INSTITUTE OF GEOPHYSICS
OF THE ACADEMY OF SCIENCES, CZECH REPUBLIC

Praha, February 22, 2022

Review

of the Thesis entitled
"Dynamic models of the earthquake source"
submitted to attain the Doctoral degree in Physics of the Earth and Planets at Charles University in Prague by Filip Kostka.

The undersigned Jan Burjánek, senior researcher at Institute of Geophysics of the Academy of the Czech Academy of sciences (ASCR), member of the Doctoral Examination Committee for evaluation of the above-mentioned thesis, states the following:

The submitted thesis elaborated by Filip Kostka deals with the numerical modelling of earthquake source processes considering the fracture mechanics concepts applied for a couple of time scales. The earthquake source physics is one of the fundamental fields of the current seismology and plays a crucial role in understanding the observed seismicity and ground shaking patterns. The topic is very present as many of the earthquake source processes are still not well understood (e.g., both, fault rupture initiation and termination) and a number of hypotheses exist. Although the topic represents primarily fundamental research, the results can be applied indirectly in earthquake risk mitigation.

The thesis consists of six chapters. Chapters 1-4 form a theoretical background based mainly on an extensive literature research. In contrast, Chapters 5-6 present the original research and have been accepted and published in international peer-reviewed journals with impact factor. The basic concept of the earthquake source modelling is presented in Chapter 1. It introduces the mathematical description of the earthquake source process, fracture propagation modes, fault constitutive laws, and fracture criteria. Various analytical formulas for the stress and slip distributions are presented in Chapter 2, considering a number of classical static, steady state and self-similar problems of brittle shear cracks. These solutions provide an insight into rupture process of a propagating rupture front during an earthquake. The model of a non-brittle shear crack including a cohesive zone behind the crack tip is thoroughly introduced in Chapter 3. Representative numerical simulations are presented in this chapter as well, showing the effects of the different initial parameters on the rupture nucleation and rupture front velocity. These results, employing also some of the analytical solutions presented in Chapter 2, are discussed here. Even more complex rate-and-state friction law is introduced in Chapter 4. Relations to previously adopted friction laws are discussed and modelling of the long-term evolution of faults driven by rate-and-state friction laws is outlined. Modelling of earthquake cycles using the state-and-rate dependent friction law is presented in Chapter 5. Various scenarios of the fault evolution in response to stress perturbations are studied. A hypothesis explaining the anomalous delay of the long-awaited M6 Parkfield 2004 earthquake was proposed. In contrast, a fast rupture process of M6.3 2017 Lesvos earthquake was studied in Chapter 6. A detailed analysis of a multi-step

Bayesian inversion scheme adopting a simplified dynamic model is presented, showing explicitly the influence of the different data types and *a priori* information on the retrieved posterior probability density functions. A short concluding chapter just summarizes the obtained results.

The thesis is very carefully written and I did not find any formal errors. The pictures are well described and of a good quality. Nevertheless, except for Chapter 5, the thesis is quite difficult to read. The theoretical background is long, very dense and contains a lot of different relations taken from the available literature. In general, I appreciate very much the presented literature review. Filip Kostka demonstrates clearly his deep knowledge and understanding of the earthquake source dynamics, however, some sections containing just lists of different relations are a bit tedious to read. The objective of introducing all the relations is not sufficiently presented (especially with respect to the original results of the thesis). Still, the theoretical introduction might be rewritten in the form of lecture notes in the future after including some illustrative figures, more detailed derivations and relevant observations.

My specific comments:

- While for semi-infinite or 2D finite problems the couple of relations for the slip and stress distributions are presented (e.g., 2.13, or 2.42 + 2.43), only the relation for the slip distribution is presented for the elliptical crack (2.79). The relations for the elliptical crack are more interesting, since they can be applied even in practice.

- How feasible is to assume Td=0 for real cases? What are the estimates for the real faults in literature?

