Seismic radiation from tensile and shear point dislocations between similar and dissimilar solids

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SUMMARY
We examine the characteristics of seismic radiation produced by localized fault-opening and shear motions in a homogeneous solid, along with the effects of having dissimilar solids across the fault on the seismic radiation. The study employs calculations of synthetic seismograms generated at various receiver locations by shear and tensile dislocation sources. The results indicate that, in contrast to the standard case of shear dislocation, the body wave amplitudes of the fault-parallel component generated at near-fault seismograms by tensile dislocation are considerably larger than those of the fault-normal component. The $P$ and $S$ arrivals from a shear dislocation at receivers on the opposite sides of a fault in a homogeneous solid have the same polarities on the fault-normal component and opposite polarities on the fault-parallel and vertical components. However, for a tensile dislocation source the situation is exactly reversed. The existence of a velocity contrast across the fault produces additional phases that mask somewhat the above signals. However, the generated amplitudes and other waveform characteristics may be used to distinguish between the physical fault plane and the auxiliary plane. The recording and analysis of the discussed signals for regular earthquakes that are dominated by shear motion will require high-resolution receivers located very close to the fault.

Keywords: Earthquake dynamics; Earthquake ground motions; Body waves; Interface waves; Theoretical seismology; Wave propagation.

1 INTRODUCTION
Earthquakes are typically assumed to be caused by shear faulting (e.g. Aki & Richards 2002). While this assumption is made explicitly or implicitly in almost all earthquake-related studies, it is recognized that earthquake sources may also have tensile components with differential motion in the fault-normal direction. Possible causes of such fault-opening motion include volumetric changes in geothermal, volcanic and other extensional regimes (e.g. Foulger & Long 1984; Julian & Sipkin 1985; Dreger et al. 2000).

Recently, there has been growing interest in the possibility that earthquake ruptures in regular tectonic (not volcanic or geothermal) environments are associated with a small amount of transient fault-opening motion. Such motion was observed in laboratory sliding experiments between two foam rubber blocks (Brune et al. 1993) and earlier experiments of Schallamach (1971) between rubbers and hard materials. Transient local fault opening motion may be produced by collisions of geometrical asperities along rough surfaces (e.g. Lomnitz-Adler 1991), Schallamach-type waves and dynamic changes of elastic moduli in the source region (e.g. Knopoff & Randall 1970; Ben-Zion & Ampuero 2009). In addition, dynamic dilation near the tip of a rupture front propagating along a bimaterial interface in the direction of slip on the compliant side of the fault can overcome the initial compressive stress and produce local transient fault-opening (e.g. Weertman 1980; Ben-Zion & Huang 2002; Shi & Ben-Zion 2006).

One obvious indication of fault-opening motion or tensile faulting may come from a mismatch between fault-normal seismograms recorded at corresponding locations on the opposite sides of a fault. However, such a comparison should take into account details of the faulting geometry and the velocity structures on the opposite sides of the fault, and is generally not easily achievable. Another set of signals that may reflect tensile faulting are non-double-couple earthquake mechanisms (e.g. Julian et al. 1998; Miller et al. 1998). However, non-double-couple mechanisms may also be produced by shear faulting in an anisotropic medium (e.g. Kawasaki & Tanimoto 1981) and a combination of several different double-couples (e.g. Frohlich et al. 1981; Kawakatsu 1991; Bailey et al. 2009). A third type of signal, consistent with theoretical estimates of Haskell (1964) and Walter & Brune (1993), are high-frequency $S/P$ spectral amplitude ratios considerably smaller than those expected for shear ruptures (e.g. Castro et al. 1991). However, the high-frequency spectral amplitudes are strongly affected by attenuation (e.g. Hanks 1981) and the lack of phase information does not allow detailed comparisons with various receiver positions.

