.19 (Dunham, 2007), which is further proven to be also related to the characteristic slip-weakening distance, and the nucleation radius (Xu et al., 2015).

The above mechanism can occur for faults in a whole space with homogeneous stress and frictional properties. However, supershear rupture can also be spurred by forms of fault heterogeneity, even if the average $S$ value over the fault is greater than that which would lead to supershear propagation via the pure Burridge-Andrews mechanism. For example, heterogeneity in stress (Day, 1982; Dunham, 2007; Liu & Lapusta, 2008) and/or fault geometry (causing a resulting stress heterogeneity on the fault) can also lead to a supershear transition (Bruhat et al., 2016; Huang et al., 2014). Rupture that propagates around a barrier can jump to supershear speeds afterward as it “catches up” past the barrier (Dunham et al., 2003). A fault bend can strongly affect rupture velocity (Poliakov et al., 2002; Rice et al., 2005); rupture that propagates around an extensional bend can (at least briefly) propagate at supershear speeds under the effects of dynamic fault unclamping, which lowers the normal stress and thus effectively reduces $S$ (Oglesby & Mai, 2012). Fault stepovers can also induce supershear rupture in a similar manner: rupture on one fault can dynamically reduce the normal stress on a neighboring fault, allowing the rupture to jump and transition to supershear on the neighboring fault. This effect persists even as the rupture propagates outside of the area of lowered $S$ on the secondary fault into an area with an $S$ that would otherwise preclude supershear rupture (Bruhat et al., 2016; Hu et al., 2016; Ryan & Oglesby, 2014).
Another key mechanism for the supershear transition is the interaction between the rupture front, the radiated wave field, and the Earth’s free surface, particularly when the fault itself intersects the surface (Kaneko & Lapusta, 2010; Zhang & Chen, 2006). This effect has been explored in detail by Kaneko and Lapusta (2010). Their work finds that the primary source of supershear rupture is the conversion at the free surface of upward propagating SV phases from the hypocenter to horizontally traveling P phases, which can load the fault at supershear speeds and facilitate supershear rupture propagation. The rupture does not jump ahead of a subshear crack as in the Burridge-Andrews mechanism; rather, it extends continuously from the main rupture front. The efficiency of this mechanism is strongly affected by depth-dependent stress heterogeneity; however, in cases of simple homogeneous stress, the overall stress level does not significantly influence the transition length of the crack to supershear. The transition length is rather scaled by the depth of the hypocenter, consistent with the importance of phase conversions to the process.

Given the multitude of mechanisms by which ruptures may transition to supershear speeds (with the free surface-induced mechanism being particularly efficient) and the multitude of large strike-slip earthquakes worldwide, it is reasonable to ask why supershear rupture is not ubiquitously observed.

One possibility is that free surface-induced supershear rupture may sometimes be ephemeral, similar to supershear rupture induced by heterogeneity in geometry or stress. Recent work by Hu et al. (2019) has further examined the mechanism of free-surface supershear rupture to address the issue of whether such supershear rupture is sustained indefinitely after the transition in speed, or whether it may revert to sub-Rayleigh speed even in homogenous stress conditions. While reproducing the results of Kaneko and Lapusta (2010) for homogeneous models with similar parameters, they found that for a variety of stress conditions, particularly for S values higher than those explored by Kaneko and Lapusta (2010), interactions with the free surface can induce supershear rupture near the free surface, but the rupture speed can later return to a sub-Rayleigh level. In general, this unsustained supershear rupture occurs for high values of S, high values of normal stress (even with similar S), low stress drop, and shallow hypocenter depth. In cases of sustained supershear rupture, the supershear daughter crack and the sub-Rayleigh parent crack persist simultaneously for a while, with the supershear crack growing in peak slip rate, and the sub-Rayleigh crack gradually attenuating. For unsustained supershear rupture, both parent and daughter cracks may persist for some distance while both propagate at sub-Rayleigh speed. This effect increases the difficulty of determining supershear rupture directly from “kinked” rupture time contours, which appear similar to supershear rupture, but, in fact, do not actually correspond to such a high rupture speed. In many cases, the daughter crack eventually merges with the parent crack. This work also noted that a strong fault-parallel component of near-source ground motion is still indicative of localized supershear rupture in the unsustained case, even if a strong Mach cone is not apparent.

The present work continues the exploration of unsustained supershear-induced rupture, with a particular focus on how this complicated rupture process can affect near-source ground motion. By characterizing the ground motion patterns associated with this process, observational seismologists may be able to detect such features and glean more details about the rupture and slip processes in real earthquakes.

2. Methods

We use the 3-D dynamic finite difference method (Zhang et al., 2014) to perform spontaneous dynamic rupture simulations of earthquakes on planar strike-slip faults that intersect the free surface. The technical details of the method are largely the same as our prior work in Hu et al. (2019). For simplicity, we use a homogeneous Poisson half space and a homogeneous stress distribution with physical and computational parameters listed in Table 1. Most models include a vertical strike-slip fault, but some include a strike-slip fault with a dip of 70°. The fault is 60-km long and 15-km wide (down-dip). All faults are prestressed in the purely strike-slip direction, although we allow slip in any direction on the fault. We use a slip-weakening constitutive law (Andrews, 1976a; Ida, 1972; Palmer & Rice, 1973) for friction on our fault, in which the yielding stress \( \tau_d \) decreases from \( \tau_{dn} = \mu_0 \tau_n \) to the residual stress \( \tau_f = \mu_0 \tau_n \) as the slip increases from 0 to the characteristic slip-weakening distance \( D_0 \). We check the resolution of our finite difference grid size of 50-m spatial grid and 0.005-s temporal step with models of 25-m spatial grid and 0.0025 temporal step and find excellent agreement, implying that our results are not grid dependent. Our nucleation procedure is to boost our prestress to failure level over an elliptical region (semimajor axis of 3 km and semiminor axis of...
### Table 1

| Parameters                          | Values            |
|------------------------------------|-------------------|
| Fault Length Along Strike          | 60 km             |
| Fault Width Along Dip              | 15 km             |
| Density $\rho$                     | 2,667 kg/m$^3$    |
| $P$ Wave Speed $V_P$               | 6,000 m/s         |
| $S$ Wave Speed $V_S$               | 3,464 m/s         |
| Static Friction Coefficient $\mu_s$| 0.677             |
| Sliding Friction Coefficient $\mu_f$| 0.525            |
| Slip Weakening Parameter $D_0$     | 0.4 m             |
| Initial Shear Prestress $\tau_0$   | 69.29 MPa         |
| Initial Normal Prestress $\tau_n$  | 120 MPa           |
| Fault Strength Parameter $S$       | 1.9               |
| Spatial Grid Size                  | 50 m              |
| Computational Time Step            | 0.005 s           |