- In the thesis, a lot of attention was paid to the rupture initiation, while rupture termination was realized by a prescribed barrier (except that the rupture did not fully developed due to 'inappropriate' initiation). I would appreciate a brief discussion of the possible rupture termination mechanisms.

- Section 3.7: Free surface is assumed in the simulations exploring the dependence on the absolute magnitude of stress. The geometry of the simulation is not clear, what is the location of the nucleation zone with respect to the free surface?

- An explanation of the anomalous delay of the 2004 M6 Parkfield earthquake is based on the stress perturbation due to 1983 Coalinga-Nuñez events, however, the time difference between these events and the Parkfield 1966 earthquake is 17 years, thus quite long with respect to the mean interval (22 years). The model (Fig 5.9d) does not predict a large delay for such late perturbations. How is the possible prediction of the delay feasible, considering the relative short duration of the specific periods, when 'Clock advance' parameter is increasing?

- Have you tried to estimate the possible delay for the next Parkfield earthquake? Based on the recent seismicity, is another delay expected?

- Only elastic model is assumed in the modelling of the earthquake cycles, what would be the effect of a viscoelastic rheology or even a viscoelastoplastic rheology of the upper lithosphere?

- Section 6.2.1: "To partially compensate for neglecting the actual dip of the fault, we stretch the along-dip positions of the velocity model interfaces, so that they conform to the actual depths along the fault." It is not very clear what kind of transformation was performed here.

- I appreciate the objective analyses of the posterior probability density function in Chapter 6. However, in general, what can we learn from such simplified dynamic modelling? What is the meaning of the estimated values (Dc, Tu, …) for non-linear problem of the spontaneous earthquake rupture, considering the heterogeneities likely present along the real faults? Could be interpreted as mean values along the fault?

- The source time function for the optimal model is comparable to the results of the other authors while it does not follow the high-density regions of the estimated probability density function (Figure 6.9). This is not discussed in the thesis.

Minor comments (not need to be discussed during the defence):

- List of symbols is missing in the thesis. This would make reading easier, since the thesis contains a lot of relations and symbols.
- Indicator functions of sets are used in some of the formulas resulting in a compact notation, which is not always easy to read. The use of these indicator functions is not used consistently in the thesis.
- Green line is hardly visible in Figure 5.3a.
- Section 6.1: "Since the differences between the relevant laws are negligible at low frequencies …" – weird formulation, I suppose it is means 'for low-pass filtered ground motions'.
- Section 4.3, p.116: "In any case, the fault depends on the combination of the two parameters in a complicated manner." Unclear formulation.
- Section 2.1.3 - Spontaneous propagation of a finite straight anti-plane crack: The discussion of the in-plane solutions within the scope of this section is confusing.
- Section 4.3.2, p.111: "The critical fault length $h_{crit} \propto 1/(b – a)$ (Eq. 4.27) is an estimate of the minimum size that a fault should assume to exhibit seismic behaviour." Unclear formulation.

- Section 4.3.3, p.116: “In any case, the fault depends on the combination of the two parameters in a complicated manner.” Unclear formulation.
- Section 6.3.p.164: “For each distribution, the number of models visited by all chains was approximately 2 500 000 within 35 days.” Does the value of 35 days refer to the computational time?
- The use of the Hellinger distance could be a step forward, however the presentation of the results in the form of tables is not very convenient for a reader. A suitable graphical representation would help.

Concluding, Filip Kostka managed to produce original results studying both the short-term and long-term behavior of tectonic faults which is a remarkable achievement. The topic is broad, includes solutions of highly non-linear problems and required a significant effort from the author. As far as I know, the problem of the dynamic source inversion has been never performed in a such detailed and objective way. The submitted thesis of Filip Kostka contains highly original research, meets the University requirements and clearly exhibits the abilities of the candidate for the independent research. After successful defence, I propose to award a doctoral degree.

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Jan Burjánek

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