Nonlinear Dynamic Rupture Inversion of the 2000 Western Tottori, Japan, Earthquake

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We have developed a systematic nonlinear inversion method for estimating rupture propagation and the underlying dynamic parameters for large historical earthquakes. The rupture modeling is carried out using a three-dimensional finite-difference method, and the inversion is implemented by a neighbourhood algorithm, minimizing the misfit between computed and observed near-fault seismograms. We test the method by estimating the stress drop within 32 regions on the causative fault for the 2000 magnitude 6.6 Western Tottori, Japan, earthquake. While the dynamic models show both similarities and differences with the conventional kinematic models, our method provides an ensemble of physically-correct models with plausible rupture propagation for the earthquake.

1. Introduction

Seismologists have attempted to unravel the rupture history of large earthquakes for decades. Such information is critical to understand how earthquakes initiate, propagate and arrest. The conventional procedure is to match recorded and synthetic accelerograms solving for the slip or sliprate on the fault [e.g., *Hartzell and Heaton*, 1984; *Cotton and Campillo*, 1995; *Zhang et al.*, 2003]. However, such kinematic rupture inversion is only based on physical plausible considerations, and does not solve the mechanical problem, and the results may be non-causal and biased by unphysical constraints on the rupture velocity and adopted source-time function [*Piatanesi*, 2003]. A more physically correct model would estimate the dynamics of spontaneous rupture propagation, i.e., the stress and friction parameters [e.g., *Madariaga et al.*, 1998]. Spontaneous rupture propagation assumes that the rupture process of an earthquake is a stress relaxation process. Rupture starts when the surrounding stress exceeds the frictional strength on the fault. Our approach, as most numerical dynamic rupture models, solves the elastodynamic equation in combination with initial conditions, the stress drop (T_e), the yield stress (T_u) and the slip weakening distance (D_c) [*Madariaga et al.*, 1998]. Forward modeling of the dynamic problem is now numerically feasible for large earthquakes with realistic rupture complexity in three dimensions (3D). For example, *Olsen et al.* [1997] carried out a large-scale spontaneous model of the 1992 Landers, California, event, using realistic initial conditions. The study showed that the rupture propagates on the fault along a complex path with highly variable speed and rise time, affecting the magnitude and pattern of the stress significantly in a strongly nonlinear fashion. *Peyrat et al.* [2001] used trial-and-error modeling to estimate a dynamic rupture model that provided a good fit to recorded strong motion records for the Landers earthquake. The results showed that the radiated waves are highly sensitive to the distribution of stress and friction parameters on the fault, an essential requirement for the inverse problem to work. However, inversion for the dynamic parameters is highly complicated due to a strong nonlinearity of the dynamic problem. Such nonlinearity raises the demands on both numerical and computational aspects of the problem tremendously. With recent advances in numerical modeling and increase in computational power we have developed a systematic, fully nonlinear method to invert for the dynamic parameters controlling rupture propagation of earthquakes from strong motion records. We illustrate this method here by inverting for the stress drop for the 2000 Western Tottori, Japan, earthquake.

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2. Inversion Method and Forward Model

The inversion method uses the neighbourhood algorithm [NA, *Sambridge*, 1999; 2001], a nonlinear derivative-free technique employing simple geometrical concepts to guide a direct search in the parameter space. At each stage the entire parameter space is partitioned into a set of Voronoi cells (nearest neighbor regions, as defined by a suitable norm), one associated with each previously sampled model. A Voronoi cell of a particular model is a polygon whose interior consists of all points in the parameter space which are closer to this particular model than to any other model. Between iterations, the new sample is recalculated in only the Voronoi cells of the previous models with the smallest misfits, thus less computationally costly than the Monte-Carlo technique. Furthermore, the NA requires less subjective 'guidance' of the solution search compared to candidate solutions from genetic algorithms and simulated annealing techniques in that it requires only two control parameters (the sample size at each iteration n_s, and the number of cells n_r in which a new sample is searched). In addition, the algorithm uses the misfit measure only to rank the fit between data and synthetics, i.e., the actual value of the misfit is not used directly. Such misfit measure helps speed up convergence for highly nonlinear problems such as rupture dynamics. To summarize the inversion technique: at the first iteration, a random set of models is generated (n_s) and the forward simulation is run for each of these models. A misfit value is computed for each of these models. At the second iteration, n_s new models are generated pseudo-randomly in n_r Voronoi cells corresponding to the n_r previous best models (with the lowest misfits).