#### 3. Results

##### 3.1. Supershear Sustainability for Different Hypocenter Depths

The hypocenter depth $H$ is a key factor in controlling the sustainability of free surface-induced supershear rupture on strike-slip faults (Hu et al., 2019). Rupture with a shallower hypocenter depth on a strike-slip fault is more likely to propagate at sub-Rayleigh speed at the end of the fault, based on the rupture scenario summation with variety values of $S$, $H$, and $\tau_n$. To examine the characteristics of near-field ground motions for unsustained and sustained free surface-induced supershear ruptures, three vertical strike-slip cases with different hypocenter depths of 5, 7.5, and 10 km are compared, recapitulating for reference some results of Hu et al. (2019). The initial normal stress $\tau_n$ is 120 MPa, corresponding to an $S$ value of 1.9. Figure 1 summarizes the rupture time contours and rupture velocity magnitudes (calculated via $\frac{V_r}{V_S}$, where $V_r$ is the rupture time distribution [Bizzarri & Das, 2012]). We see that a hypocenter depth of 10 km leads to a sustained and growing supershear rupture on the fault: Note that the yellow (supershear) area on the fault grows as the rupture progresses along strike in Figure 1c. In contrast, shallower hypocenter depths of 7.5 and 5 km lead to unsustained supershear rupture: the supershear area disappears as the rupture progresses along strike. Consistent with the results of Kaneko and Lapusta (2010), supershear rupture commences closer to the epicenter along strike for shallower hypocenters. The distance over which the supershear rupture is sustained is also related to hypocenter depth, with the supershear rupture terminating approximately 28 km along strike for the 7.5-km hypocenter depth and 10 km along strike for the 5-km hypocenter depth. As noted in Hu et al. (2019), the shape of the rupture time contours can be an unreliable indicator of supershear rupture. In the sustained case of a 10-km-deep hypocenter, the area undergoing supershear rupture is smaller than the area inside the “kinked” rupture time curves. In the case of the 7.5-km-deep hypocenter, the rupture front shows a prominent kink in rupture time contours for a distance along strike considerably longer than that of the actual supershear rupture speed. The effect is due to the fact that the supershear daughter crack returns to sub-Rayleigh speed at approximately 28 km along strike but continues to propagate at least close to the free surface until approximately 44 km along strike, at which point it coalesces with the trailing parent crack. This crack coalescence will have implications for ground motion that are explored below. We note with this example that our operational definition of sustained supershear rupture is that supershear rupture is considered sustained if it persists

![Figure 1](image-url)
until it reaches the edge of our modeled fault. With this definition, we cannot rule out the possibility that some ruptures would have transitioned back to sub-Rayleigh speed on a longer fault, but we believe that the overall conclusions of this work would remain unchanged.

3.2. Surface Slip and Rate

The different rupture evolution patterns for the cases of unsustained and sustained supershear rupture produce different patterns of slip and slip rate on the top edge of the fault, where it intersects the free surface. As shown in Figure 2a, the surface slip distributions for the cases of unsustained supershear rupture (hypocenter depths 5 and 7.5 km) are very similar and quasi-elliptical. The surface slip distribution for the sustained supershear case (hypocenter depth 10 km) has a more peaked distribution, with a slightly higher average value. With the same prestress and frictional parameters in all cases, the different slip distribution in the sustained supershear case may be attributable to a somewhat higher dynamic overshoot. It is not clear if the higher slip is caused by the more rapid rupture propagation or whether the higher slip serves to help drive the rupture at supershear speeds.

The difference between our three cases is much more obvious in the peak surface slip rate curves shown in Figure 2b. The dashed lines depict the locations along strike where the rupture propagates at supershear speed on surface. The pattern of peak surface slip rate is complicated for all three hypocenter depths. In all cases, there is a double-sided peak centered around the epicenter (0 km along strike). This peak is largely due to both higher slip at the hypocenter (due to our nucleation method) and directivity from the upward-propagating rupture front. The highest peak in this location is for the 10-km-deep hypocenter, and the lowest peak is for the 5-km-deep hypocenter; this result is understandable in terms of the greater upward propagation distance and thus greater directivity for deeper nucleation. Perhaps, a surprising difference in the peak slip rate is found farther along strike, away from the nucleation region. The highest peak slip rate from 15 km along strike onward is for the model in which the supershear rupture reverted to sub-Rayleigh the earliest (hypocenter depth 5 km). In comparison, both the sustained supershear model (hypocenter depth 10 km) and the partially sustained model (hypocenter depth 7.5 km) produce significantly lower peak slip rate over most of the fault. We attribute this difference to the presence of two rupture fronts at the surface in both the sustained and partially sustained supershear models. In both these cases, the elastic energy release is split between two slip rate pulses. In the fully sustained case, the leading rupture front is supershear and the trailing rupture front is sub-Rayleigh. In the partially sustained case, over most of the fault both rupture fronts are sub-Rayleigh. However, in the partially sustained case, we note a significant increase in surface slip rate near the edge of the fault, beyond 40 km along strike. This increase of slip rate is due to the leading rupture front merging with the trailing rupture front, resulting in a single front releasing the elastic energy in a shorter time period than elsewhere on that fault. At this point, the peak surface slip
rate is equal to that of the unsustained supershear rupture, consistent with the fact that both models only have a single rupture front in this location.

To better visualize the differences between the effects the two rupture fronts in unsustained and sustained supershear ruptures, Figure 3 depicts the shear stress change (\(\tau_0(t) - \tau_0(0)\)) and slip rate of the two points (M and N with strike coordinates of 20 and 40 km, respectively) along the fault trace intersecting with the free surface. The rupture goes at sub-Rayleigh speed at both points for the case with HD = 5 km, and the rupture speed is supershear for the point M for the case with HD = 7.5 km, but it turns to sub-Rayleigh speed for the point N. Both points M and N experience supershear speeds for the case with HD = 10 km.

