Supershear Rupture Velocity in Earthquakes

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Most of the material in this talk is from:

Direct Observation of Earthquake Rupture Propagation in the 2004 Parkfield, California, Earthquake

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submitted, Science
Apologies

In some figures the rupture travels to the right and in others to the left. Sorry.

Several recent large to very large earthquakes have evidence of supershear rupture velocity
2002 M 7.8 Denali earthquake

Aagaard and Heaton, Bull. Seismol. Soc. Am., 2004
Danham and Archuleta, Bull. Seismol. Soc. Am., 2004
and others

2001 M 7.8 Kunlunshan earthquake

Bouchon and Vallee, Science, 2003
1999 Kocaeli (Izmit), Turkey, earthquake M7.4


1979 M6.5 Imperial Valley earthquake

Archuleta, Bull. Seismol. Soc. Am, 1984
Spudich and Cranswick, BSSA, 1984
Some evidence for supershear rupture velocity in

1992 M 7.2 Landers, California, earthquake

1999 M 7.2 Duzce, Turkey earthquake
Bouchon et al., Geophys. Res. Letts., 2001
Bilgoren et al., Geophys. Res. Letts., 2004

Several recent large strike-slip earthquakes show evidence of supershear rupture velocity.

There is independent evidence that large (M>7.3) earthquakes have unexpectedly small high-frequency ground motions (still being debated).

Questions

Could supershear rupture velocity be associated with reduced high-frequency ground motions?

Is supershear rupture velocity the general rule in large strike-slip earthquakes?

Is supershear rupture velocity limited to large strike-slip earthquakes?
Comparison of 2002 Denali (rotated) and 1857 Ft. Tejon rupture lengths

All quakes on same scale

Imperial Valley M6.5

Kocaeli/Izmit M7.4

Denali M7.8

Kunlunshan M7.8
All quakes on same scale

Imperial Valley M6.5

Parkfield M6.0

Kocaeli/Izmit M7.4

Denali M7.8

Kunlunshan M7.8
Vs cross section (Thurber et al., Geophys. Res. Letts., 2004)

San Andreas fault

2004 Parkfield earthquake, east comp of acceleration at UPSAR
For a particular time window of the data, find the propagation direction (vector slowness) of the best fitting plane wave.

This vector slowness is assumed to be that which maximizes the average cross-correlation of all station pairs.

Plane wave: \( u(t - \tilde{s} \cdot \tilde{x}) \), \( \tilde{s} = (s_E, s_N, s_Z) \)

\[
\tilde{s}_Z^2 = \left( \frac{1}{v_s} \right)^2 - s_E^2 - s_N^2, \quad v_s = \text{shear wave speed}
\]

\( a_j = \text{accelerogram time series, station } j \text{ at location } \tilde{x}_j \)

Cross correlation \( C_{ij}(\tilde{s}) = \left[ \frac{(a_i(t - \tilde{s} \cdot \tilde{x}_i), a_j(t - \tilde{s} \cdot \tilde{x}_j))^2} { (a_i(t - \tilde{s} \cdot \tilde{x}_i), a_i(t - \tilde{s} \cdot \tilde{x}_i))^2 + (a_j(t - \tilde{s} \cdot \tilde{x}_j), a_j(t - \tilde{s} \cdot \tilde{x}_j))^2 } \right]^{1/2} \)

Average cross correlation \( C(\tilde{s}) = \frac{1}{N} \sum_i \sum_j C_{ij}(\tilde{s}) \)

Example: 0.5 s window around hypocentral S wave

\( \phi = \text{azimuth back to source} = \tan^{-1} \left( \frac{s_E}{s_N} \right) \)

Apparent velocity = horizontal phase velocity = \( \left( s_E^2 + s_N^2 \right)^{-1} \)
Summary of results for all time windows

Map of source locations (circles) and aftershocks (crosses) on the San Andreas fault plane
Comparison of aftershocks (red) to pre-earthquake seismicity (gray) on the San Andreas fault surface (from J. Hardebeck, USGS)

Aftershocks and pre-earthquake seismicity are in the same locations, despite presumed stress changes of main shock

Strongly suggests that the position of microearthquakes is controlled by material properties of faults, not stress distribution

Comparison with lab experiments of rupture on a bimaterial interface, by Xia, Rosakis, Kanamori, and Rice (2005)

Xia et al. geometry

Parkfield geometry
Xia et al. (2005) lab results show supershear in same direction as 2004 Parkfield earthquake

Figure 4. Rupture case-3. Experimental results for $\alpha = 25^\circ$ and $P = 13$ MPa showing transition of the eastward moving rupture to supershear. The westward rupture retains a constant velocity $V_W = +C_{GR}$.

Conclusions - 1

- 2004 Parkfield quake is smallest for which supershear rupture velocity observed
- Rupture travels at 1.18-1.25 Vs of the faster side of the fault
- Super-shear velocity to NW (in direction of slip on the faster side of the fault) is consistent with numerical predictions (Harris & Day, 1997) and lab observations (Xia et al, 2005)
- Supershear velocity is observed to occur for a 7% Vs contrast across fault (excluding 4 km wide wedge), smaller than in numerical and lab results
- Sub- to supershear transition distance < 10 km here, like the Izmit, Turkey, quake, but smaller than the 25-50 km postulated for the Kunlunshan, China, quake based on lab scaling
Conclusions - 2

- Strong acceleration pulses are well correlated, suggesting a compact source area, probably caused by acceleration or deceleration of rupture front at some barrier on the fault
- Similarity of pre-shock and aftershock distributions on the fault suggests that material or frictional property variations control the locations of microearthquakes
- Coincidental locations of the source of the supershear acceleration pulse and a cluster of aftershocks suggest that a material/frictional property variation on the fault caused the rupture to decelerate from supershear speed

THE END