Supershear Rupture, Daughter Cracks, and the Definition of Rupture Velocity

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Abstract Rupture velocity is a fundamental feature of earthquake behavior. How rupture velocity is defined can therefore affect our understanding of earthquake physics. Based on dynamic rupture simulations, we compare the tangent and average rupture velocities calculated via one- and two-dimensional gradients. Two strike-slip scenarios with free-surface-induced supershear ruptures are presented within a homogeneous and a depth-dependent stress regime, respectively. Although both scenarios produce a daughter crack that propagate over the seismogenic depth, in the depth-dependent case the 1D and 2D rupture velocities capture different features: A 1D horizontal gradient measurement implies a supershear rupture, while a 2D gradient measurement reveals sub-Rayleigh rupture propagation everywhere except very close to the free surface. A large area on the fault with the 1D horizontal tangent rupture velocity does not necessarily produce an observable Mach front, which arises the importance of rupture velocity definitions in supershear analysis.

Plain Language Summary A rupture traveling faster than the shear wave speed is termed as a supershear rupture, which could trigger the generation of a shock wave in ground motion. To determine whether a rupture is propagating at supershear speed, the direct method is to measure the travel distance of the rupture with a given time interval in numerical simulations. However, other measurements of rupture velocity, such as the 1D horizontal and 2D gradient, are also compared. We find that using the 1D horizontal measure, in some cases a rupture can be classified as a supershear rupture, even though only a small area of the fault is experiencing supershear speed via the 2D gradient calculation, which may not generate a shock wave in ground motion. The results imply that different physical properties may be associated with different metrics of rupture velocity, with implications for determining supershear rupture in nature earthquakes.

1. Introduction

The speed with which earthquake rupture propagates along a fault is strongly related to both the pattern and amplitude of near-source and far-field ground motion. A growing number of observations of primarily strike-slip earthquakes (Archuleta, 1984; Bao et al., 2019; Bouchon et al., 2000; Bouchon & Vallée, 2003; Dunham & Archuleta, 2004; Socquet et al., 2019; Wang & Mori, 2012; Yue et al., 2013) has indicated that supershear rupture, while not ubiquitous, manifests itself in a significant fraction of earthquakes, with implications for ground motion. A qualitative difference exists between earthquake rupture at speeds below the shear wave speed (subshear) and above the shear wave speed (supershear): Unlike for subshear rupture, the near-source ground motion from supershear rupture is typically dominated by a fault-parallel rather than fault-normal pulse (Aagaard & Heaton, 2004; Andrews, 2010; Dunham & Archuleta, 2004), and this fault-parallel pulse arrives earlier than the fault-normal pulse (Hu et al., 2020). Supershear fault rupture is also often associated with a Mach cone that has been observed in seismic data (Bao et al., 2019), captured by high-speed cameras (Rosakis, 1999; Xia et al., 2004), and seen with the digital image correlation method (Rosakis et al., 2020; Rubino et al., 2019) in laboratory crack experiments.

Numerical supershear simulation investigations also highlight the existence of a shear Mach front which is nearly unattenuated away from the fault (Bhat et al., 2007; Bizzarri & Spudich, 2008; Dunham & Bhat, 2008). The shear Mach front is estimated to vanish (Mello et al., 2016) when the rupture velocity equals to the Esfleby speed $\sqrt{2V_s}$ during the transition process from a sub-Rayleigh speed to a stable supershear speed.
(\sqrt{2}V_s < V_c \leq V_p). There are many physical mechanisms by which rupture may transition to supershear speed (Andrews, 1976; Bhat et al., 2007; Bruhat et al., 2016; Burridge, 1973; Das & Aki, 1977; Day, 1982; Dunham, 2007; Dunham et al., 2003; Fukuyama & Olsen, 2002; Hu et al., 2016; Liu & Lapusta, 2008; Madariaga & Olsen, 2000; Ryan & Oglesby, 2014; Weng et al., 2015). In the present work, we focus on supershear rupture generated via interactions with the Earth’s free surface (Day et al., 2008; Hu et al., 2019, 2020; Kaneko et al., 2008; Kaneko & Lapusta, 2010; Olsen et al., 1997; Xu et al., 2015; H. Zhang & Chen, 2006), which is mediated primarily by a critically converted S to P wave along the surface of the Earth (Kaneko & Lapusta, 2010; Olsen et al., 1997).

