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Identification of the meta-instability stage via synergy of fault displacement: An experimental study based on the digital image correlation method

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ABSTRACT

In stick–slip experiments modeling the occurrence of earthquakes, the meta-instability stage (MIS) is the process that occurs between the peak differential stress and the onset of sudden stress drop. The MIS is the final stage before a fault becomes unstable. Thus, identification of the MIS can help to assess the proximity of the fault to the earthquake critical time. A series of stick–slip experiments on a simulated strike-slip fault were conducted using a biaxial servo-controlled press machine. Digital images of the sample surface were obtained via a high speed camera and processed using a digital image correlation method for analysis of the fault displacement field. Two parameters, A and S, are defined based on fault displacement. A, the normalized length of local pre-slip areas identified by the strike-slip component of fault displacement, is the ratio of the total length of the local pre-slip areas to the length of the fault within the observed areas and quantifies the growth of local unstable areas along the fault. S, the normalized entropy of fault displacement directions, is derived from Shannon entropy and quantifies the disorder of fault displacement directions along the fault. Based on the fault displacement field of three stick–slip events under different loading rates, the experimental results show the following: (1) Both A and S can be expressed as power functions of the normalized time during the non-linearity stage and the MIS. The peak curvatures of A and S represent the onsets of the distinct increase of A and the distinct reduction of S, respectively. (2) During each stick–slip event, the fault evolves into the MIS soon after the curvatures of both A and S reach their peak values, which indicates that the MIS is a synergetic process from independent to cooperative behavior among various parts of a fault and can be approximately identified via the peak curvatures of A and S. A possible application of these experimental results to field conditions is provided. However, further validation is required via additional experiments and exercises.

1. Introduction

There are three elements in relation to earthquake prediction: time, location, and magnitude. From the perspective of reducing disaster losses, only the prediction of the earthquakes of relatively big magnitude makes practical sense. The three aspects of earthquake prediction are closely related to each other, however, when it comes to analyzing the influencing factors, field and experimental studies usually focus on one of three aspects. In terms of the prediction of earthquake location, Ma (1999) stressed the crucial influences of active blocks on earthquake activity in intraplate tectonic environment according to the temporal clusters of earthquakes around certain active blocks in China. Fault geometry and fault interaction also play significant role in distinguishing the focal locations of the impending mainshocks from the positions of precursors (Ma et al., 1983, 1999, 2000). The vicinities of the maximum stress gradient are identified as potential locations of the impending earthquakes via experiments and field studies (Deng et al., 1995; Rebetsky and Marinin, 2006; Rebetskii, 2007; Rebetsky and Tatevossian, 2013; Wang et al., 2012). In respect to the prediction of earthquake magnitude, the studies of the initial phase of P-wave velocity pulses showed that the duration of the slow initial phase is a measure of the earthquake size (Iio, 1995), or the impending earthquake magnitude can be determined by the frequency content of the P-wave arrival (Allen and Kanamori, 2003; Olson and Allen, 2005). Moreover, Rebetsky (2009) stressed that the size of the area with medium stress levels defines the

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magnitude of the expected earthquake. In fact, the studies above contain more or less the temporal information of earthquakes. In this study, we focus on the temporal aspect of earthquake prediction.

The idea of gradual earthquake prediction on long-, medium-, and short-term scales was proposed based on the relationship between crustal movement and earthquakes (Mescherikov, 1968) and case studies of earthquake precursors (Ma et al., 1980; Rikitake, 1975). Although this idea has been adopted widely, the time scales are obscure. For example, five-year is a short-term scale for a 100-year earthquake cycle in one place but is a long-term scale for a 10-year earthquake cycle in another. The earthquake prediction research conducted in Parkfield, which is based on the quasi-period of characteristic earthquakes (Bakun and Lindh, 1985; Sykes and Nishenko, 1984), proves that the short-term earthquake prediction still faces challenges due to the uncertainty of the quasi-period of characteristic earthquakes as well as lack of precursory information (Bakun et al., 2005; Harris and Arrowsmith, 2006). According to rock experiments, the stage before the peak strength point was defined as the long-term to medium-term stage before earthquake, and the stage between the peak strength point and the instability point was defined as the short-term to imminent stage before earthquake (Ma et al., 1995a,b). Strain analysis found that the increment stress field corresponding to the short-term to imminent stage is a four-quadrant pattern for mean stress and an eight-petaline pattern for maximum shear stress (Ma et al., 1995a,b). Thus, studying the evolution stage based on the stress state of the fault may reduce the uncertainty brought by only using the quasi-period of characteristic earthquakes, which may open another window for short-term earthquake prediction.