Figure 3. The (a) shear stress change (\(\tau_0(t) - \tau_0(0)\)) and (b) slip rate versus time at the point M on the fault with the strike of 20 km at the free surface for the vertical strike-slip cases with three different hypocenter depths (HD); Figures 3c and 3d show the shear stress change and slip rate plots at the point N on the fault with the strike of 40 km at the free surface. The rupture goes at sub-Rayleigh speed at both points for the case with HD = 5 km, and the rupture speed is supershear for the point M for the case with HD = 7.5 km, but it turns to sub-Rayleigh speed for the point N. Both points M and N experience supershear speeds for the case with HD = 10 km.
following sub-Rayleigh main crack. Moreover, a significant difference between the slip rates of the unsustained and sustained supershear ruptures is that the peak amplitude of the supershear daughter crack is larger than that of the following sub-Rayleigh main crack (blue lines in Figures 3b and 3d), while the situation is opposite for the unsustained supershear case (red lines in Figures 3b and 3d). Peak slip rate is less for the cases with two rupture fronts than with the case of a single rupture front, and the overall duration of slip is longer for the two-rupture front cases as well. This phenomenon could be useful to help to distinguish the unsustained and sustained supershear ruptures in the future.

3.3. Ground Motion

The distinct peak slip rate distributions for different hypocenter depths and thus levels of supershear sustainability are further manifested in the peak ground velocity, as shown in Figures 4a and 4b. The strongest fault-perpendicular ground velocity is found in the model with the least sustained supershear rupture, where a single rupture front propagates across the fault, concentrating the energy release. Additionally, as expected, the model with persistent supershear rupture produces the strongest fault-parallel near-source ground velocity and the weakest fault-perpendicular ground velocity. The two models for which sub-Rayleigh rupture dominates display strong directivity in the fault-normal component of motion and also display a strong stopping phase in this component propagating beyond the right of the fault edge. There are additional features in the ground motion pattern for the partially sustained and completely sustained supershear cases that bear some additional explanation.

There is a zone of high ground motion between 44 km and the right edge of the fault in the partially sustained model. This location corresponds to where the leading and trailing rupture fronts merge (Figures 1 and 2), generating high fault slip rate in this region even though the initial stress is completely homogeneous. We note that this location is not where the rupture reverts to sub-Rayleigh speed, which takes place significantly earlier along strike. A more subtle ground motion feature appears at approximately 45 km along strike in the fully sustained supershear case: a beam of somewhat higher fault-perpendicular ground motion projecting in the fault-normal direction. Close inspection of the rupture propagation in this region (t = 17 s in Movie S1 in the supporting information) reveals that this feature is caused by the intersection of the trailing sub-Rayleigh slip pulse with a healing front propagating back from the right edge of the fault (which in turn was caused by the intersection of the supershear rupture front with the same fault edge). This effect, like the burst of strong ground motion in the partially sustained case, is possible only if there are two or more slip pulses on the fault. The logarithm of the ratio of fault-perpendicular and fault-parallel peak ground velocities \( \log (\text{PGV}_{FN}/\text{PGV}_{FP}) \) is presented in Figure 4c. A negative value (red) means the amplitude of fault-parallel peak ground velocity is larger than the fault-perpendicular component, where positive (blue) means the opposite. The area close to the hypocenter is dominated by the fault-parallel component, which is similar to kinematic results (Aagaard & Heaton, 2004). As the hypocenter depth increases and the supershear rupture is more sustained, the fault-parallel component dominated area close to the hypocenter also...
increases. Although the case with the 7.5 km hypocenter depth has a larger supershear area than the case with 5-km hypocenter depth, there is little qualitative difference between the two cases. For the sustained supershear case, however, not only the Mach cone can be observed but also the maximum ratio of FP and FN component is reached at the area immediately to the left of the end of the fault.

In addition to the pattern of peak ground motion, another way in which supershear rupture manifests itself is in the arrival times of the near-source ground motion. Aagaard and Heaton (2004) noted that for supershear rupture, the peak fault-parallel velocity arrives earlier at a given receiver than the peak fault-normal velocity. It is thus possible that detection of unsustained supershear rupture could be aided by an examination of this pulse timing. Toward this end, in Figure 5, we plot the differences in arrival time between the peak fault-parallel pulse and the peak fault-normal pulse for an array of seismic stations surrounding our simulated faults. For the fully sustained supershear case, we see a strong pattern of the fault-parallel peak arriving before the fault-normal peak develop as the rupture propagates down the fault, with the time difference between these peaks growing with the rupture propagation distance. Conversely, we do not observe such a pattern for either of the unsustained cases. For the partially sustained case, we observe a brief pattern of fault-parallel ground motion arriving first right on the fault (between around 10 and 30 km along strike) for approximately the extent of supershear rupture. This pattern largely disappears as the rupture returns to sub-Rayleigh speed farther along strike. For the least sustained case, the ground motion on the fault typically produces an initial subshear peak, consistent with subshear directivity effects. Both the unsustained cases produce a somewhat chaotic pattern away from the fault, with no obvious Mach cone. We note that for the unsustained cases, the synthetic ground motion records tend to have multiple peaks with similar amplitudes, so the difference between the fault-parallel component arriving first and the fault-normal component arriving first may hinge on a small difference in the amplitudes in these peaks (Figure S1). For the sustained case, however, ground motions are simpler due to the formation of a Mach cone, and thus, the spatial pattern is much clearer.

**Figure 5.** Arrival time differences (denoted by color scale) between the maximum amplitudes of the fault-perpendicular and fault-parallel peak ground velocity at different stations on the free surface, with 5-km spatial interval along strike and 2-km interval along the fault-perpendicular direction on vertical faults. The (a) 5-, (b) 7.5-, and (c) 10-km hypocenter depth. Positive time difference (blue circles) means the maximum fault-perpendicular velocity arrives earlier than the maximum fault-parallel velocity, and the negative time difference (red circles) means the maximum fault-parallel velocity arrives earlier.
Although no Mach cone is observed for unsustained supershear ruptures from the near-fault peak ground velocity distribution as shown in Figure 4, the horizontal ground velocity snapshots shown in Figure 6 provide additional information. With a very short supershear rupture propagation distance on the free surface, only the ground motion associated with the sub-Rayleigh main crack is displayed at 9 and 15 s for the case with the 5-km hypocenter depth. For the case with 7.5-km hypocenter depth, a Mach front is observed at around 20 km along strike at 9 s, during the short time window of supershear rupture on that fault. However, the Mach wave front is totally missing at 15 s, although the “daughter” crack ahead of the main crack still exists, propagating at sub-Rayleigh speed. The sub-Rayleigh crack close to the end of the fault may significantly affect the sub-Rayleigh pattern of the near-field peak ground velocity. For the sustained supershear case with 10-km hypocenter depth, the Mach front continues to propagate to the end of the fault. The Mach front carries the near-field ground motion away from the fault with little attenuation, as noticed by Dunham and Bhat (2008) in their models for ground motion associated with a supershear rupture at a distance much larger than the fault width.