Earthquake source studies usually also assume that the media on the opposite sides of the fault have the same elastic properties. The assumed symmetry of properties across the fault and the resulting
symmetry of the radiation field from a shear dislocation lead to the well-known problem of fault-plane ambiguity in focal mechanism studies using only direct $P$-wave arrivals (e.g. Aki & Richards 2002). Many earthquakes, however, and especially moderate and large events occur on bimaterial interfaces that separate different elastic solids. This is evident from tomographic images focusing on large faults (e.g. Eberhart-Phillips & Michael 1998; Thurber et al. 2006) and analysis of head waves that refract along bimaterial interfaces in the fault zone structure (e.g. Ben-Zion & Malin 1991; Lewis et al. 2007; Zhao & Peng 2008). The radiation pattern generated by sources on a bimaterial interface should allow a distinction between the physical fault plane and the auxiliary plane of the standard homogeneous models (Ben-Zion 1990). To find additional potential seismic signatures of fault-opening motion and clarify the radiation generated by sources on a bimaterial interface, we perform a theoretical study involving analysis of synthetic seismograms generated by point sources with fault-opening components between similar and dissimilar solids. Haskell and Thomson (1972) and Thomson & Doherty (1977) calculated near-field seismograms from a finite propagating tensile dislocation in an infinite homogeneous isotropic elastic solid. The waveform characteristics were affected by the finiteness and prescribed propagation speed of the source. In the current study, however, we focus on detailed features of waveforms produced by non-propagating localized shear and tensile dislocations. The results can be considered as kernels for future calculations of seismic radiation from propagating finite sources.

The synthetic waveform calculations indicate that near-fault seismograms for the fault-parallel motion can be very useful for analysis of fault-opening motion, and that the change of radiation (for example, lose of symmetry and additional head wave phases) from sources on bimaterial interfaces associated with moderate velocity contrast can be useful for resolving the fault-plane ambiguity. The simulated seismograms provide guidelines for observational studies aiming to derive high-resolution information on earthquake source properties. The results can also be relevant for analysis of waves generated by ice-quakes, ruptures in laboratory experiments, rock bursts in mines and seismic exploration studies associated with explosions and fractures at the edges of boreholes.

2 ANALYSIS

2.1 Radiation patterns from point sources in a homogeneous isotropic solid

Using the point-source approximation, it is easy to derive the near-, intermediate- and far-field radiation patterns of body waves generated by a general moment tensor (see the Appendix). The far-field patterns of the $P$ and $S$ waves from a shear dislocation in a homogeneous solid can be expressed by (Aki & Richards 2002)

$$A_S^{FP} = (\sin 2\theta \cos \phi) \hat{r},$$  

(1a)

$$A_S^{FS} = (\cos 2\theta \cos \phi) \hat{\theta} + (-\cos \theta \sin \phi) \hat{\phi},$$  

(1b)

where $\hat{r}$, $\hat{\theta}$ and $\hat{\phi}$ are the unit basis vectors in spherical-polar coordinate system (Fig. 1).

Similarly, the far-field radiation patterns of the $P$ and $S$ waves from a tensile dislocation in a homogeneous solid (see the Appendix) are given by

$$A_T^{FP} = (\lambda/\mu + 2 \cos^2 \theta) \hat{r},$$  

(2a)

$$A_T^{FS} = (-\sin 2\theta) \hat{\theta},$$

(2b)

where $\lambda$ and $\mu$ are the Lamé parameters.

Figs 2(a) and (b) illustrate the far-field radiation patterns given by eqs (1a), (1b), (2a) and (2b) for shear and tensile dislocations. The assumed medium is a Poissonian whole space. In contrast to a shear dislocation, the radial and transverse components from a tensile dislocation have no dependence on $\phi$ and therefore the radiation patterns are axialsymmetric. In the case of a shear dislocation, there are two nodal planes for the $P$ wave, namely the fault plane and the auxiliary plane, and no nodal plane for the $S$ wave. In the case of a tensile dislocation, however, there is no nodal plane for the $P$ wave and the fault plane is a nodal plane for the $S$ wave (e.g. Haskell 1964). Therefore, the fault-plane ambiguity problem using only $P$-wave arrivals from a shear dislocation does not exist for the tensile dislocation. Moreover, the radiation patterns from these two dislocation types reach maximum amplitudes in different spatial directions. In the next two sections we examine in more detail the radiation fields generated by shear and tensile dislocation sources through calculations of synthetic waveforms.

