3-D rupture dynamics with kinematic constraints: the 1992 Landers earthquake

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Abstract

The 1992 magnitude 7.3 Landers, California, earthquake is modeled kinematically and dynamically with a three-dimensional finite-difference method. The kinematic model uses fixed, prescribed rupture parameters from the kinematic slip inversion by Wald and Heaton (1994[13]) and the dynamic models generate spontaneous ruptures controlled by a prestress distribution computed from the slip distribution used in the kinematic simulation. The dynamic ruptures that produce near-fault radiation similar to that for the kinematic simulation are characterized by propagation along a complex path with highly variable speed and rise time, and they reproduce the general slip pattern used to compute the initial stress distribution. These dynamic simulations are characterized by rupture energy releases of 5-10 MJ/$\mathbf{m^2}$.

Introduction

Olsen et al. (1997[11]) used recorded data to constrain the stress and frictional parameters for the 28 June 1992, magnitude 7.3 Landers earthquake. However, only very few near-field strong motion stations recorded the earthquake, typically located 10's of kilometers from the fault. Thus the constraints on the rupture propagation from data are limited. Another set of constraints on the rupture can be computed from a forward prediction of ground motion using the kinematic slip inversion. These ground motions are in more or less agreement with data at the recording stations used in the inversion, and represent a smooth estimate of the ground motions in between these stations. For these reasons we use the kinematic ground motion estimates at selected stations located near the fault and the moment of the earthquake to constrain the frictional parameters and stress conditions for the Landers earthquake.

Simulation method and fault parameterization

We used a 4th-order staggered-grid finite-difference solution to the three-dimensional elastic wave equation (Madariaga, 1976[7]; Olsen, 1994[10]) for both the kinematic and dynamic simulations in this study. Our scheme includes a free-surface boundary condition at the top and sponge layers in addition to absorbing boundary conditions (Clayton and Engquist, 1977[3]) at the remaining grid boundaries.

The fault that ruptured during the Landers earthquake can be divided into three segments: the Landers/Johnson Valley segment to the southeast where the hypocenter was located, the Homestead Valley segment in the central part of the fault, and the Camp Rock/Emerson segment to the northwest. For both the kinematic and dynamic simulations we replaced the three segments of the fault by a single 78-km long, planar, vertical fault plane extending from the surface down to 15 km depth.

Kinematic modeling

We simulated the Landers earthquake kinematically using the six time-window slip distribution derived by Wald and Heaton (1994[13]) by slip inversion. The slip distributions for each time window on the three fault segments were projected onto the single fault plane described above and discretized into subfaults of 200 m by 200 m area. The rupture was implemented with a constant rupture velocity of 2700 m/s using 6 1-sec isoceles triangles without overlap, each weighted by the respective slip contributions.

Dynamic Modeling

In this study we use a friction law for which slip is zero until the total stress reaches a critical yield value ($\mathbf{T_u}$). Once this stress has been attained, slip rate (and therefore slip) increases rapidly from zero while traction across the fault decreases to zero

$$\begin{aligned} \mathbf{T}(\mathbf{D}) &= \mathbf{T_u}\left[\mathbf{1} - \frac{|\mathbf{D}|}{\mathbf{D_0}}\right] \qquad \text{for} \qquad |\mathbf{D}| < \mathrm{D}_0 \qquad (1) \\ \mathbf{T}(\mathbf{D}) &= 0 \qquad\qquad\qquad \text{for} \qquad |\mathbf{D}| > \mathrm{D}_0, \end{aligned}$$

where D_0 is the slip-weakening distance. We assumed that slip occurred only along the long dimension of the fault so that the slip becomes a scalar ($D = |\mathbf{D}|$) in the simulations This assumption is consistent with kinematic source inversion results (Spudich, 1992[12]) that suggest that slip is aligned with the shear prestress, along the long dimension of a shallow strike-slip fault.

Prestress and frictional parameters

To estimate the initial stress field we used the slip distribution for the Landers earthquake proposed by Wald and Heaton (1994[13]). From this slip distribution we computed the change in static traction along the longitudinal direction of the fault using our finite-difference method. We use the distribution of this stress change with the sign reversed as the prestress for our simulations.

Since the hypocenter is located on an 'island' of elevated prestress several times less than the largest values in the distribution we promote the rupture initiation by adding a constant "tectonic stress" contribution (see, e.g., Miyatake, 1992[9]). Thus, the initial stress field is the sum of internal stresses on the fault due to preslip and previous earthquakes, plus some external spatially uniform tectonic load. For our dynamic simulations we use a tectonic stress of 40 bars which is close the value used by Olsen et al. (1997[11]), added to the prestress distribution computed from the kinematic slip distribution with the sign reversed.

