Properties of seismicity and surface deformation generated by earthquakes on a heterogeneous strike slip fault in elastic half space

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Abstract:
We attempt to develop a physical basis for earthquake dynamics and seismic hazard on large strike-slip fault zones by joint analysis of model realizations, with parameters representing specific fault zones, and multi-disciplinary observations of deformation phenomena. The model consists of discrete slip patches (representing structural segmentation) on a vertical plane in a 3-D solid, and it accounts for brittle-slip, creep-slip, realistic boundary conditions and 3-D elastic stress transfer (Ben-Zion and Rice, 1993; Ben-Zion, 1996). Recent developments extended the framework to incorporate quasidynamic rupture propagation, gradual healing, and creeping barriers along the fault (Zöller et al., 2004, 2005). The model produces for ranges of input parameters several realistic features of seismicity including frequency-size and temporal statistics, hypocenter distributions, realistic foreshock-mainshock-aftershock sequences, approach to and retreat from criticality, and accelerating seismic release. Our current efforts are directed in part toward extending the calculated observable quantities to include surface deformation, and to develop a better understanding of recurrence intervals of large earthquakes on faults with different levels of structural heterogeneities. Previous works have shown that the model behavior can be mapped onto phase diagrams that span, as a function of input parameters, several different dynamic regimes (e.g., Dahmen et al., 1998; Zöller et al., 2004). This may allow us to use various observables associated with a natural fault zone to classify the dynamic regime of the fault in terms of governing parameters, and then employ corresponding model realizations to produce long synthetic data sets of deformation phenomena. Analysis of such synthetic data sets can provide a better statistical characterization of the fault’s response than the limited available records.

1. Introduction
The understanding of spatiotemporal earthquake occurrence on natural fault systems is an important scientific challenge. While some seismicity patterns show an almost universal behavior, others are observed less frequently and follow no obvious law. For example, aftershocks following the modified Omori law are observed after almost all large continental earthquakes, whereas foreshocks are a rare phenomenon (Utsu et al., 1995). The Parkfield experiment in California demonstrates that even if a fault segment shows regular behavior over several decades, a prediction of future activity can fail. One reason for this is that the available data sets are too limited to provide enough information for the understanding of the complex relationships between the various physical mechanisms in the earth's crust. This highlights the importance of model simulations which may cover many seismic cycles and enable a study of the dependency of seismicity and other deformation phenomena on the underlying parameters.
In this study, we analyze various quantities in data generated by a discrete model of a vertical strike-slip fault in a 3-D elastic half-space (Ben-Zion and Rice, 1993; Zöller et al., 2005). The model combines computational efficiency with realistic representation of a large heterogeneous fault zone. The simulations cover 1000s of years and allow us to reproduce seismicity patterns as well as postseismic and interseismic creep deformation. The model ingredients, including laws for brittle and creep deformation, stress transfer, and boundary conditions, are compatible with empirical macroscopic knowledge. Several relationships between imposed model parameters (e.g., frictional parameters, creep velocities, spatial heterogeneities) and observed seismicity quantities like frequency-size distributions, hypocenter profiles, and aftershock clustering have been previously quantified using analytical and numerical parameter-space studies (Ben-Zion, 1996; Fisher et al., 1997; Ben-Zion et al., 2003; Zöller et al., 2005). In this paper we consider end-member cases representing a relatively homogenous fault, a strongly heterogeneous fault, and a fault without dynamic weakening during rupture (“instantaneous healing”). Since the underlying properties of natural faults are generally not known, we examine whether observable parameters based on seismic catalogs and the surface deformation field can serve as proxies to identify the governing properties and evolving dynamics of a fault. We also analyze the statistics of inter-event and recurrence times of large earthquakes, which are of particular interest for seismic hazard assessment, in the framework of the model. The overall goal is an attempt to classify the dynamic regime of large a individual fault zones like San Andreas and San Jacinto faults by means of a small number of observable parameters, and then use this knowledge to provide refined estimated of seismic hazards associated with the faults.

2. The model

Our model includes a single rectangular fault embedded in a 3D elastic half space. A fault region of 70 km length and 17.5 km depth is covered by a computational grid, divided into 128x32 uniform cells (see Fig. 1), where deformational processes are calculated. Tectonic loading is imposed by a motion with constant velocity 35 mm/year of the regions around the computational grid. The space-dependent loading rate provides realistic boundary conditions. Using the static stress transfer function for slip in elastic solid, the continuous tectonic loading for each cell on the computational grid is a linear function of time and plate velocity. Additional loadings on a given cell occur due to brittle and creep failures on the fault. In a recent study (Zöller et al., 2005), creeping barriers (black in Fig. 1) have been introduced to account for aseismic regions between seismic fault segments.

3. Results and Discussion

In previous works, it has been shown that the model produces realistic frequency-size and temporal statistics, of earthquakes realistic hypocenter distributions, realistic foreshock-mainshock-aftershock sequences, realistic slip histories, approach to and retreat from criticality, and accelerating seismic release (e.g., Ben-Zion et al., 2003; Zöller et al., 2004,
Systematic analytical and numerical parameter-space studies indicate the existence of three basic dynamic regimes. The first is associated with strong fault heterogeneities, power law frequency-size statistics of earthquakes, and random or clustered temporal statistics of intermediate and large events. The second is associated with homogeneous or relatively regular faults, peaked frequency-size statistics (compatible with the characteristic earthquake distribution), and quasi-periodic temporal occurrence of large events. For a range of parameters, there is a third regime in which the response switches back and forth between the foregoing two modes of behavior. The results can be understood in terms of phase diagrams and intermittent criticality (Dahmen et al., 1998; Ben-Zion et al., 2003; Zöller et al., 2004).

Fig. 2 illustrates recent results which are closely related to the critical point concept for large earthquakes:

Figure 2: The frequency-magnitude distribution of all earthquakes, foreshocks and aftershocks, respectively. The dotted lines refer to b-values of 1 and 2.

While the frequency-size distribution for an entire synthetic earthquake catalog shows characteristic earthquake behavior, the foreshocks follow a Gutenberg-Richter law. In the view of the critical point concept, this gradual change of the frequency-size statistics can be interpreted as evolution from an uncritical state to a critical (scale-free) state, in which earthquakes of all magnitudes can occur. Therefore, the size distribution of earthquakes can serve as a proxy for the distance from the critical point. Additional seismicity parameters that may serve as a proxy for the evolution toward a critical state include the depth distribution of hypocenters and other spatial parameters (Eneva and Ben-Zion, 1997; Zöller et al., 2001).

In the present study, we follow this approach of linking model parameters to observational properties by investigating the surface deformation field for several end-member cases of faults. In a first step, we consider surface deformation fields produced by mainshocks and focus on the degree of disorder of these fields. Initial results indicate that the disorder of the stress field correlates with the disorder of the surface deformation field.

4. Conclusion

We attempt to combine systematic theoretical parameter-space studies with observational results of multi-disciplinary deformation signals. Phase diagrams spanned by key controlling parameters summarize the expected behavior of various observables in different dynamic regimes. Analysis of observed data associated with large individual fault zones may be used, together with the phase diagrams, to classify the dynamic regime of the faults. If this can be done, it will improve the understanding of earthquake dynamics and provide a contribution to the problem of predictability of large events.
5. References