We may gain further insight into the signatures of unsustained and sustained supershear rupture by examining sample synthetic ground motion time histories. Figure 7 displays such ground motion for stations at an along-strike position of 45 km and at multiple distances perpendicular to strike (0, 2, 4, 6, 8, and 10 km, respectively) in different frequency bands. With our 50-m spatial grid, the maximum grid-resolved frequency is $f_{max} = 8.6$ Hz. We present synthetic ground motion records lowpass filtered to this frequency and also filtered using a 1 Hz low-frequency filter and a 1- to 3-Hz bandpass filter, respectively. The filter we adopt is a finite impulse response filter (Hu et al., 2018). The time histories in Figure 7 correspond well to the overall patterns of ground motion and timing seen in Figures 4 and 5. The low-frequency seismograms have similar pattern as the broadband signals, but their amplitudes are smaller and display no sharp transition of the waveform shape, which is contained in the high frequency information. For the unsustained supershear cases, the fault-perpendicular peak ground velocity (black) is larger than the fault-parallel component (red) for all stations. Although the unsustained supershear case in Figure 7b has a larger area where rupture propagates at supershear speeds, it still cannot trigger the observable supershear characteristics at the near field as shown in Figure 7c, which has an earlier arrival of fault-parallel peaks with a larger amplitude. However, the maximum fault-perpendicular amplitude in this case is smaller compared to the case of 5-km hypocenter depth.

In the high-frequency (HF) range, it is easier to distinguish the unsustained and sustained supershear ruptures. Two main features can be observed. First, the HF amplitude decreases more rapidly with distance to the fault plane for the unsustained supershear ruptures. Conversely, for sustained supershear ruptures, the HF wave signals are still clearly shown even as the distance from the station to the fault plane increases to...
10 km. Second, for sustained supershear ruptures, the earlier arriving fault-parallel (red) peaks form an observable supershear phase (Mach cone) at different stations at the fault-perpendicular direction in the HF range. As suggested by prior work on fully sustained supershear rupture (Dunham & Archuleta, 2004; Ellsworth et al., 2004), this phenomenon could be used to help discern the presence of supershear rupture in natural earthquakes.

3.4. Effects of Fault Dip

Of course, while strike-slip faults do not necessarily have a perfectly vertical dip, a nonvertical dip angle and the consequent breaking of symmetry with respect to the free surface can have important implications for the dynamics of dip-slip faults (e.g., Brune, 1996; Oglesby et al., 1998; Rudnicki & Wu, 1995), but the effects of fault dip on strike-slip faulting have not been thoroughly explored. In particular, since the current models investigate the effect of the free surface on supershear rupture, it is important to determine how additional free surface interactions could affect rupture speed. For a vertical fault in a half space, symmetry implies that the normal stress is constant in time. However, for a dipping fault, wave reflections from the free surface can cause the normal stress on the fault to be time dependent, which can have a significant effect on rupture propagation and slip. To explore any potential effects of fault dip, we set up dynamic models with 70° dip angles that are otherwise equivalent to our prior vertical faults. Nucleation is at downdip distances of 5, 7.5, and 10 km. Figures 8a–8c show rupture time contours and rupture speeds for these dipping models, with a left-lateral strike-slip case with 7.5-km downdip hypocenter depth also shown for comparison in Figure 8d.

The dipping fault with a 5-km downdip hypocenter depth (Figure 8a) shows a very brief burst of supershear rupture a short distance along strike, much like the results for its vertical counterpart. The dipping fault with the 7.5-km downdip hypocenter depth (Figure 8b) produces a free surface-induced supershear rupture that lasts until the edge of our faulting model. By our operational definition, this rupture pattern would be called “sustained supershear,” although one may observe that the depth of the lower limit of supershear rupture speed appears to be decreasing along strike toward the edge of fault; it is likely that this rupture would have reverted to sub-Rayleigh speed if our fault had been longer along strike. Nonetheless, this result is in contrast...
to those of the 7.5-km-deep hypocenter on the vertical fault (Figure 1b), which reverted to sub-Rayleigh speed significantly earlier along strike. The dipping fault with a 10-km downdip hypocenter depth (Figure 8c) produces sustained supershear rupture, although it does not extend over as large an area of the fault as in the vertical case. Similar to the right-lateral result, the left-lateral 7.5-km downdip hypocenter case (Figure 8d) also generates sustained supershear rupture.

One possible factor in the different rupture behavior for the dipping faults is that with the same downdip distance, each hypocenter is slightly shallower (by a factor of $\frac{1}{\sin 70°} \approx 6\%$) with respect to the free surface for the dipping fault. By itself, according to our previous results, a shallower hypocenter should make sustained supershear rupture less likely. A likely more important factor in the dipping fault results is the time-dependent normal stress pattern induced by the breakage of symmetry with respect to the free surface. In an examination of the dynamics of dip-slip and strike-slip faults, Oglesby et al. (2000) showed that thrust and normal faults produce strong time dependence of normal stress near their intersection with the free surface and, essentially, no such effect for otherwise equivalent strike-slip faults. However, those results were for points down the center line of bilaterally rupturing faults, which are at a location of high symmetry with respect to the fault. For general points on a dipping strike-slip fault, rupture propagation and slip are coupled with normal stress and can in fact produce a significant time variation in normal stress. This effect in the context of the current faulting models is shown in Figure 9.