A perhaps subtle issue embedded in the above discussion is the formal definition of rupture velocity. In 3D dynamic rupture modeling of earthquakes with heterogeneous pre-stress (Day, 1982), notes two ways to calculate rupture velocity. The first is the local or “tangent” rupture velocity, which can be calculated at every point on the fault as the reciprocal of the gradient of the rupture time at that point. The second is the average or “secant” rupture velocity, which is simply the distance of a point from the hypocenter divided by the rupture time at that point (Day, 1982). shows that these two calculations can give quite different results for the same earthquake, including supershear speed in the former but not in the latter. Using 3D dynamic rupture models of faults with both homogeneous and depth-dependent initial stress, we explore these and other methods of calculating rupture velocity in the presence of free-surface-induced supershear rupture.

We find that in some cases, different methods of calculating rupture velocity can give very different results as to whether the rupture is propagating at supershear speed. These different methods of calculation may be linked to different physical observables in real earthquakes, with implications for the detection and interpretation of supershear rupture.

2. Methods

We use the 3D dynamic finite difference method (Z. Zhang et al., 2014), which has been validated following the SCEC/USGS Dynamic Rupture Code Verification exercises (Harris et al., 2009, 2018), to model earthquakes on vertical planar faults of size 60 km along strike and 15 km in depth, which intersect the surface of a homogeneous half-space. We assume linearly elastic material behavior and slip-weakening friction (Andrews, 1976; Palmer & Rice, 1973). For a given point on the fault, rupture starts when the shear stress \( \tau_0 \) increases to the yielding strength \( \tau_y = \mu_s \tau_0 \) and linearly decreases to the residual stress \( \tau_d = \mu_r \tau_d \) as the slip increases to the characteristic slip-weakening distance \( d_0 \), which equals 0.4 m in this study. The static and dynamic friction coefficients \( \mu_s \) and \( \mu_r \) are 0.677 and 0.525, respectively.

The P wave speed is 6 km/s, and the S wave speed is 3.464 km/s, with density 2,670 kg/m\(^3\). To allow comparison of our results with prior work, we focus on and duplicate two of the models of Kaneko and Lapusta (2010) by applying a time-varying shear stress perturbation (Equation A1 of Supporting Information) while performing a new analysis. Our prior work has shown that the results are sensitive to the physical depth of nucleation, but not to the details of the artificial nucleation procedure (Hu et al., 2019). The first model is a homogeneous stress model whose initial normal stress is 120 MPa, while the normal stress for the depth-dependent stress model is \( \min[1.0 + 16.2z, 120] \) MPa, with \( z \) equals to the depth in kilometers (Figure S1). The relative fault strength \( S = \frac{\tau_y - \tau_0}{\tau_0 - \tau_d} \) is 1.6 for the two models, which prevents supershear transition via Burridge-Andrews mechanism (Andrews, 1976; Das & Aki, 1977; Day, 1982; Dunham, 2007). A new analysis on the rupture speed of the three homogeneous stress models (presented by Hu et al., 2020) are also shown. We focus on the free-surface-induced supershear mechanism, although the results have implications for supershear rupture in general, especially for the cases with a large angle of the daughter crack propagation with respect to the horizontal direction. We use a spatial grid of 50 m and a time step of 0.0025 s; grid size independence is verified by good comparison of the results with selected models with half the spatial grid and time step.

To calculate rupture speed, we utilize four different definitions.

The 2D tangent rupture speed is calculated following Bizzarri and Das (2012):

\[
V_{rt}^{2D}(y,z) = \frac{1}{\|\nabla_{(y,z)} f_r(y,z)\|} = \frac{1}{\sqrt{(\partial f_r / \partial y)^2 + (\partial f_r / \partial z)^2}}
\] (1)
where \( t_r(y,z) \) is the rupture time for a point on the fault, and

\[
\frac{\partial}{\partial y} t_r(y,z) = \frac{t_r(y + h, z + h) - t_r(y - h, z + h) + t_r(y + h, z - h) - t_r(y - h, z - h)}{4h} \tag{2}
\]

\[
\frac{\partial}{\partial z} t_r(y,z) = \frac{t_r(y + h, z + h) - t_r(y + h, z - h) + t_r(y - h, z + h) - t_r(y - h, z - h)}{4h} \tag{3}
\]

and \( h \) is the grid spacing. The 1D horizontal tangent rupture speed is calculated using:

\[
V_{r,ld}^t(y,z) = \frac{1}{\frac{\partial}{\partial y} t_r(y,z)} \equiv \frac{2h}{t_r(y, z) - t_r(y + h, z)} \tag{4}
\]

The 2D secant (average) rupture speed is calculated using:

\[
V_{r,secant}^s(y,z) = \frac{\text{Dist}_\text{hypo}}{t_r(y,z)} \tag{5}
\]

Where \( \text{Dist}_\text{hypo} \) is the distance from the point to the hypocenter.