2.2 Synthetic seismograms for dislocation sources in a homogeneous solid

We employ a numerical implementation of the 3-D analytical solution of Ben-Zion (1990, 1999) to calculate synthetic seismograms generated by a general dislocation on an interface separating similar (this section) or dissimilar (next section) elastic solids. The solution is for two joined half-spaces without a free surface. The model geometry and the employed coordinate system are illustrated in Fig. 3(a). The fault lies on the $x_1$-$x_2$ plane and the dislocation source, located at the $x_1$-axis, can have fault-parallel (shear in the $x_1$-direction) and/or fault-normal (tensile in the $z$-direction) components. A ramp source-time function is used with a rise time of 0.01 s. In this section we set the $P$-wave speed to be $c_p = 5196$ m s$^{-1}$ and the $S$-wave speed to be $c_s = 3000$ m s$^{-1}$. The source depth is fixed at $x_1 = 1$ km for all calculations done in this study. The receivers are located on the $y$-$z$ plane in various configurations labelled in Fig. 3(b) as RCA, RCB, RCC and RCD. The parameter $\theta$ defined in Fig. 3(a) is used in RCA and RCD as an alternative indication for the fault-normal distance of the receivers.

As a part of code validation, we show in Fig. 4 comparisons between the synthetic seismograms given by our code and numerical implementation of the analytical expressions of body wave radiations given in the Appendix for a shear dislocation. The receiver configuration RCD is employed. In this figure and later waveform

![Figure 1. Cartesian and spherical-polar coordinate systems. The fault lies on the $x_1$–$x_2$ plane with the $x_3$-axis as the fault normal. For a shear dislocation source the fault slips along the $x_1$-axis direction and for a tensile dislocation the fault motion is along the $x_3$-axis direction.](image)
Figure 2. Far-field radiation patterns of $P$ wave (top plots) and $S$ wave (bottom plots) from (a) a shear dislocation source and (b) a tensile dislocation source in a Poisson solid ($\nu = 0.25$). Fault-normal direction and slip directions are labelled and ‘N’ denotes the neutral axis.

Figure 3. (a) A model consisting of two half-spaces with the $x$–$y$ plane as the fault and the $z$-axis in the fault-normal direction. The dislocation source (red star on the $x$-axis) can have both fault-parallel (marked as 1) and fault-normal (marked as 2) components. $x_s$, $z_r$ and $R$ are the source depth with respect to the receiver plane (fixed at 1 km), fault-normal distance of the receiver and the hypocentral distance. (b) Various receiver configurations on plane $x = 0$ employed in the calculations of synthetic seismograms: Configuration ‘RCA’ with receivers along a straight line $y = 0$ which is normal to the fault and through the epicentre; Configuration ‘RCB’ with receivers along two straight lines parallel (and very close) to the fault trace with $z = \pm 0.1$ m; Configuration ‘RCC’ with receivers along a circle centred at the epicentre with radius $r = 0.2$ km; and Configuration ‘RCD’ with receivers along a straight line $y = 1$ km. The receivers in every configuration are in pairs symmetric about the fault plane.
Radiation forms point dislocations

Figure 4. Three-component synthetic seismograms from a shear dislocation recorded with array RCD. The red and blue traces are obtained from numerical implementation of the analytical solution given by Ben-Zion (1990, 1999) whereas the black thin traces are obtained from numerical implementation of the analytical solution given in Aki & Richards (2002).

Figure 5. The radiation curves (amplitude profiles of $P$ and $S$ phases) obtained from theoretical formula (solid lines) and measurements from synthetic seismograms (diamond and circle symbols) from a shear dislocation in a homogeneous solid with (a) array RCA where $\theta$ is defined in Fig. 3(a), (b) array RCB and (c) array RCC where $\alpha$ is the angle measured from $+y$-axis clockwise on the $y$–$z$ plane.

Figure 6. The radiation curves (amplitude profiles of $P$ and $S$ phases) obtained from theoretical formula (solid lines) and measurements from synthetic seismograms (diamond and circle symbols) from a tensile dislocation in a homogeneous solid with (a) array RCA where $\theta$ is defined in Fig. 2(a), (b) array RCB and (c) array RCC where $\alpha$ is the angle measured from $+y$-axis clockwise on the $y$–$z$ plane.
Figure 7. Three-component synthetic seismograms from a shear dislocation in a homogeneous solid recorded with array (a) RCA (b) RCB and (c) RCC. The vertical components in (a) are identically zero. Both fault-parallel and vertical components in (b) are several orders of magnitudes smaller than the fault-normal components. The vertical components in (c) are amplified by 10 times. The largest waveform amplitudes are labelled on the right-hand side in unit of m. The blue and red traces denote seismograms recorded at receivers with $z < 0$ and receivers with $z > 0$, respectively.
Tensile dislocation in a homogeneous solid