As expected, a vertical fault induces no change in normal stress (Figure 9a). However, for right-lateral slip on our dipping faults (Figure 9b), rupture propagation produces decreased normal stress (unclamping) ahead of the crack tip as it propagates along strike, and increased normal stress (clamping) behind the crack tip. The normal stress perturbation is reversed for left-lateral fault stress on otherwise equivalent faults (Figure 9b). In such case, there is increased normal stress ahead of the crack tip and decreased normal stress behind. In both cases, the time-dependent increment of normal stress does not persist after the rupture front passes, in contrast to the permanent effect on normal stress that is produced by slip on dip-slip faults (Oglesby et al., 2000). The importance of this normal stress effect on the free surface-induced supershear rupture can be seen in Figure 8d, which displays the rupture time and rupture speed for the left-lateral version of the 7.5-km-deep hypocenter model. Whereas the supershear area in the right-lateral rupture in Figure 8b appears to decay along the fault, the left-lateral case has a larger supershear area, which appears to increase as the

**Figure 8.** Rupture front contours and dimensionless rupture velocity distribution of a planar strike-slip fault with 70° dip angle and initial $S = 1.9$. The initial stresses and friction parameters are in Table 1. Downdip distance to hypocenters on right-lateral faults is (a) 5, (b) 7.5, and (c) 10 km, respectively. The result of the left-lateral 70° dip angle strike-slip fault with the same stress and friction parameters is shown in Figure 8d for the 7.5-km downdip hypocenter depth.
rupture propagates to the edge of the fault. The temporarily lowered normal stress immediately behind the rupture front may decrease the nondimensional $S$ ratio and facilitate fault slip in the left-lateral case, which could add more energy to the rupture front and allow a more sustained supershear speed. This interpretation is reinforced by a comparison of the surface slip distributions for the four dipping fault models, which is displayed in Figure 10. As in the case of the vertical faults (Figure 2), the deeper hypocenters that produce more sustained supershear rupture also produce slightly higher slip. However, the left-lateral fault with a hypocentral depth of 7.5 km produces noticeably higher peak slip than that of the otherwise identical right-lateral fault.

A nonvertical fault dip also manifests itself strongly in the near-source peak horizontal ground velocity displayed in Figures 11a and 11b. As expected by the asymmetry between the hanging wall and footwall (Oglesby et al., 2000), the hanging wall experiences stronger motion overall. However, we may still observe characteristics of supershear rupture propagation in the sustained supershear cases (the 7.5- and 10-km-deep hypocenters), including stronger fault-parallel motion than fault-normal motion. The 10-km-deep hypocenter model has larger ground motion than the 7.5-km-deep hypocenter model, likely due to the larger area over which supershear rupture persists. In the sustained supershear cases, we still observe the amplified fault-normal ground motion at approximately 45 km along strike associated with the intersection of the trailing Rayleigh pulse with the healing front from the edge of the fault. Figure 11c shows the distribution of log (PGV_FN/PGV_FP), whose negative value (red) indicates the fault-parallel component being larger than the fault-perpendicular component and positive (blue) meaning the...
opposite. Similar to the purely vertical strike-slip cases (Figure 4), the area close to the epicenter at 0 km is still dominated by the fault-parallel component; however, the area is asymmetric for the sustained supershear cases. A larger fault-parallel dominated area close to the epicenter is observed on the footwall. The Mach cone presented in the fault-parallel peak ground velocity (Figure 11b) is also observed just to the left of the end of the fault in the ratio of fault-perpendicular and fault-parallel peak ground velocities (Figure 11c). With a larger sustained supershear area on the fault for the 10-km hypocenter depth case, its absolute value of log (PGV_FN/PGV_FP) is also larger in the hanging wall than that of the case with the 7.5-km hypocenter depth, whose sustained supershear area shrinks as the rupture propagates toward the end of the fault (Figure 8b). A fault-parallel component dominated area is also seen in the footwall beyond the end of the fault for the case with the 7.5-km hypocenter depth.

The relative timing of the fault-parallel and fault-normal peaks for the dipping models also retains their noticeable characteristics for the sustained supershear cases. Figure 12 displays a strong pattern of the fault-parallel peak preceding the fault-normal peak over much of the hanging wall and a smaller amount of the footwall for the 10-km hypocenter depth. The Mach cone area, which is present at the points with negative values in Figure 12c, is smaller compared to the purely vertical case. The dashed line in Figure 12c shows the Mach cone boundary of the purely vertical strike-slip fault with 10-km hypocenter depth for comparison. The pattern earlier arrival of fault-parallel peak is similar to the vertical case on the hanging wall, but the area is smaller on the footwall. In the less sustained case of the 7.5-km-deep hypocenter, we still observe this pattern, although not as strongly, which is consistent with the smaller fault area undergoing supershear rupture. As in the vertical faulting cases, the 5-km-deep hypocenter case does not show a strong Mach cone of fault-parallel ground motion, although it does display a fault-parallel motion tending to arrive earlier on the hanging wall and fault-normal motion arriving earlier on the footwall.

Figure 13 displays synthetic velocity seismograms at multiple stations 45 km along strike and multiple distances to the fault plane. These time histories display two main features related to the nonvertical nature of the strike-slip faults. First, the only unsustained supershear case here (5-km downdip hypocenter) shown in Figure 13a presents larger fault-perpendicular component in all frequency ranges, while the other two sustained supershear cases (Figures 13b and 13c) display an earlier arrival of the higher amplitude fault parallel peaks in the near fault area, independent of whether the supershear rupture area is increasing or decreasing as the rupture propagates. Moreover, the observable supershear phase in the HF range is clearly shown as a Mach cone in the hanging wall direction, although later arrivals corresponding to the sub-Rayleigh pulse in the intermediate frequencies are more concentrated on the footwall. However, the waveform amplitude, especially in the HF range, is smaller for the 7.5-km downdip hypocenter case (Figure 8b), which has a decreasing supershear area as rupture propagates. Thus, the rupture speed at the point when the stopping phase is generated may be important for the near-fault ground motion. Another main feature which differs from the result of the vertical case is the break of the symmetry in the near-field ground motion. Larger
amplitudes of ground motions are noticed in the hanging wall direction, especially for the supershear phase in the HF range.