Finally, the 1D horizontal average rupture speed is calculated using:

\[
V_{r,ave,ld}^t(y,z) = \frac{\text{Dist}}{t_r(y, z) - t_r(y_{0}, z)} \tag{6}
\]

Where \( \text{Dist} \) is the horizontal distance between the observer \((y, z)\) and the point \((y_{0}, z)\). In their work on free-surface-induced supershear rupture, Kaneko and Lapusta (2010) utilize \( V_{r,secant}^s \) and \( V_{r,ld}^t \) to characterize their ruptures as supershear or subshear. Weng and Ampuero (2020) used an average of \( V_{r,ld}^{2d} \) and \( V_{r,ld}^t \) to characterize rupture speed in their study of supershear rupture on oblique faults. Here we compare the results for our four definitions and explore the implications of their differences, which may highlight the challenge of interpreting inferences of supershear rupture.

3. Results

We compare slip rate snapshots, rupture time distributions, and different methods of calculating rupture speed for the homogeneous and depth-dependent stress models in Figure 1. The slip rate snapshots of the two models (Figures 1a and 1f) match the results of Figures 6 and 5 of Kaneko and Lapusta (2010), respectively. Both models produce a daughter crack that propagates out ahead of the main rupture front, as can be seen by the thin zone of high slip rate to the right of the main crack in the rupture snapshots, as well as by sharp kinks in the rupture time contours. Both daughter cracks eventually propagate down to the bottom of their respective faults. However, there is a qualitative difference between the two daughter cracks. In the homogeneous stress case, the daughter crack develops a largely vertical shape while propagating along strike. In contrast, the daughter crack in the depth-dependent stress case retains a diagonal shape with the crack leading at the free surface as it propagates to the right.

As shown in Figures 1b–1e, the homogeneous stress model shows a free-surface-induced supershear transition by all measures of rupture speed, and as the daughter crack propagates, the area experiencing supershear rupture speed gradually grows to encompass the entire depth of the fault. Nonetheless, important differences exist between the different rupture speed estimates. The 2D gradient \( V_{r,ld}^{2d} \) shows that the area undergoing supershear rupture does not necessarily correspond precisely to the area of the fault for which the daughter crack arrives earlier than the parent crack (the daughter crack arrives first for points on the fault above the sharp kink in rupture contours). In other words, even if the daughter crack causes a point on the fault to rupture ahead of the main sub-Rayleigh crack, that does not necessarily imply that the propagation speed is supershear at that point. Conversely, the supershear area defined by the 1D horizontal gradient \( V_{r,ld}^t \) precisely corresponds to the boundaries of the area in which the daughter crack arrives before the parent
crack. Finally, both average rupture speeds \( V_{r_{\text{secant}}} \) and \( V_{r_{\text{ave1d}}} \) show supershear speed over the majority of the fault, with the 1D horizontal average \( V_{r_{\text{ave1d}}} \) producing a higher estimate of rupture speed over more of the fault.

Differences between the various rupture speed calculation methods for the depth-dependent stress model are more significant. For this model the 2D gradient \( V_{r_{\text{2d}}} \) indicates a rupture that is almost entirely subshear (Figures 1g–1j). Close examination reveals that there is a very thin (<200 m in depth) zone of horizontally propagating supershear rupture immediately below the surface (Figure 2b), but the zone is too small to be seen in the plots in Figure 1g. The daughter crack is revealed to be a sub-Rayleigh crack propagating diagonally downwards from the free surface. The orientation of the rupture contours for the daughter crack is similar to the wavefronts of a converted horizontal P to downward S wave along the fault (Figure S2).

