Rupture velocity inferred from near-field shear strain analysis

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Accepted 2014 September 8. Received 2014 September 7; in original form 2014 June 16

SUMMARY
We propose a new technique to determine the rupture velocity of large strike slip earthquakes. By means of simple numerical ground motion simulations, we show that when the rupture penetrates a shallow layer of sediment or fractured rock, shock waves propagate along the surface fault trace in the forward rupture direction. Such shock waves, which are insensitive to the complexity of slip over the fault plane, propagate at a phase velocity equal to the rupture speed. We show that those shock waves can be easily isolated in the frequency domain, and that phase velocity can then be simply obtained from shear strain.

Key words: Fourier analysis; Earthquake ground motions; Earthquake source observations.

1 INTRODUCTION
Recordings of ground-motion in the vicinity of faults provide information about the spatiotemporal evolution of the rupture process. Important features such as the rupture velocity and the spatial distribution of slip are generally obtained using inversion techniques. Those features are then inevitably biased due to trade-offs between sought source parameters (e.g. Beresnev 2003; Zahradnik & Galovic 2010). This arises because all source features and observations are jointly inverted, while the dataset is often too sparse. In addition, imperfect knowledge of the ground structure can propagate further uncertainties into the inversion solution. Recently, Bernauer et al. (2014) have shown that non-uniqueness issues may be partially solved by including ground rotation recordings.

By means of synthetic experiments, Luco & Sotiropoulos (1980) and Bouchon & Aki (1982) noted that phase velocities of strong ground-motions are not controlled by the near-surface velocities but by the basement rock shear wave velocity and the rupture velocity, supporting experimental evidence for phase velocities larger than the soil top layer wave velocity (Tamura et al. 1977). We propose to extend those earlier synthetic experiments to demonstrate a powerful approach to constrain rupture velocity, in the case of strike slip earthquakes propagating at a subshear rupture velocity (i.e. lower than the shear wave velocity). The main idea is to consider only ground-motion observations for which the contributions from rupture velocity and spatial slip complexity are clearly separated. This condition is excepted in case of shock wave formation, that is when the energy contribution from different parts of the fault arrive simultaneously, because slip complexity is then focused in a short pulse, sensitive to the sum of the slip over the fault area—and not to slip heterogeneities. We investigate at which locations and in which frequency band ranges such shock waves can be observed. Next, we show that rupture velocity can be deduced from phase velocity, which can be simply obtained from shear strain, without modelling of seismic wave propagation. The potential of the method is highlighted based on ground-motion simulations for a vertical strike slip 1-D fault, assuming a complex slip distribution and a unilateral rupture propagating at a fixed subshear rupture velocity.

2 COMPUTATION OF GROUND VELOCITY AND SHEAR STRAIN
We simulate ground displacement at a set of two-stations arrays parallel to the fault direction, from which we compute shear strain. Shear strain is defined as the spatial derivative, along the fault plane, of the transverse displacement. The wave propagation is modelled using discrete wavenumber technique (Bouchon 1981) assuming a homogeneous elastic medium covered with a 1.5-km-thick low velocity layer, with shear wave velocities of 3500 and 1000 m s\(^{-1}\), respectively (Fig. 1). Although very simple, the chosen velocity structure represents the decrease of the wave velocity at shallow depth, due to the presence of sediments or altered rock. In order to compute shear strain up to 2 Hz, the distance between two stations is set to 125 m, that is a quarter of the minimum wavelength (Spudich & Fletcher 2008). Other relationship between spatial sampling, error estimate of the spatial derivative and resolvable frequency bandwidth for finite-difference spatial derivative schemes can be found in Langston (2007). In practice, for accurate strain estimation, a priori knowledge on the shallow shear wave velocity is then required to estimate either the maximum resolvable frequency for a given station separation or the minimum station separation for a
target maximum frequency. This can be easily achieved by using rapid and inexpensive methods (e.g. Boore & Asten 2008; Bard et al. 2010). The source mechanism is a vertical strike-slip and the rupture on the fault plane is modelled as a line source rupturing unilaterally at a constant subshear rupture velocity \( V_{R,i} \), in such a way that all arrays see the rupture moving forward. The line source assumption is chosen for simplicity, and is relevant for ruptures with large length over width ratio \( (>2) \), which is the case for many crustal earthquakes (e.g. Somerville et al. 1999). The considered values for \( V_{R,i} \), 2300 m s\(^{-1}\) (\( \sim 0.65 \) \( V_S \)) and 3000 m s\(^{-1}\) (\( \sim 0.85 \) \( V_S \)), span the range of rupture velocities expected for most earthquakes (e.g. Heaton 1990). The source length is 20 km and the mean slip is 1 m, equivalent to a moment magnitude \( M_w \sim 6 \). The line source is placed at the bottom of the low velocity layer, mimicking a strike slip event that would extend up to the ground surface. Finally, in order to account for slip heterogeneity, we assume a \( k \)-square source model (Bernard et al. 1996). Slip is then the sum of cosine functions of various wavelengths, with slip duration proportional to the wavelength, resulting in a complex spatiotemporal slip distribution.