4. Discussion

The possibility of unsustained free surface-induced supershear rupture was first explored by Hu et al. (2019), who found that the sustainability of such rupture was controlled by both the shear and normal stress levels on the fault, as well as the depth of the hypocenter. In the current work, we examine faults with three different hypocentral depths, resulting in different degrees of supershear rupture sustainability, but with identical stress magnitudes so that we may isolate the purely dynamic effects of supershear rupture sustainability without the confounding effects of differing stress drop and favorability for rupture. A key observation in the current study is that heterogeneous rupture propagation, even when the initial stress pattern is homogeneous outside of the nucleation zone, can lead to highly heterogeneous ground motion patterns in the near field. This result is not surprising, as seismologists have long known (e.g., Spudich & Frazer, 1984) that spatial variations in rupture propagation and slip amplitude both can lead to bursts of seismic radiation. However, it is worth emphasizing that the heterogeneous ground motion patterns seen in Figures 4 and 11, as well as the differences between the ground motions within each figure, are due to the different geometric relationships for how the dynamic rupture develops and propagates. In particular, the zones of high ground motion around 45 km along strike in the 7.5- and 10-km hypocenter depth models with vertical dip are only possible if there are multiple slip pulses (the daughter and the following main slip pulse) on the fault—a hallmark of the sustained and partially sustained supershear rupture patterns. Still, if a researcher were presented only with the different ground motion patterns of Figures 4a and 4b and had no prior knowledge of the rupture process, the researcher would be tempted to infer that the bottom model had a higher stress
Thus, the current models are a reminder that it may be tempting to map variability in rupture propagation into variability in stress/slip or vice versa. In reality, the only difference in the setups of the three models is the depth of rupture nucleation. Given that the nucleation depth is one of the less well-constrained properties of a real-world hypocenter, the strong dependence of the ground motion on hypocenter depth may introduce significant uncertainty into ground motion prediction.

We find that dipping faults with sustained supershear rupture display most of the hallmarks of such rupture on vertical faults, including relatively larger fault-parallel motion that arrives before the fault-normal motion, coupled with higher ground motion overall on the hanging wall. However, the dipping fault geometry and consequent feedback between slip and normal stress introduces an asymmetry in rupture propagation and slip between different slip directions. In our results, if the rupture propagation is in the same direction as the displacement of the hanging wall, there is a dynamic clamping ahead of the crack tip and an unclamping behind the crack tip. The reverse is true for rupture propagation in the opposite direction. Rupture propagation in the direction of hanging wall displacement could be considered somewhat more favored, in that it produces more sustained supershear rupture, and somewhat larger slip than rupture propagation in the other direction. This result is analogous to that of a bimaterial interface (Andrews & Ben-Zion, 1997; Dalguer & Day, 2009; Harris & Day, 1997), with the role of the hanging wall in the current models corresponding to the role of the more compliant material at the bimaterial interface. In both of these physical situations, the changes in normal stress tend to return to zero after the rupture front passes, unlike the sustained normal stress perturbations induced by dip-slip motion on a dipping fault.

An important question is whether it is possible to detect unsustained free surface-induced supershear rupture through ground motion measurements. With the advent of relatively inexpensive nodal seismic stations that can be employed at very high density in near-fault regions (e.g., Ben-Zion et al., 2015; Lin et al., 2013), it may be possible in the future to produce heterogeneous peak ground motion and timing plots that begin to resemble those in Figures 4, 5, 11, and 12. However, given all the additional sources of complexity in ground motion prediction.
motion (including stress, frictional properties, and fault geometry) and the nonuniqueness of typical earthquake source models, it may be difficult to find compelling evidence of only partially sustained supershear rupture; a fully developed Mach cone or a seismic station right next to the supershear portion of the fault (Dunham & Archuleta, 2004) may be necessary.

In natural earthquakes, unsustained supershear ruptures may widely exist. Depth-dependent stress, which is extensively observed in shallow crust (Sibson, 1982), may be one of the possible stimuli. The pioneering work by Kaneko and Lapusta (2010) discovered that a local supershear transition on the free surface may not turn to fault-spanning supershear rupture with depth-dependent stress. To have a better understanding of the effect of depth-dependent stress in controlling rupture velocities on faults, we further carry out a study with depth-dependent stress (Figure 14a). The effective normal stress is defined by 
\[
\tau_n = \min\{50 + 14z, 120\} \text{ MPa},
\]
where \(z\) is in kilometers. \(\tau_n\) increases with depth and becomes constant (120 MPa) at depths larger than 5 km. Many stress measurements have indicated depth-dependent stress characteristics in the shallow crust, for example, the measurements using the hydrofrac technique in the oil and gas fields in Colorado, New Mexico, Utah, and Wyoming and in the Michigan basin at depths extending to 5.1 km (McGarr & Gay, 1978), and scientific drilling projects, such as Earth-Scope’s San Andreas Fault Observatory at Depth project (Hickman et al., 2004). With depth-dependent normal stress, we assign the initial shear stress also to be depth-dependent with a constraint of \(S = 1.9\). Although the initial stresses close to the nucleation area are the same as the homogeneous case in Figure 1c, the rupture is no longer a sustained supershear, as shown in Figure 14b, and the daughter crack, which emerges as a supershear daughter crack ahead of the main crack, turns to sub-Rayleigh speed at the strike close to 30 km and propagates to the end of the fault. The near field peak ground velocities presented in Figure 14c in both fault-perpendicular and fault-parallel components also show the sub-Rayleigh characteristics. Thus, depth-dependent stress may change the stress regimes for sustained supershear rupture. It would be interesting to further investigate the relationship between the depth-dependent stress and sustainability of free surface-induced supershear ruptures, which may provide useful insights to help to detect the stress condition from inferred rupture velocities on faults.

5. Conclusions

The present work builds on the work of Zhang and Chen (2006), Kaneko and Lapusta (2010), and Hu et al. (2019), who explored the mechanism by which a rupture may transition to supershear rupture speeds due to its interaction with the free surface of the Earth. In particular, we continue the work of Hu et al. (2019) in examining the cases in which such supershear rupture may be sustained on the fault or may transition.
back to sub-Rayleigh speed. We focus in the present work on how the rupture patterns on the fault translate into ground motion, and how such motion differs between unsustained, partially sustained, and sustained supershear rupture cases. Partially sustained and fully sustained free surface-induced supershear rupture can give rise to significant complexity in rupture propagation even on homogeneous faults, leading to complex ground motion patterns that could be easily mapped into heterogeneity in stress, slip, or other properties on the fault. The effect of length scale of supershear propagating distance on strike-slip faults in controlling near-field ground motion still needs to be considered in the future. Near the supershear regions of the fault, classical signals of supershear rupture such as relatively large fault-parallel motion may be observed. It remains to be seen if these particular characteristics of ground motion can be effectively detected in the real world.