Figure 1. Snapshots of slip rate and rupture time contours (the labeled contours indicate the location and timing (in seconds) of the rupture front after nucleation) with different rupture speed calculations for the homogeneous stress case (panels a–e) and the depth-dependent stress case (panels f–j). Rupture speeds are calculated using \( V_{r_{\text{2d}}} \) (panels b and g), \( V_{r_{\text{1d}}} \) (panels c and h), \( V_{r_{\text{secant}}} \) (panels d and i), and \( V_{r_{\text{ave1d}}} \) (panels e and j). Ruptures are nucleated at (0, −10 km) on the faults where a circle area with the radius of 2.5 km is triggered by adding a symmetric shear stress perturbation (Equation A1 of Supporting Information).
In contrast to the almost entirely sub-Rayleigh $V_{r}^{2d}$, the 1D horizontal gradient $V_{r}^{1d}$ indicates a large area propagating at supershear speed—the entire area for which the daughter crack arrives before the parent crack. Inspection of the rupture time contours indicates the reason for this supershear estimate: because the daughter crack is propagating at a large angle with respect to the horizontal, the rupture time contours are farther apart in the along-strike direction than in the direction normal to the contours (i.e., the direction of the 2D gradient), leading to a larger apparent velocity in that direction (Figures S3–S4). The effect is analogous to the large apparent horizontal phase velocity seen on the surface of the Earth from a diagonally incident seismic wave. The 2D secant (average) rupture speed $V_{r}^{secant}$ and the 1D horizontal average $V_{r}^{ave1d}$ both show a significant amount of supershear rupture on the fault, but less than the 1D horizontal gradient $V_{r}^{1d}$. It should be noted that in this model, the secant rupture speed displays a larger area of supershear rupture than the 2D gradient speed, which is the opposite of the effect observed by (Day, 1982), in which the 2D gradient speed displayed supershear rupture speed where the secant speed did not.

More information about the spatial patterns of the various rupture speed estimates can be gained by examining their distributions along strike, as shown in Figure 2. In the homogeneous stress case, at the free surface all rupture speeds with the exception of $V_{r}^{secant}$ are supershear and above the Eshelby speed, which is the lower limit for the stable steady supershear regime ($\sqrt{2V_s} < V_r < V_p$) (Burridge et al., 1979). Rupture speeds at a depth of 0.2 km are similar to those at the free surface. At the hypocentral depth of 7.5 km, $V_{r}^{1d}$ has an almost step-function increase from subshear to supershear as it passes to the part of the fault ruptured initially by the daughter crack, while the other measures of rupture velocity more gradually increase to supershear speed along strike. In particular, $V_{r}^{2d}$ eventually increases to above the Eshelby speed. In contrast to the homogeneous stress case, the depth-dependent stress model displays clear supershear rupture at the free surface for all rupture velocity definitions except for $V_{r}^{secant}$, which appears to vary between supershear and subshear along strike. $V_{r}^{ave1d}$ is above the Eshelby speed, while other definitions are below.

An experiment with a smaller spatial grid of 25 m (Figure S5) indicates that there is a very thin zone of clear supershear rupture right at the free surface by the $V_{r}^{2d}$ definition, but this speed is still below the stable Eshelby speed. At 0.2 km depth, $V_{r}^{2d}$ is clearly subshear, while the other definitions indicate supershear rupture. The thin, surficial nature of the supershear rupture is why there is no observable blue color for this model in Figure 1g. At hypocentral depth we can see greater differentiation between the different rupture velocity calculations: only $V_{r}^{1d}$ becomes clearly supershear (but sub-Eshelby) for areas ruptured first by the daughter crack.

![Figure 2](image-url)
An issue of considerable practical importance in supershear rupture observations is the existence of the shear Mach front, which is generated by superposition of $S$-wave fronts (Bernard & Baumont, 2005; Dunham & Archuleta, 2005; Dunham & Bhat, 2008; Mello et al., 2010) and is observed in laboratory crack experiments (Rosakis, 1999; Rubino et al., 2019; Xia et al., 2004). Numerical simulations show that besides the shear Mach front, a Rayleigh Mach front also propagates to the far field with little attenuation (Dunham & Bhat, 2008). Figure 3 displays snapshots of fault slip rate and strike-perpendicular ground velocity for the homogeneous (a and b) and depth-dependent (c and d) stress cases. The homogeneous stress case produces clear Mach fronts on the Earth's surface for both the Shear and Rayleigh waves; these fronts also are observed on both the fault itself and on a vertical cross-section perpendicular to strike. The depth-dependent stress case produces almost no perceptible Mach front in the fault-perpendicular component, although a very weak shear Mach front is perceptible in the fault-parallel component (Figure S6). Moreover, the Mach cone half-angle to the fault plane $\alpha = \sin^{-1} \left( V_s / V_p \right)$ is less than $\pi / 4$ for the stable supershear speed ($\sqrt{2} V_s < V_p < V_p$), but greater than $\pi / 4$ if $V_s < V_p < \sqrt{2} V_s$, which is an unstable supershear rupture speed (Mello et al., 2010). As shown in Figures 3b and 3d, the shear Mach cone half-angle is 40.2°, while the Rayleigh Mach cone half-angle is 35.5°; both $\alpha$ values are lower than $\pi / 4$, representing a stable supershear speed. However, $\alpha$ is 48.6° for the depth-dependent stress case (Figure 3d), which emphasizes the unstable supershear velocity.