The forward problem of fully spontaneous rupture propagation in a 3D medium on a vertical strike-slip fault is solved using a fourth-order staggered-grid finite-difference (FD) method [*Madariaga et al.*, 1998]. A common rule-of-thumb for fourth-order schemes is to discretize the rupture front and radiated waves by at least 5-6 grid points per minimum wavelength. To ensure accuracy of the results we use 9

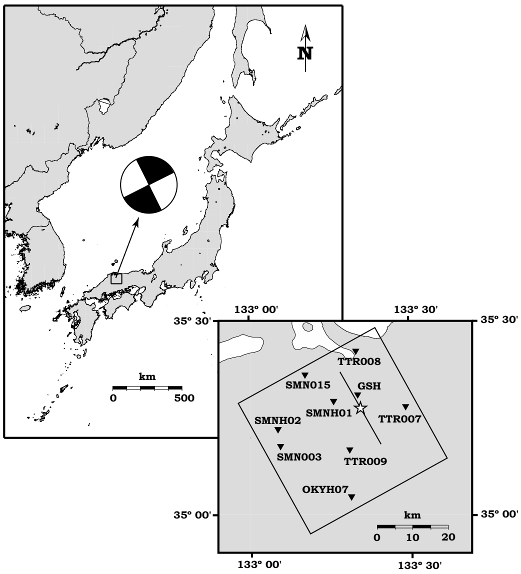

Figure 1. Location of the 2000 Western Tottori earthquake and fault mechanism. Inset depicts the epicenter (star), surface projection of the fault (straight line), extent of the FD model (rectangle), and strong motion stations included in the inversion (triangles).

points per minimum S wavelength with a spatial discretization of 500 m. Our scheme includes a free-surface boundary condition at the top and the efficient perfectly matched layers (PML) absorbing boundary conditions at the remaining grid boundaries. The PML method decreases the computational requirements considerably compared to other absorbing boundary conditions [*Marcinkovich and Olsen*, 2003]. Rupture is controlled entirely by the distributions of stress drop on the fault, as well as the constitutive friction law.

3. Tottori Earthquake

We test our dynamic inversion method on the Tottori earthquake which occurred on October 6, 2000 in the western Honshu, Japan, on a near-vertical, left-lateral strike-slip fault (Figure 1). Our choice of the Tottori earthquake is primarily justified by a large amount of near-fault, high-resolution strong motion records (K-net and KiK-net networks operated by the National Institute for Earth Sciences and Disaster Prevention (NIED)) and the apparent slip history simplicity suggested from kinematic inversion studies [*Iwata and Sekiguchi*, 2001; *Dalguer et al.*, 2003; *Mikumo et al.*, 2003]. Based on these studies and *Fukuyama et al.* [2003], we approximated the earthquake as a pure strike-slip event on a single planar, vertical segment, of azimuth 150^o, 24 km long and 14 km deep, with the top of the fault located 1 km below the ground surface. The hypocenter of the mainshock was located at 35.274^o N and 133.348^o E at a depth of 13 km. We used 12 strong motion stations (including 3 located in boreholes) in order to estimate the stress drop on the fault. The data and synthetic displacement time histories were bandpass filtered between 0.05 Hz and 0.5 Hz, and we assume that the parameters of the friction law (T_u and D_c) were constant over the fault. The slip weakening distance was chosen to be 28 cm, estimated from strong motion data [*Olsen et al.*, 2002], and the yield stress was constrained to 5 MPa which provided the fastest convergence from a set of trial inversions. We inverted for the stress drop on the fault within 32 patches with dimensions of 3 km by 3.5 km using a least-squares misfit measure ($\sqrt{\sum(obs - synth)^2 / \sum(obs^2)}$). We allow a constant temporal shift for all stations in order to take into account the delay caused by the artificial initiation of the rupture. This rupture initiation was forced by lowering the value of the yield stress in a small patch of radius 1.5 km at the hypocenter, which was fixed for all models. For the forward problem, we used a spatial and temporal discretization of 500 m and 0.025 s, respectively, in a model with dimensions of 80 km along 150^o and 240^o, and 25 km along vertical. The velocity structure is listed in Table 1. The search is carried out from random walks between -2 MPa and 5 MPa for the stress drop, and the starting models were selected pseudo-randomly [*Press et al.*, 1992]. We computed 40 models (n_s) for each of the 1500 iterations. The number of Voronoi cells in which new models are generated at each iteration was n_r=14.

