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Student Name: Filip Kostka
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Thesis Title: Dynamic models of the earthquake source

Examiner's Report

This doctoral thesis investigates the behavior of earthquake source processes and long-term fault slip using dynamic models. Unlike more conventional, kinematic models, these models are referred to as 'dynamic models' in which the earthquake sources are described by the forces that govern their motion. Over the last 40 years, numerical modeling of this kind has been developed and utilized to understand various aspects of earthquake source processes. Yet, there remain many outstanding questions in the community, such as which constitutive laws is appropriate for describing earthquake sources, how do earthquakes interact at short-term and long-term time scales, and what is the proper way to model large earthquakes. This thesis tackles some of these outstanding questions.

The first four chapters constitute a thorough and extensive review of dynamic earthquake modeling and the relevant concepts based on seismology and fracture mechanics, which demonstrates the author's comprehensive and in-depth understanding of the state-of-the-art knowledge in the field. The subsequent chapters present two original research studies based on dynamic modeling of earthquake sources. In the first part, the author numerically examines the effect of a sudden stress perturbation (due to nearby tectonic activities) on the long-term behavior of seismic cycles. The results highlight the importance of stress interactions on the long-term behavior of seismic cycles, with important implications for seismic hazard worldwide. Based on the insight gained from the numerical experiments, the author further provides a plausible explanation for an unusual delay of the 2004 magnitude 6.0 earthquake observed on the San Andreas fault in California. In the second part, the author develops and applies a dynamic source inversion method to study the magnitude 6.3 Lesvos earthquake in the Aegean Sea. Dynamic source inversion is a relatively new, innovative way to study earthquake sources, but the high computational demand and difficulty in assessing of the parameter tradeoffs complicate the interpretations of the results, preventing their widespread applications. The author demonstrates feasibility and usefulness in applying Bayesian-based dynamic source inversion to a large earthquake by estimating the source parameters that have been difficult to retrieve with conventional kinematic source inversion, and by rigorously analyzing the uncertainties in the estimated source parameters and their tradeoffs.

I believe that this thesis constitutes a significant and original contribution to the seismology community. The thesis is well written in precise scientific language and clearly laid out methods, results, analysis and interpretations. It is also clear that the author has great capacity for independence, innovative and critical thinking and will continue to make exciting contributions in the field.

Overall, the thesis is exceptionally well written, and I only have some minor suggestions as outlined below. The author can go through and adopt them as they see fit. I believe that the thesis should be accepted (with very minor changes) for the Doctor of Philosophy. I look forward to the thesis defense and discussion. Please let me know if further information is required.

Best wishes,

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Title: "Dynamic models of the earthquake source" is too general. I think word "dynamic source inversion" or something equivalent should be included in the title, to better reflect the main content of the original research.

Chapter 1:

+ It's a bit odd not to include any citations/references in the Introduction.
+ Page 8: A period is missing from the sentence ending with "the San Andreas fault"

Chapters 2 – 4:

+ These chapters present a thorough and in-depth review of the literature and include author's modeling results and analysis in relation to the previous knowledge, which provides more than enough background information for the later Chapters. One suggestion I have is that the author should make an effort to link the information described in Chapters 2–4 in the subsequent chapters describing original research (Chapters 5-6) as much as possible. Some examples are listed below.
+ Page 19: "Fractional and frictional" must be "Fracture and frictional"

Chapter 5:

+ Why do you assume the aging law in this study? Please justify. Recent studies showed that the slip law fits better the experimental data than the aging law does (Bhattacharya et al., 2015; 2017; Kaneko et al., 2016). This is one of the several examples where the information described is earlier Chapters is not linked as much.

+ Page 137: The content of Chapter 5 was already published, but I would like to point out that some of the model responses described here is qualitatively similar to the numerical results of Kaneko and Lapusta (2008). For example, they showed that a step-like stress perturbation can result in a creep event, delaying the onset of the next anticipated seismic event (see Figure 10 of Kaneko and Lapusta, 2008). Also, the importance of a slip rate at the time of a stress perturbation in the subsequent fault-slip behavior is demonstrated in their study.

+ Page 142: Discussion. If the model includes enhanced velocity weakening as evident from high-speed rock friction experiments (e.g., Di Toro et al., 2011), the conclusion may change dramatically (e.g., Noda and Lapusta, 2013). It would be useful to speculate or comment on how including this effect may change the outcome of the modelling.

+ Page 138 and Figure 5.8 caption: Change "bars" to "MPa" for consistency throughout the thesis.

Chapter 6:

+ Page 163: I am wondering why the author chose to use displacement waveforms rather than velocity waveforms. Farfield velocity waveforms are proportional to the moment accelerations, which would be of more relevance to dynamic rupture modeling.

+ Page 163: It is stated that the choice of low-pass frequency (i.e., 0.15 Hz = 6.7 s) is related to imperfect velocity model as well as uncertainty in fault geometry. What about the source parameterization? The period of 6.7 s is roughly equivalent with the length scale of ~20 km, assuming the S-wave speed of 3 km/s. So any features that are smaller than ~10 km are difficult to resolve from the data used. The author discusses how resolution issues may have influenced the inversion result. I suspect that the choice of the low-pass frequency is the most critical issue and may deserve more comments.

+ While the main purpose of this Chapter is to analyze a set of plausible source models and the parameter tradeoffs, it would be useful and interesting to constrain the range of plausible source models further with additional information, such as aftershock distributions or afterslip locations, or geodetic data presented in other studies.

+ Related to the comment above, the radiated energy of large earthquakes is routinely estimated by IRIS (e.g., https://ds.iris.edu/spud/eqenergy/13574143), and their estimated value of this event is 46 TJ in agreement with the range obtained by the present dynamic inversion. I was surprised that this information was not even mentioned in this Chapter.

+ It would have been interesting to consider higher frequency waves, say upto 0.30 Hz (= 3.3 s), and see what the Bayesian inversion shows. It may be computationally more demanding, but if it is doable, one will learn a lot from such exercise.