Figure 8. Three-component synthetic seismograms from a tensile dislocation source in a homogeneous solid recorded with array (a) RCA (b) RCB and (c) RCC. The vertical components in (a) and fault-normal components in (b) are identically zero. The largest waveform amplitudes are labelled on the right-hand side in unit of m. The blue and red traces denote seismograms recorded at receivers with $z < 0$ and receivers with $z > 0$, respectively.
results, blue traces denote seismograms recorded at receivers with $z < 0$ (slower medium for dissimilar solids) and red traces denote seismograms recorded at receivers with $z > 0$ (faster medium for dissimilar solids). We note that the amplitudes of the $P$ and $S$ phases on all traces are well matched. Since the fault in this case is a nodal plane for the $P$ wave and a maximum plane for the $S$-wave, the $P$-wave approaches zero and the $S$-wave approaches maximum as the receiver gets closer to the fault, that is, $|\theta| \to 90^\circ$.

Fig. 5 shows the amplitude profiles of $P$ and $S$ phases along different receiver configurations from a shear dislocation. The solid lines are the theoretical radiation curves of the $P$-wave (blue) or $S$-wave (red) amplitudes given by the sum of the intermediate- and far-field radiation terms (eqs A7–A10 in the Appendix). The $P$ and $S$ amplitudes in each panel are normalized by a common maximum factor. Since the $P$ and $S$ waves are mixed in the near-field term (eq. A6) and the contribution from the near-field radiation is less than 5 per cent of the total field at the employed receivers, the near-field term is not included in plotting the solid lines. This might lead to some discrepancies between the radiation curves and measurements from the whole-field synthetic seismograms. For the receiver configuration RCA (Fig. 5a), the $S$-wave amplitude has a local minimum at $\theta = \pm 45^\circ$ and the $P$-wave amplitude reaches a maximum at $\theta \approx \pm 55^\circ$. For RCB (Fig. 5b), the receivers are close to the fault, which is a nodal plane for the $P$ wave and maximum plane for the $S$ wave. The largest discrepancies occur for the $S$-wave amplitudes near the ends of RCB (Fig. 5b). Fig. 6 gives corresponding amplitude profiles from a tensile dislocation. The $P$ and $S$ amplitudes in Figs 6(a) and (c) are normalized as in Fig. 5 by a common maximum, while in Fig. 6(b) each of the $P$ and $S$ amplitudes is normalized with respect to its own maximum due to the large difference in the amplitudes of these signals. In this case, the largest discrepancies between the theoretical curves and results associated with the synthetic seismograms occur for the $S$-wave amplitudes at receivers close to the fault ($\alpha = 0^\circ$ and $180^\circ$) for the RCC array (Fig. 6c). The excellent general agreement between the amplitude measurements from our synthetic seismograms and the theoretical curves provides additional validation for the employed numerical code.

Fig. 7 shows the three-component synthetic seismograms from a shear dislocation using receiver arrays RCA, RCB and RCC. For the receiver configuration RCA, the vertical components are identically zero (Fig. 7a). For RCB both fault-parallel and vertical components are several orders of magnitude smaller than the fault-normal components (Fig. 7b). Fig. 8 shows the corresponding seismograms from a tensile dislocation. The vertical components for RCA (Fig. 8a) are identically zero and the fault-normal components for RCB (Fig. 8b) are several orders of magnitude smaller than the other two components.

In the case of a shear dislocation, the $P$ and $S$ arrivals at receivers across the fault have the same polarities on the fault-normal

Figure 9. The radiation curves (amplitude profiles of $P$ and $S$ phases) measured from synthetic seismograms for a shear dislocation source between dissimilar solids (10 per cent velocity contrast) with array (a) RCA, (b) RCB and (c) RCC. Solid and dashed curves denote measurements on the fast-medium side and slow-medium side, respectively.