4. Discussion and Conclusions

Our numerical results imply that the definition of rupture speed based on the two-dimensional rupture time gradient ($V_p^{2d}$) is most consistent with traditional ground-motion-based inferences of supershear rupture, such as the formation of a Mach front and stronger FP than FN initial pulses (Aagaard & Heaton, 2004; Dunham & Bhat, 2008). However, the inferences of supershear rupture speeds can be interpreted to have different consequences, depending on how the rupture speed is calculated. For example, back-projection studies of long along-strike ruptures tend to trace the movement of the zone of maximum energy radiation in map view (Bao et al., 2019; Ishii et al., 2005; Walker & Shearer, 2009). Associating this zone of maximum energy radiation with the location of the rupture front, it is straightforward to take the horizontal distance...
of rupture propagation divided by the time taken for such propagation to calculate a rupture velocity. This rupture velocity definition corresponds more closely to \( V_{r}^{1d} \) or \( V_{r}^{ave1d} \) than to \( V_{r}^{2d} \). Inferences of supershear rupture propagation based on the rotation of surface wave polarization (Bouchon & Vallée, 2003) may similarly be associated more closely with \( V_{r}^{1d} \) or \( V_{r}^{ave1d} \) than with \( V_{r}^{2d} \).

For the homogeneous stress model, there is little distinction between the amount of the fault that experiences supershear rupture between the different rupture velocity definitions. This model is unequivocally supershear by all definitions, and would also likely be indicated to be supershear by all observables. However, the depth-dependent model is more equivocal. It indeed does have at least a small zone of supershear rupture by all definitions, but the area of the fault that is indicated to be supershear differs and depends on the definition. As shown in Figure S7, this more equivocal case does not display strongly the near-source ground motion signatures (Mach front, strong FP pulse) expected from supershear rupture. One can imagine that the famous Pump Station 10 record in the 2002 Denali Fault earthquake (Dunham & Archuleta, 2004) might not have produced evidence of supershear rupture if it had had a stress distribution similar to our hypothetical depth-dependent case.

The depth-dependent case has an extremely small percentage of the fault experiencing supershear rupture by the \( V_{r}^{2d} \) definition, which explains why it does not generate a significant Mach front or strong FP pulse: Due to its small area and low stress drop, the supershear \( V_{r}^{2d} \) zone radiates little energy and does not strongly affect the ground motion. Of course, it is possible that in the real world, stable friction near the free surface, or velocity-strengthening behavior at shallow depth (Kaneko et al., 2008) could either eliminate this superficial supershear rupture. Our depth-dependent stress model produces a striking diagonally downward-directed rupture from the daughter crack at the surface. Tang et al. (2020) also noticed this feature on dipping strike-slip faults with largely subshear rupture, and argued that the rupture which was not directed purely in the mode II direction suppressed supershear rupture (analogous to the mixed-models of Andrews, 1994 and Weng & Ampuero, 2020). Our interpretation, in contrast, is that the diagonal rupture fronts are a consequence of the supershear rupture right at the surface leading the subshear rupture at depth; the diagonal rupture fronts in our interpretation are a symptom, rather than a cause, of the subshear rupture at depth.

Hu et al. (2019, 2020) have shown that the existence of a daughter crack in strike-slip faults cannot guarantee a sustained supershear rupture, since the daughter crack is possible to be absorbed by the following main crack, which turns into an unsustained supershear rupture. Our simulations show even if the “supershear” (in the 1D gradient view) daughter crack can propagate to the fault bottom, its near field ground motion could still present sub-Rayleigh characteristics as revealed in the 2D gradient. Thus, it is interesting to compare the two metrics of rupture velocities in characterizing unsustained supershear ruptures. As shown in Figure 4, we compare the 1D and 2D rupture velocity distributions of the three rupture scenarios.
in a homogeneous stress model (Figure 1 of Hu et al., 2020). The hypocenter depth is the only different simulation parameter among the three cases which transits from a sub-Rayleigh rupture (Figure 4d) to a sustained supershear rupture (Figure 4f) as the hypocenter depth increases from 5 to 10 km. The difference between the 1D and 2D rupture velocities in the sustained supershear case in the homogeneous stress model (Figures 4c and 4f) is similar as discussed in Figure 1. However, for the unsustained supershear cases, both 1D and 2D metrics can unveil the fading away process of the supershear daughter crack, although slight differences still exist, especially when the angle of the tangent direction of the rupture front deviates from the vertical direction.