The value of the yield stress determining the initiation of slip is more or less unconstrained and may vary on the fault. The general effect of increased yield stress is to increase rupture resistance. The other important parameter is the slip weakening distance D_0 which must be a fraction of the maximum slip on the fault. For the moment D_0 remains unconstrained, although a recent study of the Kobe earthquake in Japan (Ide and Takeo, 1997[6]) and the first dynamic study of Landers (Olsen et al., 1997[11]) have proposed rather large values for D_0. We choose to use constant values of D_0 and yield stress, but to vary the parameters in order to estimate their effect for the wavefield.

Before the simulation we constrained the initial stress on the fault to values just below the specified yield level in order to prevent rupture from several locations. We use the same regional one-dimensional (1D) model of velocities and densities as Wald and Heaton (1994[13]) in our simulations. Rupture was forced to initiate by lowering the yield stress in a patch of radius 4 km inside a high-stress region near the hypocenter towards the southern end of the fault, as inferred from the kinematic results. We used a spatial and temporal discretization of 200 m and 0.013 s, respectively, in a model defined by $430 \cdot 100 \cdot 97$ grid points.

Moment and duration constraints

The seismic moment and duration of the Landers earthquake have been estimated by several studies and can be considered reasonably well constrained. The total moment release and duration for the combined slip model by Wald and Heaton (1994[13]) were estimated at $7.7e^{19}$ Nm and 24 seconds, respectively. The moment release and duration for the dynamic simulations are controlled in part by the prestress, the slip weakening distance, and the yield stress. It is therefore reasonable to use the moment release and duration as constraints for the rupture dynamics. We limit the analysis to yield stress levels below 140 bars, above which the synthetics for the dynamic simulations are found to overpredict those for the kinematic simulation.

Figure 1 shows the moment and duration as a function of slip weakening distance and peak stress. The moment increases with larger values of yield stress and smaller slip weakening distance, for combinations of these parameters that allow rupture. The duration increases with the slip weakening distance. Only the product of the slip weakening distance and the yield stress is constrained, or in other words, the rupture energy, $\frac{1}{2}T_u D_0$. Figure 1 suggests that combinations of the parameters with rupture energy in the range 5-10 MJ/m^2 provide a moment and duration similar to those obtained from the kinematic analyses.

Figure 2 shows the prestress and final slip distributions for a dynamic rupture with (D_0,T_u) = (2 m, 80 bars), that produces a moment and a duration similar to those for the kinematics (depicted by a star in Figure 1).

Figure 3 shows sequences of snapshots of the dynamic rupture propagation. The sliprate history shows a confined rupture pulse (Heaton, 1990[5]) that generally propagates unilaterally along a continuous path on the fault, with possible backward rupture at the segment step-overs. The rupture velocity varies strongly from sub-sonic to super-sonic. On average, the rupture propagates with velocities close to the lo-

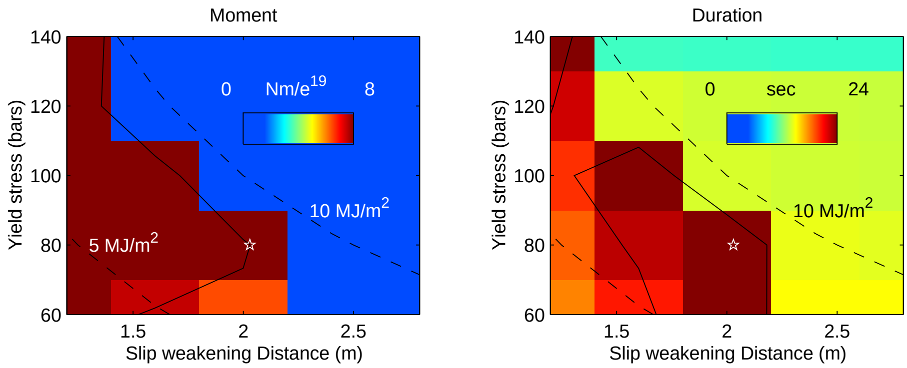

Figure 1: Moment and duration as a function of yield stress and slip weakening. Tectonioc stress was 40 bars. The solid contour lines depict values of $7.7e^{19}$ Nm for the moment, and 24 seconds for the duration plots. The dashed lines depict rupture energy release of 5 and 10 MJ/m^2.