Figure 10. The radiation curves (amplitude profiles of $P$ and $S$ phases) measured from synthetic seismograms for a tensile dislocation source between dissimilar solids (10 per cent velocity contrast) with array (a) RCA, (b) RCB and (c) RCC. Solid and dashed curves denote measurements on the fast-medium side and slow-medium side, respectively.
components and opposite polarities on the fault-parallel and vertical components (Fig. 7). In contrast, the situation is reversed in the case of a tensile dislocation (Fig. 8). It is also interesting to note that at the receiver configuration RCB the fault-parallel components are several orders larger than the fault-normal components in the case of a tensile dislocation, while it is exactly the opposite in the case of a shear dislocation.

2.3 Synthetic seismograms for dislocation sources between dissimilar solids

To examine the effects of having dissimilar media across the fault on the seismic radiations generated by shear and tensile sources, we use in this section a model consisting of two dissimilar half-spaces. The $P$- and $S$-wave speeds of the faster medium ($z > 0$), $c_{p1}$ and $c_{s1}$, are the same as in the previous section. The $P$- and $S$-wave speeds for the slower medium ($z < 0$), $c_{p2}$ and $c_{s2}$, are set to be 10 per cent smaller than those of the faster side: $c_{p2} = c_{p1}/1.1 = 5196/1.1 = 4723.6 \text{ m s}^{-1}$ and $c_{s2} = c_{s1}/1.1 = 3000/1.1 = 2727.3 \text{ m s}^{-1}$.

**Figure 11.** The spatial distribution of amplitudes of $P$ and $S$ waves on a receiver plane $x = 0$ radiated from a shear dislocation between (a) similar and (b) dissimilar solids. The amplitudes are normalized with the maximum value measured. The fault-normal distance (along $z$-axis) and the along-strike distance (along $y$-axis) are both normalized by the source depth $x_s$. The solid line at $z = 0$ denotes the fault trace and the dot at $(0, 0)$ denotes the epicentre. The head waves are recorded as first arrivals in the region between the dashed line and the solid line (fault).
case (Fig. 5c) becomes the maximum and the overall amplitude on the slower side of the fault is significantly larger than on the faster side.

To get a more complete picture of the effects of dissimilar solids on the radiation patterns, we plot in Figs 11 and 12 the $P$- and $S$-wave amplitudes generated at the receiver plane $x = 0$ by a shear dislocation and a tensile dislocation, respectively. A comparison between the left- and right-hand panels of Figs 11 and 12 highlights the asymmetric radiation across the fault in cases where the fault separates dissimilar solids. Another distinctive feature in the radiation generated for two dissimilar solids, seen clearly for both the $P$ and $S$ waves produced by both shear and tensile dislocations, is the existence of lens-shaped areas with maximum wave amplitudes on the slower-medium side within a fault-normal distance from the fault of $z \approx 0.5x_s$ or $\theta \approx 63.4^\circ$. The lens-shaped areas with increased amplitudes are generated by $P$ or $S$ head waves contributing to the $P$ or $S$ direct arrivals when their duration times overlap. The amplitude pattern within the lens-shaped area depends on the relations between the differential arrival times of the head and direct waves and the rise time of the source-time function. The differential arrival times of the head and direct waves decreases with increasing fault-normal distance, up to a critical value beyond which head waves disappear (e.g. Ben-Zion 1990). The pattern is also modified by the effect of geometrical spreading.

Fig. 13 illustrates with analytical calculations the expected interference effect of the head and direct waves for $S$ waves radiation as a function of their differential traveltimes and the source rise time. For the region beyond the critical fault-normal distance designated in Fig. 13 by the dashed line, there is no head wave and hence no interference effect. For the region between the dash–dotted line and the fault in Fig. 13, the differential traveltime is larger than 1.5 times the rise time, and hence there is little to no interference effect. Between the dashed line and dash–dotted line, there is an overlap between the head wave and the direct wave. The degree of interference between the two different phases is represented by a cosine taper function with centre and width equal to the rise time and 1.5 times the rise time, respectively, and amplitudes accounting for the geometrical spreading of body waves.

Figs 14 and 15 show the three-component synthetic seismograms from shear and tensile dislocations, respectively, at the receiver configurations RCA, RCB and RCC. As expected, we observe $P$ and $S$ head waves in seismograms recorded on the slower side of the fault.