As observed by Bouchon & Aki (1982), shear strain \( \frac{\partial \gamma}{\partial t} \) scaled by the average phase velocity \( C \), and ground velocity \( \dot{v}(t) \) are very similar:

\[
\dot{v}(t) \approx C \frac{\partial \gamma}{\partial t}.
\]

In order to assess the phase velocity, we then scale shear strain so as to obtain the best fit, in the least-square sense, with ground velocity. We show subsequently how rupture velocity can be inferred from simple frequency analysis of the phase velocity.

3 RUPTURE VELOCITY REVEALED BY PHASE VELOCITY OF SHOCK WAVES

Although shock waves are generally associated with supershear ruptures (e.g. Bernard & Baumont 2005; Dunham & Bhat 2008; Vallée & Dunham 2012), they can also be generated in the common case of subshock ruptures, in case the rupture penetrates a shallow sediment layer characterized by \( S \)-wave velocity smaller than the rupture speed (Bouchon 1979).

3.1 Generation of SH shock wave

If \( V_R \) exceeds 1000 m s\(^{-1}\) (i.e. the \( S \)-wave velocity in the shallow layer), ground motion on top of the fault is dominated by a \( S \) shock wave related to a large amplitude pulse of short duration on the transverse ground-motion component, due to coherent summation of the waves emitted along the line source. This shock wave is clearly observable at stations of array 1 (Fig. 2a). In case of homogeneous source (constant slip over the fault plane), the phase...
velocity of this pulse is essentially controlled by the rupture velocity. Ground velocity and shear strain related to the pulse are then perfectly correlated, and their ratio provides a robust estimation of the rupture velocity. In case of heterogeneous $k$-square source model, shear strain associated to the pulse is affected by large-scale slip heterogeneities, small-scale heterogeneities remaining invisible due to coherent summation inside the shock wave. In order to obtain a good approximation of the rupture velocity, a high-pass filter is then necessary (above $\sim 0.5$ Hz) before computing the phase velocity (Figs 2b–d).

Beyond the fault zone in the forward rupture direction, the SH shock wave disappears because it is not supplied by the rupture anymore.

### 3.2 Generation of Love shock waves

The penetration of the line source inside the shallow layer results in a strong Love waves excitation. Each Love mode $n$ is associated with phase velocities $C_n(f)$ between the shear wave velocities of the top and the bottom layer (1000 m s$^{-1}$ < $C_n(f)$ < 3500 m s$^{-1}$). If the rupture is subshear and $v_R$ exceeds 1000 m s$^{-1}$, Love wave phases that satisfy the condition $C_n(f) = v_R$, sum coherently in the forward rupture direction, giving rise to very high amplitude Love shock waves. Such phases propagate at the rupture speed and are easily identifiable in the frequency domain by normalizing displacement amplitude as following: (1) division by a Brune (1970) source spectrum to screen out average source effects; (2) division by the spectrum of a point source (or aftershock spectrum in case of real earthquake) to screen out propagation effects and (3) scaling so as to obtain a spectral ratio of 1 at zero frequency. This normalization directly exhibits frequency ranges amplified by rupture propagation (Fig. 3). The computation of phase velocity from velocity and shear strain bandpass filtered in the previously determined frequency ranges provides then a direct estimation of the rupture velocity (Fig. 4). Note that these Love shock waves are formed right after the fault termination (array 2) and persist up to—at least—a few rupture lengths (array 3).

### 4 CONCLUSION AND DISCUSSION

We have presented a new approach to characterize the rupture velocity of subshear strike slip earthquakes. This approach rests on the hypothesis that the rupture penetrate a shallow layer of sediment or fractured rock associated with a low shear wave velocity (i.e. lower than the rupture velocity). First, this layer has the potential of focusing seismic energy aside the fault surface trace in a SH shock wave traveling at the rupture speed. Secondly, due to wave dispersion, rupture speed information spreads away from the source termination in the shallow layer, in the shape of SH Love waves propagating at the rupture speed. Unlike kinematic inversions, the proposed method is free from non-uniqueness issues, is based on basic processing techniques and does not require detailed information about the ground structure, except the local shear wave velocity. The later can be easily estimated from rapid and inexpensive methods (e.g. Boore & Asten 2008; Bard et al. 2010).

This study points out the strong potential of ground strain observations for source imaging. Our results give useful insight on where to install dense sensor arrays, rotation sensors, or simply two nearby sensors at the vicinity of large strike slip faults to analyse earthquake rupture propagation. Due to the simplicity of the assumptions made, the following effects still need to be investigated so as to better define the conditions in which the proposed approach is robust: (1) ruptures on 2-D faults; (2) deeper sources; (3) incoherency in the rupture propagation and (4) wave propagation in more complex structures.

### ACKNOWLEDGEMENTS

We are grateful to Michel Bouchon for fruitful discussions and for suggestions to improve the paper. We also thank Martin Mai and an anonymous reviewer for their thorough review and helpful comments.
Figure 4. (a) Comparison between transverse ground velocity and shear strain scaled by phase velocity \( v_a \) at array 2. Left-hand panel: in the frequency range \( 0-2 \) Hz; Right-hand panel: after bandpass filtering so as to isolate Love waves amplified due to source propagation (third higher mode). (b) Same as (a) but at array 3 and considering the first higher mode. The frequency ranges chosen for band-pass filtering are indicated by arrows on Figs 3(a) and (b). Note that correlation coefficient always exceeds 0.98, indicating an excellent level of fit.

REFERENCES


