

Temporal Evolution of Friction Parameters and Foreshock

Activity in Large-Scale Rock Friction Experiments

大型岩石摩擦実験における摩擦パラメータの変遷と前震活動の
推移

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Abstract

Rock friction experiments have been considered a powerful tool for earthquake research, as they enable us to control physical parameters, such as stress and loading rate, and also to observe multiple seismic cycles. These experiments also allow for nearby measurements of rock friction, providing valuable insights into the relationship between fault slip and friction. In recent years, large-scale (meter-scale) rock friction experiments have been increasingly utilized. Compared to traditional centimeter-scale experiments, they offer improved representation of natural fault conditions, including surface roughness and other heterogeneities, and can reproduce the stick-slip behavior over longer slip distances; the stick-slip observed in such experiments is considered to have a comparable mechanism to that of natural earthquakes. Therefore, this study analyzes laboratory data obtained from large-scale rock friction experiments.

After an introduction into the topic in Chapter 1, the thesis focuses in Chapter 2 on the rate-and-state friction (RSF) parameters derived from laboratory experiments. Although the RSF law is widely used to characterize the frictional behavior of rocks, the effects of heterogeneous fault conditions, such as variations in gouge layer distribution, on the apparent RSF parameters are not fully quantified. To investigate their temporal variation, the RSF parameters were estimated for over 100 stick-slip cycles. Given the large volume of data, a machine learning-based approach using Random Forests (RF) was developed to conduct efficient analysis. A one-degree-of-freedom spring–slider model was used to generate synthetic training data, which consist of RSF parameters and corresponding frictional responses. The trained random forest model was then applied to the experimental data. The estimated RSF parameters showed significant variations during the early stage of the experiment, followed by less pronounced variations in the later steady-state phase. This temporal evolution can be reasonably reproduced by a formulation based on the development of the gouge layer during the experiment.

In Chapters 3 and 4 we focused on the acoustic emissions (AEs) observed during large-scale rock friction experiments. AEs are commonly considered as an analog of microseismicity observed on tectonic faults and have significantly contributed to understanding the rupture process, nucleation, and foreshock activity on faults. In a recent study, Yamashita et al. (2021) detected more than 1,000 AE events using the STA/LTA (short-term average-long-term average ratio) technique (Allen, 1978) and provided new insights into the mainshock initiation process. The present study aimed to further investigate the foreshock–mainshock mechanism by detecting AE events that have not

been detected in the previous work of Yamashita et al. (2021). We first developed a template matching approach (Chapter 3) that combines coherency, which is defined as the normalized cross-correlation function in the frequency domain, and kurtosis, which is known as a higher-order statistic. Using the newly proposed method, we detected more than twice as many AE events as those reported by Yamashita et al. (2021), and approximately 1.7 times more than those detected by the conventional MFT. Our approach is considered effective in detecting events in the pre-mainshock period, where event signals become unclear due to noise caused by the mainshock preparation process. This advantage enabled us to observe foreshock migration and related phenomena that were not captured using the STA/LTA technique and more conventional template matching methods.

In Chapter 4 we analyzed the AE catalog (foreshock catalog) obtained using the proposed template matching, along with observed shear stress data. A detailed comparison of individual mainshock cycles revealed various patterns of foreshock activity. In some cases, only a few foreshocks were detected, while in other cases, many foreshocks and their space-time migration were clearly observed. In addition, stress changes are found to occur at different timescales. Among them, gradual stress changes over longer time periods were interpreted to reflect the underlying slow, aseismic slip. By quantifying these gradual shear stress changes (GSSC events), we found that cases with more GSSC events (suggesting the presence of more significant slow slip) exhibited more frequent foreshocks. Moreover, a positive correlation was found between the number of foreshocks and the heterogeneity of the initial shear stress conditions at the beginning of the mainshock cycle, for each analyzed mainshock case. Such observations suggest that stress heterogeneity may have promoted foreshock occurrence. In addition, when more GSSC events (i.e., more pronounced aseismic slip) are observed, the recurrence interval of the mainshock tends to be shorter. Finally, we schematically summarize our findings concerning the foreshock-mainshock generation process, which depends on two factors, aseismic slip and heterogeneity of the initial stress state. Chapter 5 provides a general discussion of the findings reported in the thesis and Chapter 6 presents some final conclusions.