**Figure 12.** The spatial distribution of amplitudes of $P$ and $S$ waves on a receiver plane $x = 0$ radiated from a tensile dislocation between (a) similar and (b) dissimilar solids. The notations and symbols are the same in Fig. 11.
fault within a critical distance \( z_c = r \cdot \tan[\cos^{-1}(c_2/c_1)] \), where \( r \) is the distance the head wave travels along the bimaterial interface and \( c_1 \) and \( c_2 \) are the faster and slower \( P \)- or \( S \)-wave speeds (Benzion 1990). Due to the velocity difference of the solids, there is an obvious time shift between the \( P \)- and \( S \)-wave phases at receivers on opposite sides of the fault with equal hypocentral distances. Compared with the homogeneous case, seismograms from a dislocation source between dissimilar solids have more complicated waveform shapes, which masks somewhat the differences between the radiations generated by shear and tensile dislocation sources.

The largest waveform amplitudes at RCA and RCC for both shear and tensile dislocations (Figs 14a and c, 15a and c) are \( \sim 1.5-2 \) times those of the homogeneous case (Figs 7a and c, 8a and c). On the other hand, for the RCB array the largest waveform amplitudes (Figs 14b and 15b) remain at the same level or lower than those of the homogeneous case (Figs 7b and 8b). It is also interesting to note that in the case of a shear dislocation with array RCB (Fig. 14b), the amplitudes of the fault-parallel and vertical components gained appreciably whereas the fault-normal components have slightly lower amplitudes compared to the corresponding results in the homogeneous case (Fig. 7b). In the case of a tensile dislocation and receivers array RCB, the fault-normal components in the homogeneous case are several orders smaller than the other components (Fig. 8b). However, in the case of two dissimilar solids the amplitudes of the fault-normal components with same source and receiver configuration (Fig. 15b) are comparable to those of the other components.

3 DISCUSSION

Earthquake motions are dominated overall by tangential slip along faults. However, a small-supersposed transient fault-opening motion can change dramatically the physics of the processes involved and the energy partition between dissipation and radiation. As mentioned in the introduction, many mechanisms including geometrical irregularities, presence of fluids and contrasts of elastic properties across faults can produce a small component of tensile motion.

It is thus important to search for indicative signals of transient fault-opening motion that may be observable for faulting events dominated overall by shear motion. Towards this end, we performed detailed calculations of synthetic seismograms generated by shear and tensile dislocations between similar and dissimilar solids using various source-receiver geometries.

The results indicate that careful examination of fault-parallel and fault-normal seismograms at appropriate receiver configurations may provide evidence for the existence of a small amount of fault-opening motion. Receivers located very close to the fault (e.g. array RCB) are expected to record essentially zero fault-parallel seismograms from a shear dislocation (Fig. 7b). However, such receivers can have fault-parallel waveforms with appreciable amplitudes (Fig. 8b) if the source has some tensile component. Near-fault seismograms generated by a failure process consisting primarily of shear slip with a small amount of superposed tensile motion will have considerably larger fault-normal components than fault-parallel components. Differential fault-normal seismograms at corresponding positions across the fault, and non-zero fault-parallel seismograms recorded very close to the fault, can indicate the existence of some tensile motion in the source region. We also note that the \( P \) and \( S \) arrivals from a shear dislocation at receivers on opposite sides of a fault in a homogeneous solid have the same polarities on the fault-normal component, and opposite polarities on the fault-parallel and vertical components, while for a tensile dislocation the situation is exactly reversed (Figs 7 and 8). This may not be useful for regular earthquakes for which shear faulting is dominant and likely to mask the polarity signals. However, the discussed polarity information may be useful for laboratory experiments and seismic exploration studies involving tensile cracking with magnitude comparable to or larger than shearing.

The presence of velocity contrast across the fault makes noticeable differences in the radiation patterns (Figs 5–6 and 9–12) and waveform characteristics (Figs 7–8 and 14–15) for both shear and tensile dislocation sources. In general, both the \( P \) and \( S \) phases have larger amplitudes on the slower-medium side due to the lower elastic moduli (Figs 11 and 12). However, the velocity contrast across the fault masks the distinctions between shear and tensile dislocations by changing the polarities of the first arrivals and the amplitude ratios of the fault-parallel to fault-normal components of motion. Another mechanism that can change the amplitude ratios of the fault-normal and fault-parallel seismograms is supershear rupture near the vicinity of the receiver array (e.g. Aagaard & Heaton 2004). However, the arrival times and additional phase characteristics can be used easily to distinguish between supershear rupture, bimaterial interface and fault-opening motion.