Thus, the presence of the leading daughter crack makes it tempting to identify the fault areas for which it arrives first as undergoing supershear rupture, but it is possible that this supershear speed is only obtained via one-dimensional gradient or average velocity definitions, not two-dimensional local gradients like $V_{1d}$, especially when the daughter crack is downward propagating. More information than just the presence of a daughter crack is necessary to identify widespread supershear rupture.

In conclusion, we argue that the most physically meaningful definition of supershear rupture is based on $V_{1d}$, earthquake ruptures with large areas that are supershear by this definition will be considered supershear using a range of observables. However, other definitions of supershear rupture may well be useful for other seismological techniques, such as back projection or surface wave polarization rotation. In reality, fault zones (Huang et al., 2016), fault roughness (Bruhat et al., 2016), off-fault yielding (Bhat et al., 2007), velocity-strengthening friction near the Earth’s surface (Kaneko et al., 2008), sediment effect (Xu et al., 2021), and topography effect (Z. Zhang et al., 2016) may make rupture fronts complicated, which further complicates rupture velocity behavior and thus the differences between $V_{1d}$ and $V_{2d}$. However, no matter which definition of rupture velocity is chosen, we argue that the existence of a Mach front produced by an earthquake is evidence of a true supershear rupture.

Data Availability Statement
The simulated rupture front datasets are available at https://doi.org/10.5281/zenodo.4635460.

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References
Aagaard, B. T., & Heaton, T. H. (2004). Near-source ground motions from simulations of sustained intersonic and supersonic fault ruptures. Bulletin of the Seismological Society of America, 94(6), 2064–2078. https://doi.org/10.1785/0120030249
Andrews, D. J. (1976). Rupture velocity of plane strain shear cracks. Journal of Geophysical Research, 81(32), 5679–5687. https://doi.org/10.1029/JB081i032p05679
Andrews, D. J. (1994). Dynamic growth of mixed-mode shear cracks. Bulletin of the Seismological Society of America, 84(4), 1184–1198.
Andrews, D. J. (2010). Ground motion hazard from supershear rupture. Tectonophysics, 493(3–4), 216–221. https://doi.org/10.1016/j.tecto.2010.02.003
Archuleta, R. J. (1984). A faulting model for the 1979 Imperial Valley earthquake. Journal of Geophysical Research, 89(B6), 4559–4585. https://doi.org/10.1029/JB089i06p04559
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, 200–205. https://doi.org/10.1038/s41561-018-0297-z
Bernard, P., & Baumont, D. (2005). Shear Mach wave characterization for kinematic fault rupture models with constant supershear rupture velocity. Geophysical Journal International, 162(2), 431–447. https://doi.org/10.1111/j.1365-246x.2005.02611.x
Bhat, H. S., Dmowska, R., King, G. C. P., Klinger, Y., & Rice, J. R. (2007). Off-fault damage patterns due to supershear ruptures with application to the 2001Mw8.1 Kokoxili (Kunlun) Tibet earthquake. Journal of Geophysical Research, 112(B6). https://doi.org/10.1029/2006JB004425
Bizzarri, A., & Das, S. (2012). Mechanics of 3-D shear cracks between Rayleigh and shear wave rupture speeds. Earth and Planetary Science Letters, 357–358, 397–404. https://doi.org/10.1016/j.epsl.2012.09.053
Bizzarri, A., & Spudich, P. (2008). Effects of supershear rupture speed on the high-frequency content of S waves investigated using spontaneous dynamic rupture models and isochrone theory. Journal of Geophysical Research, 113(B5). https://doi.org/10.1029/2007jb005146
Bouchon, M., Toksöz, N., Karabulut, H., Bouin, M.-P., Dietrich, M., Aktar, M., & Edie, M. (2000). Seismic imaging of the 1999 Izmit (Turkey) rupture inferred from the near-fault recordings. Geophysical Research Letters, 27(18), 3013–3016. https://doi.org/10.1029/2000gl011761
Bouchon, M., & Vallée, 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.1068632
Bruhat, L., Fang, Z., & Dunham, E. M. (2016). Rupture complexity and the supershear transition on rough faults. Journal of Geophysical Research: Solid Earth, 121(1), 210–224. https://doi.org/10.1002/2015jb012512
Burridge, R. (1973). Admissible speeds for plane-strain self-similar shear cracks with friction but lacking cohesion. Geophysical Journal International, 35(4), 439–455. https://doi.org/10.1111/j.1365-246x.1973.tb00608.x
Burridge, R., Conn, G., & Freund, L. B. (1979). The stability of a rapid mode II shear crack with finite cohesive traction. Journal of Geophysical Research, 84(B5), 2210–2222. https://doi.org/10.1029/jb084ib05p22210
Das, S., & Aki, K. (1977). Fault plane with barriers: A versatile earthquake model. Journal of Geophysical Research, 82(36), 5658–5670. https://doi.org/10.1029/JB082i036p05658

Geophysical Research Letters 10.1029/2021GL092832
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.