Acknowledgments
This work was supported by the National Natural Science Foundation of China (grant 41774044). We are very grateful to the Editor Yehuda Ben-Zion, the Associate Editor Yoshhiro Kaneko, the anonymous reviewer, and Valère Lambert for their constructive remarks and suggestions that led to the improvement of the study. Data were not used nor created for this research.

References
Aagaard, B. T., & Heaton, T. H. (2004). Near-source ground motions from simulations of sustained interseismic and supersonic fault ruptures. Bulletin of the Seismological Society of America, 94(6), 2064–2078. https://doi.org/10.1785/0120030249
Andrews, D. J. (1976a). Rupture propagation with finite stress in Antiplane strain. Journal of Geophysical Research, 81(20), 3575–3582. https://doi.org/10.1029/JB081i020p03575
Andrews, D. J. (1976b). Rupture velocity of plane strain shear cracks. Journal of Geophysical Research, 81, 5679–5687.
Andrews, D. J., & Ben-Zion, Y. (1997). Wrinkle-like slip pulse on a fault between different materials. Journal of Geophysical Research, 102(1), 552–571.
Archuleta, R. J. (1984). A faulting model for the 1979 Imperial Valley earthquake. Journal of Geophysical Research, 89(B6), 4550–4585.
Bao, H., Ampuero, J. P., Meng, L., Fielding, E. J., Liang, C., Milliner, C. W. D., et al. (2019). Early and persistent supershear rupture of the 2018 magnitude 7.5 Palu earthquake. Nature Geoscience, 12(3), 200–205. https://doi.org/10.1038/s41561-018-0297-z
Ben-Zion, Y., Vernon, F. L., Ozakin, Y., Zigone, D., Ross, Z. E., Meng, H., et al. (2015). Basic data features and results from a spatially dense array on the San Jacinto fault zone. Geophysical Journal International, 202(1), 370–380. https://doi.org/10.1093/gji/ggv142
Bizzarri, A., & Das, S. (2012). Mechanics of 3-D shear cracks between Rayleigh and shear wave rupture speeds. Earth and Planetary Science Letters, 357, 397–404.
Bouchon, M., & Vallee, M. (2003). Observation of long supershear rupture during the magnitude 8.1 Kunlunshan earthquake. Science, 301(5634), 824–826. https://doi.org/10.1126/science.1086832
Bruhat, L., Fang, Z., & Dunham, E. M. (2016). Rupture complexity and the supershear transition on rough faults. Journal of Geophysical Research: Solid Earth, 121, 210–224. https://doi.org/10.1002/2015JB012512
Brune, J. N. (1996). Particle motions in a physical model of shallow angle thrust faulting. Proceedings Of The Indian Academy Of Sciences-earth And Planetary Sciences, 105(2), 197.
Burridge, R. (1973). Admissible speeds for plan-strain shear cracks with friction but lacking cohesion. Geophysical Journal of the Royal Astronomical Society, 35, 439–455.
Dalguer, L. A., & Day, S. M. (2009). Asymmetric rupture of large aspect-ratio faults at bimaterial interface in 3D. Geophysical Research Letters, 36, L23307. https://doi.org/10.1029/2009GL040303
Das, S., & Aki, K. (1977). A numerical study of two-dimensional spontaneous rupture propagation. Geophysical Journal of the Royal Astronomical Society, 50, 643–668.
Day, S. M. (1982). Three-dimensional simulation of spontaneous rupture: The effect of nonuniform prestress. Bulletin of the Seismological Society of America, 72(6A), 1881–1902.
Dunham, E. M. (2007). Conditions governing the occurrence of supershear ruptures under slip-weakening friction. Journal of Geophysical Research, 112, B07302. https://doi.org/10.1029/2006JB004717
Dunham, E. M., & Archuleta, R. J. (2004). Evidence for a supershear transient during the 2002 Denali fault earthquake. Bulletin of the Seismological Society of America, 94(6), S256–S268. https://doi.org/10.1785/0120030249
Dunham, E. M., & Bhat, H. S. (2008). Attenuation of radiated ground motion and stresses from three-dimensional supershear ruptures. Journal of Geophysical Research, 113, B08319. https://doi.org/10.1029/2007JB005182
Dunham, E. M., Favreau, P., & Carlson, J. M. (2003). A supershear transition mechanism for cracks. Science, 299(5612), 1557–1559. https://doi.org/10.1126/science.1080650
Ellsworth, W. L., Celebi, M., Evans, J. R., Jensen, E. G., Nyman, D. J., & Spudich, P. (2004). Processing and modeling of the pump station 10 record from the November 3, 2002, Denali Fault, Alaska earthquake. Paper presented at the 11th International Conference on Soil Dynamics and Earthquake Engineering, Berkeley, CA.
Galia, M., Pelties, C., Kristek, J., Moczo, P., Ampuero, J. P., & Mai, P. M. (2015). On the initiation of sustained slip-weakening ruptures by localized stresses. Geophysical Journal International, 200(2), 888–907. https://doi.org/10.1093/gji/ggu436
Harris, R. A., & Day, S. M. (1997). Effects of a low-velocity zone on a dynamic rupture. Bulletin of the Seismological Society of America, 87(5), 1267–1280.
Hickman, S., Zoback, M., & Ellsworth, W. (2004). Introduction to special section: Preparing for the San Andreas Fault Observatory at Depth. Geophysical Research Letters, 31, L11201. https://doi.org/10.1029/2004GL020688
Hu, F., Oglesby, D. D., & Chen, X. (2019). The sustainability of free-surface-induced supershear rupture on strike-slip faults. Geophysical Research Letters, 46, 9537–9543. https://doi.org/10.1029/2019GL084318
Hu, F., Wen, J., & Chen, X. (2018). High frequency near-field ground motion excited by strike-slip step overs. Journal of Geophysical Research: Solid Earth, 123, 2303–2317. https://doi.org/10.1002/2017JB015027
Hu, F., Xu, J., Zhang, Z., & Chen, X. (2016). Supershear transition mechanism induced by step over geometry. Journal of Geophysical Research: Solid Earth, 121, 8738–8749. https://doi.org/10.1002/2016JB013333
Huang, Y., Ampuero, J. P., & Helmberger, D. V. (2014). Earthquake ruptures modulated by waves in damaged fault zones. Journal of Geophysical Research: Earth and Planetary Sciences, 119, 3133–3154. https://doi.org/10.1002/2013JB010724
Ida, Y. (1972). Cohesive force across the tip of a longitudinal shear crack and Griffith’s specific surface energy. Journal of Geophysical Research, 77, 3796–3805.
Kaneko, Y., & Lapusta, N. (2010). Supershear transition due to a free surface in 3-D simulations of spontaneous dynamic rupture on vertical strike-slip faults. Tectonophysics, 493(3–4), 272–284.