The discussed results are based on simple model calculations with localized non-propagating sources between two similar or dissimilar uniform half-spaces without a free surface. Observed seismograms are generally considerably more complex than the calculated waveforms, and include effects of finite propagating sources, structural heterogeneities off the fault, attenuation of high frequency signals, etc. Radiation from more realistic propagating sources surrounded by media with heterogenous velocity structures may be obtained from our results by convolution integrals.

Efforts to detect the calculated signals should employ high-resolution near-fault data and analyses techniques such as stacking and deconvolution that amplify the target signals and reduce other effects. In some situations such as tensile ice-quakes, tensile cracking in laboratory experiments, borehole studies with tensile fractures, and rock bursts in mines with simple velocity structures between the sources and receivers, the results provide guidelines.
Shear dislocation between two dissimilar solids

Figure 14. Three-component synthetic seismograms from a shear dislocation between two dissimilar solids (10 per cent velocity contrast) recorded with array (a) RCA (b) RCB and (c) RCC. $P$ and $S$ head waves are present on seismograms recorded within critical fault-normal distances. The vertical components in (c) are amplified by 10 times. The largest waveform amplitudes are labelled on the right-hand side in unit of m. The blue and red traces denote seismograms recorded at receivers on the slower-medium side ($z < 0$) and the faster-medium side ($z > 0$), respectively.
Radiation from point dislocations

Tensile dislocation between two dissimilar solids

Figure 15. Three-component synthetic seismograms from a tensile dislocation between two dissimilar solids (10 per cent velocity contrast) recorded with array (a) RCA (b) RCB and (c) RCC. P and S head waves are present on seismograms recorded within critical fault-normal distances. The vertical components in (c) are amplified by 10 times. The largest waveform amplitudes are labelled on the right-hand side in unit of m. The blue and red traces denote seismograms recorded at receivers on the slower-medium side ($z < 0$) and the faster-medium side ($z > 0$), respectively.

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that can be used directly to identify tensile dislocation sources. For natural earthquakes and other processes that are dominated by shear dislocations, the detection of a tensile component of motion at the source remains a very challenging task. A useful strategy should employ a combination of signals such as those discussed in the present work, anomalously low $S/P$ spectral ratio of the high-frequency radiated waves (e.g. Haskell 1964; Castro et al. 1991; Walter & Brune 1993), and isotropic component of high-frequency radiation in regular tectonic environments (e.g. Spudich & Chiou 2008; Ford et al. 2009).

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REFERENCES


APPENDIX

The body wave radiation from a general moment tensor $\mathbf{M}$ corresponding to a point source (Aki & Richards 2002) can be expressed as

$$ M_{pq} \ast G_{np,q} = u_n^\oplus(t) + u_s^\delta(t) + u_s^\delta(t) + u_a^\delta(t) + u_a^\delta(t). \quad (A1a) $$

where

$$ u_n^\delta(t) = \frac{15\gamma_n\gamma_p\gamma_q - 3\gamma_p\delta_{pq} - 3\gamma_q\delta_{pq} - 3\gamma_q\delta_{np}}{4\pi\rho} \times \frac{1}{r} \int_{r_{\min}}^{r_{\max}} \tau M_{pq}(t - \tau) d\tau, \quad (A2) $$

$$ u_s^\delta(t) = \frac{6\gamma_p\gamma_q\gamma_r - 3\gamma_p\delta_{qr} - 3\gamma_q\delta_{qr} - 3\gamma_r\delta_{np}}{4\pi\rho a^2} \frac{1}{r^2} M_{pq}(t - \frac{r}{c}). \quad (A3a) $$

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(1) Pure-shear dislocation source