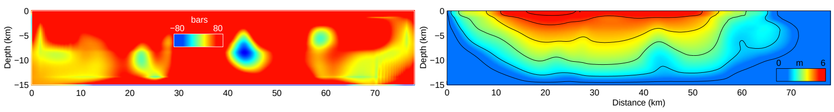

Figure 2: (left) Prestress and (right) slip distributions for a dynamic simulation of the Landers earthquake with T_u = 80 bars and D_0 = 2 m. Slip contour interval is 1 m.

cal S-wave speed and terminates about 24 s after initiation. The sub-sonic rupture velocities generally occur within and near the low-stress areas on the fault while super-sonic ones dominate within highly-stressed patches of the fault where the rupture resistance is relatively low. Super-sonic velocities are particularly dominating near the surface. These shallow super-sonic rupture velocities are likely caused by the free surface which promotes the generation of S-P converted head waves (S*) (Madariaga et al., 1997[8]). The existence of super-sonic rupture velocities has been documented in earlier rupture models (Day, 1982[4]) but evidence from seismic data (Archuleta, 1982[2]) is sparse, perhaps due to limited resolution of the inversion methods. In addition to promoting super-sonic velocities, the free surface enhances the slip significantly near the surface, in agreement with previous dynamic results (Archuleta and Frazier, 1978[1]).

Figure 4 shows a comparison of synthetics at five sites 5 km off the fault, for the kinematic simulation to those for the dynamic one using T_u = 80 bars and D_0 = 2 m.

While the two sets of synthetics correlate reasonably well at several sites (e.g.,

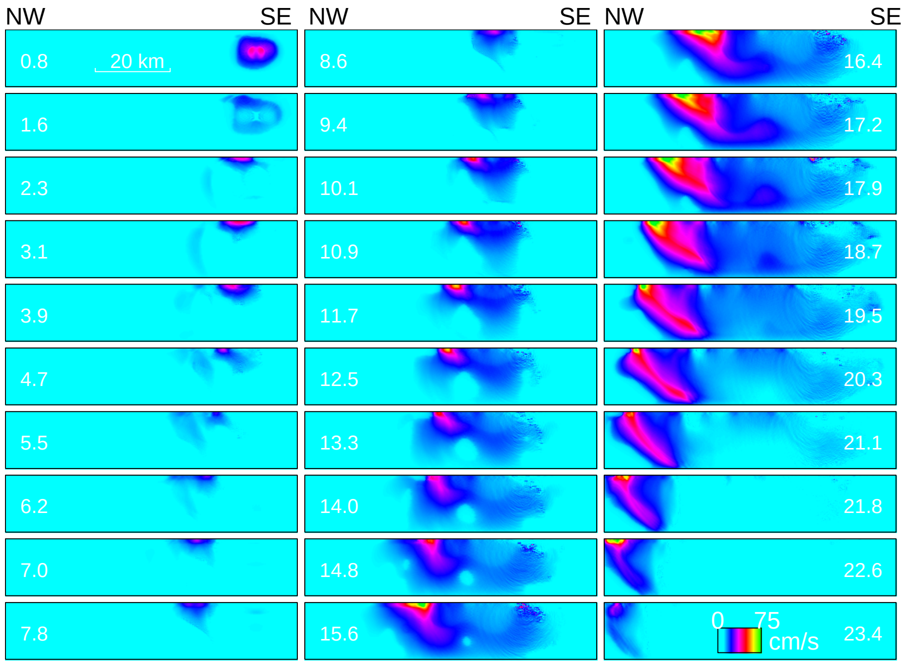

Figure 3: Sliprate history for the dynamic simulation of the Landers earthquake with T_u = 80 bars and D_0 = 2 m.

sites 1-2 and 4-5), discrepancies at other sites (e.g., site 3) suggest that the accuracy of the dynamic rupture simulation can be improved. Future research should focus on estimating the frictional parameters that produce dynamic ruptures with improved correlation between kinematic and dynamic synthetics. In order to improve this goal, we plan to compute synthetics for dynamic ruptures with a series of different values of D_0 and T_u, and to include a depth-varying slip weakening distance and rate weakening friction in the model.

Conclusions

We use results from kinematic slip inversion to compute prestress and constrain frictional parameters and dynamic rupture propagation for the 1992 Landers earthquake. The dynamic ruptures with moment and duration similar to those from the kinematic studies are characterized by propagation along a complex path with highly variable speed and rise time and rupture energy releases of 5-10 MJ$/m^2$. In addition, these ruptures reproduce the general slip pattern used to compute the initial stress distribution. The dynamic simulations with moments and durations constrained by the kinematic results generate near-fault ground motions at the surface in overall agreement to those computed by the kinematic rupture. However, discrepancies at specific stations between ground motion synthetics for the kinematics and simulations of dynamic ruptures with a simple friction law suggest that variation of the prestress and frictional parameters can lead to improved knowledge of the rupture