Table 1. Earth Structure

V_p (km/s)	V_s (km/s)	Density (g/cm^3)	Thickness (km)
4.70	2.35	2.00	0.6
5.26	3.04	2.53	2.4
5.48	3.17	2.57	1.0
6.11	3.53	2.70	11.0
6.50	3.76	2.79	

4. Inversion Results

The slip, sliprate, and stress histories for the model with the smallest misfit are shown in Figure 2. The rupture is

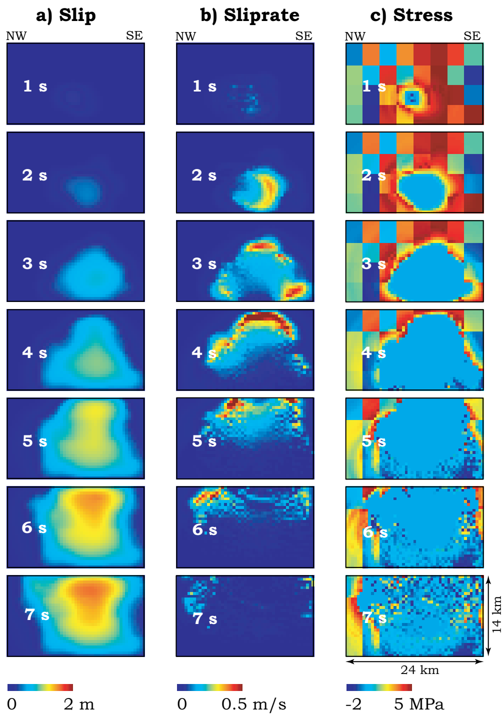

Figure 2. 7 second histories of slip, sliprate, and stress for the dynamic model generating synthetics with the best fit to 12 near-fault strong motion records.

initiated in the lower central part of the fault and gains strength propagating toward the surface. The moment release for our preferred model is 9.3×10^{18} Nm, corresponding to a moment magnitude of **M**6.6, in agreement with observations (Japan Meterological Agency, JMA). The slip history, final slip and stress drop distributions from the dynamic inversion agree with those from most kinematic results on the location of a large asperity extending from about 5 km NW to about 10 km SE of the hypocenter, from the top of the fault to a depth of 12-19 km (Figure 2). The maximum stress drop (5 MPa) and slip (2 m) from the dynamic inversion are similar to some [*Mikumo et al.*, 2003] but are smaller than other kinematic results [*Iwata and Sekiguchi*, 2001; *Dalguer et al.*, 2003]. Part of this variation is likely caused by the choice of data and rupture velocity used in the kinematic analyses. However, a more important and fundamental cause of the variation is that stress drop and friction cannot be resolved independently by waveform modeling [*Guatteri and Spudich*, 2000; *Peyrat et al.*, 2004]. Future work will show whether this trade-off can be relaxed in our inversion method.

Note that the variation of the misfit for the models with the smallest misfit (here, 19 models are shown) in Figure 3 is similar (less than 3%), indicating that all these models are plausible rupture scenarios for the Tottori earthquake. However, the standard deviation is much larger for the regions on the fault outside the asperity (Figure 3). Although the resolution of the parameters within the cells of small or no slip is limited, the results suggest that the dynamic inversion is able to resolve the asperities better than the barriers, a result expected using an asperity model of the rupture. Two classical and idealized models describe heterogeneous fault rupture. *Das and Aki* [1977] proposed the barrier model, where the fault contains areas of increased rupture resistance. The nucleation occurs in a region of weak rupture resistance and the rupture propagates between barriers. Alternatively, *Kanamori and Stewart* [1978] proposed the asperity model, where the fault contains areas of stress concentrations due to former earthquakes or aseismic slip. The barrier and asperity models are viewed as complementary in describing dynamic rupture propagation. Although our results are limited by data resolution and coverage, Figure 4 shows that the final model generates long-period displacement time histories that provide a good fit to selected strong motion data.

We computed a total of 60,000 forward FD simulations of rupture propagation for the Tottori earthquake. Figure 5 shows the smallest misfit per iteration throughout the inversion, demonstrating a relatively slow convergence due to the strong nonlinearity of the problem. While it is desir-