Day, S. M., Gonzalez, S. H., Anosovshepor, R., & Brune, J. N. (2008). Scale-model and numerical simulations of near-fault seismic directivity. *Bulletin of the Seismological Society of America*, 98(3), 1186–1206. https://doi.org/10.1785/0120070190

Dunham, E. M. (2007). Conditions governing the occurrence of supershear ruptures under slip-weakening friction. *Journal of Geophysical Research*, 112(B7). 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/10.1785/0120040616

Dunham, E. M., & Archuleta, R. J. (2005). Near-source ground motion from steady state dynamic rupture pulses. *Geophysical Research Letters*, 32(3). https://doi.org/10.1029/2004GL021793

Dunham, E. M., & Bhat, H. S. (2008). Attenuation of radiated ground motion and stresses from three-dimensional supershear ruptures. *Journal of Geophysical Research*, 113(B8). https://doi.org/10.1029/2007JB005182

Dunham, E. M., Faveau, P., & Carlson, J. M. (2005). A supershear transition mechanism for cracks. *Science*, 299(5612), 1557–1559. https://doi.org/10.1126/science.1080650

Fukuoyama, E., & Olsen, K. B. (2002). A condition for super-shear rupture propagation in a heterogeneous stress field. In *Earthquake processes: Physical modeling, numerical simulation and data analysis Part I* (pp. 2047–2056). Springer. https://doi.org/10.1007/978-3-0348-8203-3_9

Harris, R. A., Barall, M., Archuleta, R. B., Ma, S., Roten, D., Olsen, K., et al. (2018). A suite of exercises for verifying dynamic earthquake rupture codes. *Seismological Research Letters*, 89(3), 1146–1162. https://doi.org/10.1785/02SR20170222

Huang, Y., Ampuero, J.-P., & Helmberger, D. V. (2016). The potential for supershear earthquakes in damaged fault zones—Theory and physical modeling, numerical simulation and data analysis Part I. *Journal of the Mechanics and Physics of Solids*, 56(11), 25–50. https://doi.org/10.1016/j.jmps.2007.06.005

Huang, Y., Ampuero, J.-P., & Helmberger, D. V. (2016). The potential for supershear earthquakes in damaged fault zones—Theory and observations. *Earth and Planetary Science Letters*, 433, 109–115. Retrieved from http://www.sciencedirect.com/science/article/pii/S0012821X15006822

Ishii, M., Shearer, P. M., Houston, H., & Vidale, J. E. (2005). Extent, duration and speed of the 2004 Sumatra-Andaman earthquake imaged by the Hi-Net array. *Nature*, 438(7044), 933–936. https://doi.org/10.1038/nature04367

Kaneko, Y., & Lapusta, N. (2010). Supershear transition due to free surface in 3-D simulations of spontaneous dynamic rupture on vertical strike-slip faults. *Tectonophysics*, 493(3–4), 272–284. https://doi.org/10.1016/j.tecto.2010.06.015

Kaneko, Y., Lapusta, N., & Ampuero, J.-P. (2008). Spectral element modeling of spontaneous earthquake rupture on rate and state faults: Ef- fect of velocity-strengthening friction at shallow depths. *Journal of Geophysical Research*, 113(B9). https://doi.org/10.1029/2007JB005553

Liu, Y., & Lapusta, N. (2008). Transition of mode II cracks from sub-Rayleigh to insonic speeds in the presence of favorable heterogeneity. *Journal of the Mechanics and Physics of Solids*, 56(11), 25–50. https://doi.org/10.1016/j.jmps.2007.06.005

Madariaga, R., & Olsen, K. B. (2000). Criticality of rupture dynamics in 3-D. *Pure and Applied Geophysics*, 157(11–12), 1981–2001. https://doi.org/10.1007/pl00001071

Mello, M., Bhat, H. S., Rosakis, A. J., & Kanamori, H. (2010). Identifying the unique ground motion signatures of supershear earthquakes: Theory and experiments. *Journal of Geophysical Research*, 115(B9). 297–326. https://doi.org/10.1029/2010JB007003