In this case we have
\[ \nu \tilde{u}_t = 0, \]  
(A11)
and the following correspondence
\[ 2\nu \gamma_\nu \gamma_{\nu} \tilde{u}_p \leftrightarrow \{ \tilde{u} \sin 2\theta \cos \phi \tilde{r} \} \]
(A12a)
\[ \gamma_{\nu} \gamma_{\nu} \tilde{u}_p \leftrightarrow 0 \]
(A12b)
\[ 2\nu_\nu \gamma_{\nu} \tilde{u}_p \leftrightarrow \{ \tilde{u}(\sin 2\theta \cos \phi \tilde{r} - 2 \sin^2 \theta \cos \phi \tilde{\theta}) \} \]
(A12c)
\[ 2\nu_\nu \gamma_{\nu} \tilde{u}_\alpha \leftrightarrow \{ \tilde{u} \sin 2\theta \cos \phi \tilde{r} + 2 \cos^2 \theta \cos \phi \tilde{\theta} \} \]
(A12d)
where \( \{ \}_n \) denotes the nth component of a vector.

Substitution of eqs (A12) into eqs (A6b), (A7b), (A8b), (A9b) and (A10b) with the constraint of eq. (A11) yields
\[ A^S_S = (9 \sin 2\theta \cos \phi) \tilde{r} + (-6 \cos 2\theta \cos \phi) \tilde{\theta} + (6 \cos \theta \sin \phi) \tilde{\phi} \]
(A13)
\[ A^S_P = (4 \sin 2\theta \cos \phi) \tilde{r} + (-2 \cos 2\theta \cos \phi) \tilde{\theta} + (2 \cos \theta \sin \phi) \tilde{\phi} \]
(A14a)
\[ A^S_P = (-3 \sin 2\theta \cos \phi) \tilde{r} + (3 \cos 2\theta \cos \phi) \tilde{\theta} + (-3 \cos \theta \sin \phi) \tilde{\phi} \]
(A14b)
\[ A^S_S = (\cos 2\theta \cos \phi) \tilde{r} + (-\cos \theta \sin \phi) \tilde{\phi} \]
(A15b)

Eqs (A13)–(A15) duplicate the classical results for shear dislocation given in eq. (4.33) of Aki & Richards (2002). Below we derive corresponding radiation patterns generated by a tensile dislocation.

(2) Pure-tensile dislocation source

In this case we have
\[ \nu \tilde{u}_t = \tilde{u}, \]
(A16)
and the following correspondence
\[ 2\nu_\nu \gamma_{\nu} \gamma_{\nu} \tilde{u}_p \leftrightarrow \{ \tilde{u}(\sin 2\theta \cos \phi \tilde{r} - 2 \sin^2 \theta \cos \phi \tilde{\theta}) \} \]
(A17a)
\[ \gamma_{\nu} \gamma_{\nu} \tilde{u}_p \leftrightarrow \{ \tilde{u} \} \]
(A17b)
\[ 2\nu_\nu \gamma_{\nu} \tilde{u}_p \leftrightarrow \{ \tilde{u}(2 \cos^2 \theta \tilde{r} - \sin 2\theta \tilde{\theta}) \} \]
(A17c)
\[ 2\nu_\nu \gamma_{\nu} \tilde{u}_\alpha \leftrightarrow \{ \tilde{u}(2 \cos^2 \theta \tilde{r} - \sin 2\theta \tilde{\theta}) \} \]
(A17d)
where \( \{ \}_n \) denotes the nth component of a vector.

Substitution of eqs (A17) into eqs (A6b), (A7b), (A8b), (A9b) and (A10b) with the constraint of eq. (A16) yields
\[ A^S_S = (18 \cos^2 \theta - 6) \tilde{r} + (6 \sin 2\theta) \tilde{\theta} \]
(A18)
\[ A^S_P = (\lambda / \mu - 2 + 8 \cos^2 \theta) \tilde{r} + (2 \sin 2\theta) \tilde{\theta} \]
(A19a)
\[ A^S_S = (2 - 6 \cos^2 \theta) \tilde{r} + (-3 \sin 2\theta) \tilde{\theta} \]
(A19b)
The far-field radiation terms given by eqs (A20a) and (A20b) have similar forms to the radiations given by eq. (41) of Rice (1980).

In summary, the body wave radiation patterns from a pure-shear dislocation source are given by expressions (A13)–(A15) and the corresponding patterns from a pure-tensile dislocation are given by expressions (A18)–(A20). Graphic representations of the far-field terms of these fields are given in Figs 2(a) and (b).