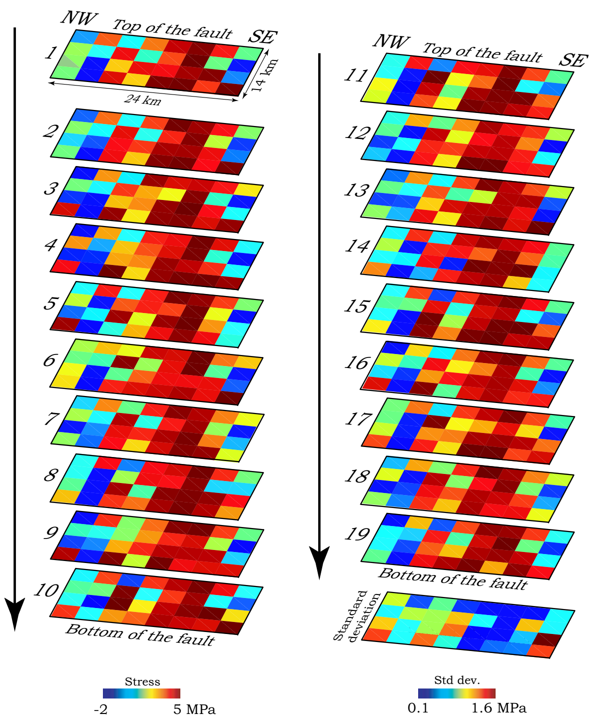

Figure 3. Initial stress for the 19 models with the smallest misfit (all between 0.36 and 0.37), as well as their standard deviation (bottom right).

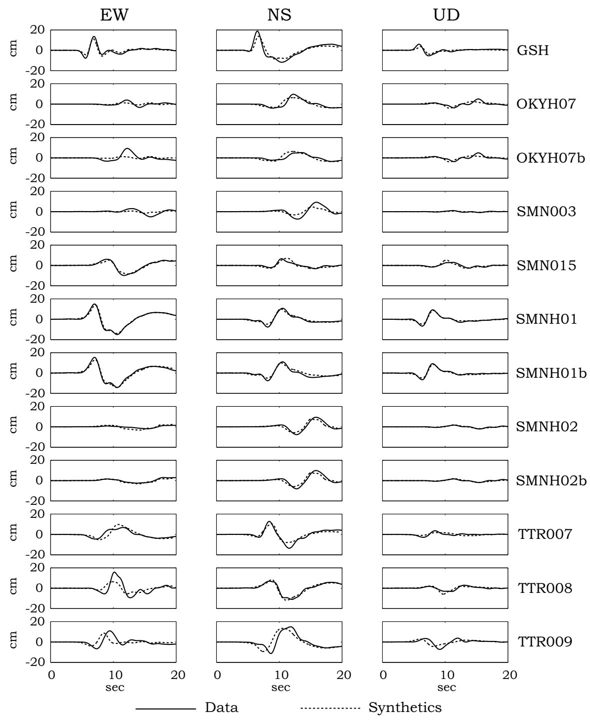

Figure 4. Comparison between displacement histories of synthetics and data along east-west, north-south and vertical for the model generating the smallest misfit after 1500 iterations. Both data (solid) and synthetics (dashed) are band-filtered between 0.05 and 0.5 Hz.

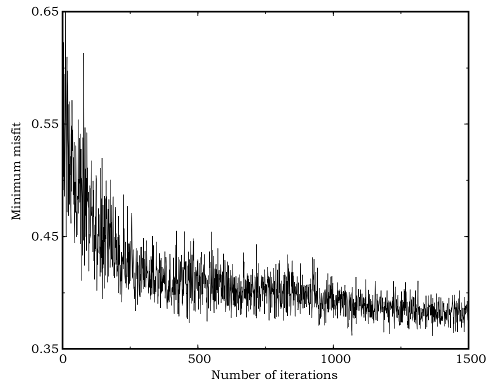

Figure 5. Smallest misfit per iteration between synthetics and observations as a function of the number of iterations in the dynamic inversion.

able to increase the number of inversion parameters and the frequency content to improve the resolution, the computational requirements are significant. The inversion required about 37 days using 8 processors on a SUN Enterprise computer (7 mins per forward model) or 40 hours (1.6 mins per forward model) using 40 processors (1 per forward model per processor) on a Linux Cluster. The forward FD modeling consumed 99.5% of the computation. Current efforts include tuning of the inversion code for high-performance parallel super-computers.

5. Conclusions

Although the dynamic inversion for the Tottori earthquake was successful, issues remain to be addressed in future work, including resolution of the inversion parameters. The rupture propagation for the Tottori earthquake is relatively simple, and more complex events may be considerably more challenging, both numerically and computationally. Moreover, in this study we only inverted for one parameter, namely the stress drop. Future efforts will show whether it is possible to invert for stress drop and friction simultaneously. However, our method provides an objective procedure for systematically estimating dynamic rupture parameters in a nonlinear fashion for large earthquakes. Seeking a single model of the earthquake rupture history with the smallest misfit to data, the common procedure in kinematic inversions, is likely to discard important information provided by other, equally acceptable models. The nonlinear dynamic inversion, on the other hand, provides an ensemble of plausible rupture models, which may yield much more valuable details of the earthquake physics. Finally, the method may allow us to improve the accuracy of large-scale ground motion estimates in state-of-the-art 3D models of sedimentary basins, where a limiting factor in the accuracy of the predicted ground motions is reliable knowledge about the details of earthquake rupture.

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