During experiments modeling fault stick–slip behavior, Ma et al. (2012) found that the impending stick–slip instability can be predicted in real time via the accelerated decrease in the differential stress displayed on the loading system. After the differential stress reaches its peak value, the sample experiences a quasi-static to quasi-dynamic stress release process before the instability occurs. The MIS is the stage between the peak differential stress and the onset of sudden stress drop (Ma et al., 2012), which is characterized by the stress release of the sample. We cannot identify the MIS via directly monitoring the differential stress of the fault in the field due to the unknown loading condition of the earth's crust. Therefore, experimental studies of the characteristic of the MIS on relative physical fields of the fault zone may be a bridge connecting the experimental studies and field survey and help to assess the proximity of the fault to the earthquake critical time.

Characteristics of the MIS, such as the synergetic process of temperature field (Ma et al., 2012; Ren et al., 2013), fault displacement field (Zhuo et al., 2013), and strain field (Ma et al., 2014), were revealed experimentally. The term "Synergy" is a concept derived from synergetics (Haken et al., 1995) and is used to describe the process from independent to cooperative behavior among various parts of a fault (Ma et al., 2012; Zhuo et al., 2013). Synergetic processes were also detected in field studies before some earthquakes, including the consistency of fault planes derived from focal mechanism solutions of foreshocks (Chen, 1978), the similar directions between the local principal stresses of foreshocks and the regional principal stresses (Diao et al., 2004, 2011), the reducing information entropy of the foreshocks spatiotemporal distribution (Zhu, 1988; Zhu and Wang, 1988; Zhou and Zhu, 1995; Zhang et al., 2002), and the decreasing complexity of electromagnetic pre-seismic emissions (Karamanos et al., 2006; Potirakis et al., 2012). These indicate that the synergetic process of the MIS can be detected via various physical properties in laboratory and field.

However, the detection of synergetic processes of the MIS via the deformation field is seldom reported in field work, and the quantitative parameters necessary for identifying the MIS were not constrained in previous experimental studies. Thus, identifying the MIS via the deformation field will be significant for detecting the MIS in field work. In this study, a planar strike-slip fault model was designed, and the fault displacement field of the sample surface was analyzed for building a quantitative criterion to approximately identify the MIS.

2. Experiment design

The experiments were conducted on a biaxial servo-controlled press machine (Fig. 1). The 300 mm square and 50 mm thick granodiorite sample is from Fangshan County, Beijing, and is described schematically in Fig. 2a. A 400 mm long planar fault was cut diagonally through the sample. Five experiments (#64–#68) were conducted on the sample, and in each experiment, the loading process was as follows. First, load was applied synchronously in *X*- and *Y*-direction at a rate of 20 kg/s up to ~7.5 tons (~5 MPa). Then, the *X*-direction load was held constant at ~5 MPa, but the *Y*-direction load was varied to simulate displacement control at different rates. The loading rates of the *Y*-direction ranged from 0.1, 0.5, to 1.0 μm/s in Experiments #64 and #65 and from 0.05, 0.1, to 0.5 μm/s in Experiments #66–#68. A high speed camera was placed over the sample to record digital images at a speed of 1000 frames per second during stick–slip events. The images cover the central part of the sample surface of size 112.2 mm by 107.1 mm (Fig. 2a). The length of a pixel in the images is equal to 170 μm in the sample. Three stick–slip events were recorded by the camera in Experiment #65 and selected as examples to study the identification of the MIS. These three stick–slip events, denoted by E, F and G (Fig. 2b), occurred under the loading rates of 0.1, 0.5 and 1.0 μm/s, respectively. The recording duration of the camera was 34.925 s, 12.458 s and 9.557 s during Events E, F and G, respectively. The displacement fields of the sample surface during these three recording durations were calculated via the digital image correlation method. The details of the sample, the experimental setup and Event E can be found in Zhuo et al. (2013).

3. Data processing

3.1. Digital image correlation method and analysis area

Digital image correlation (DIC) is a pattern-matching technique that uses the correlation of image subregions to identify points (the

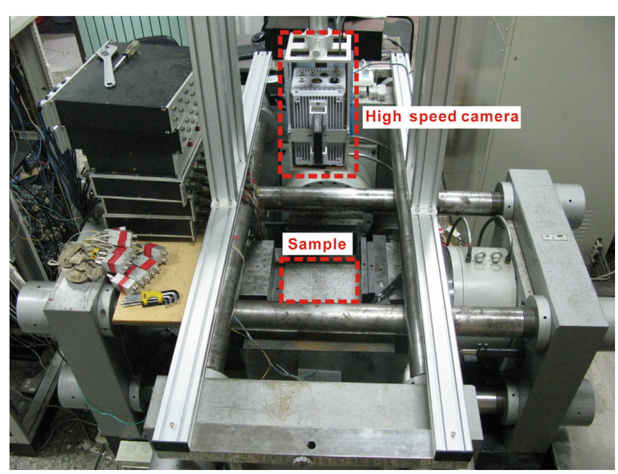

Fig. 1. Experimental setup.