Mello, M., Bhat, H. S., Rosakis, A. J., & Solids, P. o. (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. https://doi.org/10.1016/j.jmps.2016.02.031

Olsen, K. B., Madariaga, R., & Archuleta, R. J. (1997). Three-dimensional dynamic simulation of the 1992 Landers earthquake. *Science*, 278(5399), 834–838. https://doi.org/10.1126/science.278.5399.834

Palmer, A. C., & Rice, J. R. (1973). The growth of slip surfaces in the progressive failure of over-consolidated clay. *Geophysical Research Letters*, 1(1), 301–308. https://doi.org/10.1029/GL013i001p00340

Palmer, A. C., & Rice, J. R. (1974). The growth of slip surfaces in the progressive failure of over-consolidated clay. *Geophysical Research Letters*, 1(3), 2194–2206. https://doi.org/10.1029/GL013i001p00340

Rubino, V., Rosakis, A. J., & Lapusta, N. (2019). Full-field ultra-high-speed quantification of dynamic shear ruptures using digital image correlation. *Journal of Applied Mechanics*, 87(3). https://doi.org/10.1115/1.4045715

Rubino, V., Rosakis, A. J., & Lapusta, N. (2019). Full-field ultra-high-speed quantification of dynamic shear ruptures using digital image correlation. *Experimental Mechanics*, 59(5), 551–582. https://doi.org/10.1007/s11340-019-00501-7

Ryan, K. I., & Oglesby, D. D. (2014). Dynamically modeling fault step overs using various friction laws. *Journal of Geophysical Research: Solid Earth*, 119(7), 5814–5829. https://doi.org/10.1002/2014JB011511

Soczewinski, A., Hollingsworth, I., Pathier, E., & Bouchon, M. (2019). Evidence of supershear during the 2018 magnitude 7.5 Palu earthquake from space geodesy. *Nature Geoscience*, 12(3), 192–199. https://doi.org/10.1038/s41561-018-0296-0

Tang, R., Yuan, J., & Gan, L. (2020). Free-surface-induced supershear transition in 3-D simulations of spontaneous dynamic rupture on oblique faults. *Geophysical Research Letters*, 47(8), e2020GL091621. https://doi.org/10.1029/2020GL091621

Walker, K. T., & Shearer, P. M. (2009). Illuminating the near-sonic rupture velocities of the intracontinental Kocoxili M-W 7.8 and Denali fault M-W 7.9 strike-slip earthquakes with global P wave back projection imaging. *Journal of Geophysical Research*, 114. https://doi.org/10.1029/2008JB005738

Wang, D., & Mori, J. (2012). The 2010 Qinghai, China, Earthquake: A moderate earthquake with supershear rupture. *Bulletin of the Seismological Society of America*, 102(1), 301–308. https://doi.org/10.1785/01201001034

Weng, H., & Ampuero, J.-P. (2020). Continuum of earthquake rupture speed enabled by oblique slip. *Nature Geoscience*, 13, 817–821.

Weng, H., Huang, J., & Yang, H. (2015). Barrier-induced supershear ruptures on a slip-weakening fault. *Geophysical Research Letters*, 42(12), 4824–4832. https://doi.org/10.1002/2015GL064281

Xia, K., Rosakis, A. J., & Kanamori, H. (2004). Laboratory earthquakes: The sub-Rayleigh-to-supershear rupture transition. *Science*, 305(5685), 1859–1861. https://doi.org/10.1126/science.1094022

Xu, J., Zhang, H., & Chen, X. (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/ggq284
Xu, J., Zhang, Z., & Chen, X. (2021). The effects of sediments on supershear rupture. Tectonophysics, 805, 228777. https://doi.org/10.1016/j.tecto.2021.228777

Yue, H., Lay, T., Freymueller, J. T., Ding, K., Rivera, L., Ruppert, N. A., & Koper, K. D. (2013). Supershear rupture of the 5 January 2013 Craig, Alaska (Mw 7.5) earthquake. Journal of Geophysical Research: Solid Earth, 118(11), 5903–5919. https://doi.org/10.1002/2013jb010594

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. https://doi.org/10.1111/j.1365-246x.2006.03102.x

Zhang, Z., Xu, J., & Chen, X. (2016). The supershear effect of topography on rupture dynamics. Geophysical Research Letters, 43(4), 1457–1463. https://doi.org/10.1002/2015gl067112

Zhang, Z., Zhang, W., & Chen, X. (2014). Three-dimensional curved grid finite-difference modeling for non-planar rupture dynamics. Geophysical Journal International, 199(2), 860–879. https://doi.org/10.1093/gji/ggu308