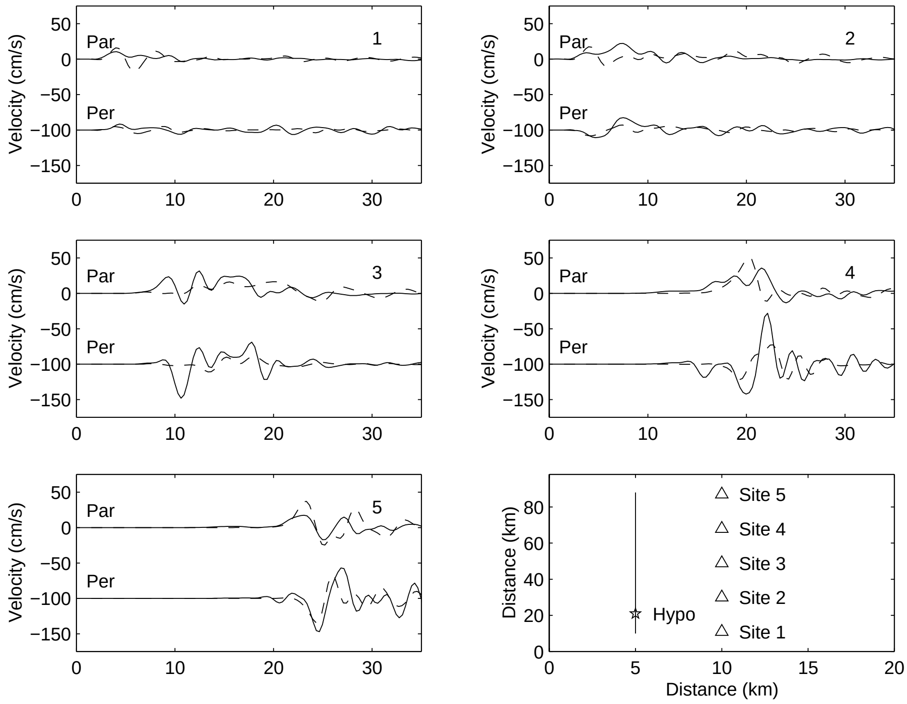

Figure 4: Comparison of synthetics for a kinematic simulation (solid traces) of the Landers earthquake to those for a dynamic simulation (dashed traces) using T_u = 80 bars and D_0 = 2 m. 'Par' and 'Per' depict fault-parallel and fault-perpendicular traces, respectively.

process of the Landers earthquake.

Acknowledgments

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http://quake.crustal.ucsb.edu/∼kbolsen.

References

[1] Archuleta, R.J. and Frazier, G., 1978, *Three-dimensional numerical simulations of dynamic faulting in a half-space,* Bull. Seis. Soc. Am. **68**, 541-572.

[2] Archuleta, R.J., 1982, *Analysis of near-source static and dynamic measurements from the 1979 Imperial Valley earthquake,* Bull. Seis. Soc. Am. **72**, 1927-1956.

[3] Clayton, R. and Engquist, B., 1977, *Absorbing boundary conditions for acoustic and elastic wave equations,* Bull. Seism. Soc. Am. **67**, 1529-1540.

[4] Day, S., 1982, *Three-dimensional simulation of spontaneous rupture: the effect of non-uniform prestress,* Bull. Seis. Soc. Am. **72**, 1881-1902.

[5] Heaton, T., 1990, *Evidence for and implications of self-healing pulses of slip in earthquake rupture,* Phys. Earth. Planet. Int. **64**, 1-20.

[6] Ide, S. and Takeo, M., 1997, *Determination of the constitutive relation of fault slip based on wave analysis,* J. Geophys. Res. **102**, 27,379-27,391.

[7] Madariaga, R., 1976, *Dynamics of an expanding circular fault,* Bull. Seism. Soc. Am. **66**, 639-667.

[8] R. Madariaga, Olsen, K.B., and Archuleta, R.J., 1997, *3-D finite-difference simulation of a spontaneous rupture,* Seismol. Res. Lett **68**, 312.

[9] Miyatake, T., 1992, *Reconstruction of dynamic rupture process of an earthquake with constraints of kinematic parameters,* Geophys. Res. Lett. **19**, 349-352.

[10] Olsen, K., 1994, *Simulation of three-dimensional wave propagation in the Salt Lake Basin,* Ph.D. Thesis, University of Utah, Salt Lake City, Utah, 157 p.

[11] Olsen, K., Madariaga, R., and Archuleta, R., 1997, *Three dimensional dynamic simulation of the 1992 Landers earthquake,* Science **278**, 834-838.

[12] Spudich, P., 1992, *On the inference of absolute stress levels from seismic radiation,* Tectonophys. **211**, 99-106.

[13] Wald, D. and Heaton, T., 1994, *Spatial and temporal distribution of slip for the 1992 Landers, California earthquake,* Bull. Seis. Soc. Am. **84**, 668-691.