Lin, F., Li, D., Clayton, R. W., & Hollis, D. (2013). High-resolution 3D shallow crustal structure in Long Beach, California: Application of ambient noise tomography on a dense seismic array. Geophysics, 78, Q45–Q56.

Liu, Y., & Lapusta, N. (2008). Transition of mode II cracks from sub-Rayleigh to intersonic speeds in the presence of favorable heterogeneity. Journal of the Mechanics and Physics of Solids, 56(1), 25–50. https://doi.org/10.1016/j.jmps.2007.06.005

Lu, X., Rosakis, A. J., & Lapusta, N. (2009). Analysis of supershear transition regimes in rupture experiments: The effect of nucleation conditions and friction parameters. International Journal of Geophysics, 177, 717–732.

Madariaga, R., & Olsen, K. B. (2000). Criticality of rupture dynamics in 3-D Pure and Applied Geophysics, 157, 1981–2001.

McGarr, A., & Gay, N. (1978). State of stress in the Earth’s crust. Annual Review of Earth and Planetary Sciences, 6(1), 405–436.

Mello, M., Bhat, H. S., & Rosakis, A. J. (2016). Spatiotemporal properties of sub-Rayleigh and supershear rupture velocity fields: Theory and experiments. Journal of the Mechanics and Physics of Solids, 93, 153–181.

Oglesby, D. D., Archuleta, R. J., & Nielsen, S. B. (1998). Earthquakes on dipping faults: The effects of broken symmetry. Science, 280(5366), 1055–1059. https://doi.org/10.1126/science.280.5366.1055

Oglesby, D. D., Archuleta, R. J., & Nielsen, S. B. (2000). The three-dimensional dynamics ofipping faults. Bulletin of the Seismological Society of America, 90, 616–628.

Oglesby, D. D., & Mai, P. M. (2012). Fault geometry, rupture dynamics, and the ground motion from potential earthquakes on the North Anatolian fault under the sea of Marmara. Geophysical Journal International, 188(1), 1071–1087. https://doi.org/10.1111/j.1365-246X.2011.05289.x

Olson, A. H., & Apel, R. J. (1982). Finite faults and inverse-theory with applications to the 1979 Imperial Valley earthquake. Bulletin of the Seismological Society of America, 72, 1969–2001.

Palmer, A. C., & Rice, J. R. (1973). The growth of slip surfaces in the progressive failure of overconsolidated clay. Proceedings of the Royal Society of London, A332, 527–548.

Passelegue, F. X., Schubnel, A., Nielsen, S., Bhat, H. S., & Madariaga, R. (2013). From sub-Rayleigh to supershear ruptures during stick-slip experiments on crustal rocks. Science, 340(6137), 1208–1211. https://doi.org/10.1126/science.1235637

Poljakov, A. B., Dmowska, R., & Rice, J. R. (2002). Dynamic shear rupture interactions with fault bends and off-axis secondary faulting. Journal of Geophysical Research, 107(B11), 2295. https://doi.org/10.1029/2001JB000572

Rice, J. R., Sammis, C. G., & Parsons, R. (2005). Off-fault secondary failure induced by a dynamic slip pulse. Bulletin of the Seismological Society of America, 95(1), 109–134.

Rosakis, A. J., Samudrala, O., & Coker, D. (1999). Cracks faster than the shear wave speed. Science, 284(5418), 1337–1340. https://doi.org/10.1126/science.284.5418.1337

Rudnicki, J., & Wu, M. (1995). Mechanics of dip-slip faulting in an elastic half-space. Journal of Geophysical Research, 100(B11), 22,173–22,186.

Ryan, K. J., & Oglesby, D. D. (2014). Dynamically modeling fault step overs using various friction laws. Journal of Geophysical Research - Solid Earth, 119, 5814–5829. https://doi.org/10.1002/2014JB011151

Sibson, R. H. (1982). Fault zone models, heat flow, and the depth distribution of earthquakes in the continental crust of the United States. Bulletin of the Seismological Society of America, 72(1), 151–163.

Socquet, A., Hollingsworth, J., Pathier, E., & Bouchon, M. (2019). Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy. Nature Geoscience, 12(3), 192.

Spudich, P., & Frazer, L. N. (1984). Use of ray theory to calculate high-frequency radiation from earthquake sources having spatially variable rupture velocity and stress drop. Bulletin of the Seismological Society of America, 74(6), 2061–2082.

Vallee, M., & Dunham, E. M. (2012). Observation of far-field Mach waves generated by the 2001 Kokoxili supershear earthquake. Geophysical Research Letters, 39, L05311. https://doi.org/10.1029/2011GL050725

Wu, F. T., Thomson, K., & Kuenzler, H. (1972). Stick-slip propagation velocity and seismic source mechanism. Bulletin of the Seismological Society of America, 62(6), 1621–1628.

Xia, K., Rosakis, A. J., & Kanamori, H. (2004). Laboratory earthquakes: The sub-Rayleigh-to-supershear rupture transition. Science, 303(5655), 1859–1861. https://doi.org/10.1126/science.1094022

Xu, J. K., Zhang, H. M., & Chen, X. F. (2015). Rupture phase diagrams for a planar fault in 3-D full-space and half-space. Geophysical Journal International, 202(3), 2194–2206. https://doi.org/10.1093/gji/ggv328

Zhan, Z., Helmberger, D. V., Kanamori, H., & Shearer, P. M. (2014). Supershear rupture in a Mw 6.7 aftershock of the sea of Okhotsk earthquake. Science, 345(6193), 204–207.

Zhang, H., & Chen, X. (2006). Dynamic rupture on a planar fault in three-dimensional half-space–II. Validations and numerical experiments. Geophysical Journal International, 167(2), 917–932.

Zhang, Z., Zhang, W., & Chen, X. (2014). Three-dimensional curved grid finite-difference modelling for non-planar rupture dynamics. Geophysical Journal International, 199(2), 860–879.