Physics of the Earth and Planetary Interiors 257 (2016) 115–127

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Complex events in a fault model with interacting asperities

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A R T I C L E   I N F O

Article history:
Received 22 February 2016
Received in revised form 18 May 2016
Accepted 24 May 2016
Available online 30 May 2016

Keywords:
Theoretical seismology
Fault mechanics
Nonlinear dynamical systems
Seismic source models
Asperity models

A B S T R A C T

The dynamics of a fault with heterogeneous friction is studied by employing a discrete fault model with two asperities of different strengths. The average values of stress, friction and slip on each asperity are considered and the state of the fault is described by the slip deficits of the asperities as functions of time. The fault has three different slipping modes, corresponding to the asperities slipping one at a time or simultaneously. Any seismic event produced by the fault is a sequence of n slipping modes. According to initial conditions, seismic events can be different sequences of slipping modes, implying different moment rates and seismic moments. Each event can be represented geometrically in the state space by an orbit that is the union of n damped Lissajous curves. We focus our interest on events that are sequences of two or more slipping modes: they show a complex stress interchange between the asperities and a complex temporal pattern of slip rate. The initial stress distribution producing these events is not uniform on the fault. We calculate the stress drop, the moment rate and the frequency spectrum of the events, showing how these quantities depend on initial conditions. These events have the greatest seismic moments that can be produced by fault slip. As an example, we model the moment rate of the 1992 Landers, California, earthquake that can be described as the consecutive failure of two asperities, one of which has a double strength than the other, and evaluate the evolution of stress distribution on the fault during the event.

1. Introduction

Fault surfaces are characterized by an inhomogeneous friction distribution, entailing a nonuniform distribution of coseismic slip. The friction distribution can be represented by an asperity model, representing the fault as a surface with high- and low-friction patches (Lay et al., 1982; Ruff and Kanamori, 1983; Scholz, 2002). Most earthquakes are due to the failure of a small number of asperities. Examples of earthquakes that were modeled with the failure of two asperities are the 1964 Alaska earthquake (Christensen and Beck, 1994), the 1992 Landers earthquake (Kanamori et al., 1992), the 1995 Kobe earthquake (Kikuchi and Kanamori, 1996), the 2004 Parkfield earthquake (Johanson et al., 2006), the 2010 Maule earthquake (Delouis et al., 2010) and the 2011 Tohoku-Oki earthquake (Noda and Lapusta, 2013).

Some of these events have been ascribed to the consecutive, but separate, failure of the two asperities, where slipping of the second asperity is triggered by that of the first one. Other events include a phase of simultaneous slip of the asperities. In general, the retrieval of earthquake source functions from seismic data shows that fault slip takes place in an irregular fashion, with a complex interplay between different asperities, indicating a continuous stress transfer between the asperities during the earthquake.

One of the first events for which this complex behavior was observed is probably the 1992 Landers, California, earthquake (Kanamori et al., 1992; Wald and Heaton, 1994), an $M_w = 7.3$ event that caused a surface break extending over 70 km with an offset as large as 6.5 m. Dynamic models of the earthquake source (Olsen et al., 1997; Peyrat et al., 2001) showed that the initial stress distribution on the fault was far from being homogeneous and that the emitted radiation was very sensible to initial conditions.

An insight into the relationship between stress state and slip rate during fault slip can be obtained from the study of a fault model with two asperities of different strengths. Discrete fault models, considering the fault as made of a small number of patches, were originally introduced by Nussbaum and Ruina (1987),Ruff (1992), Rice (1993),Turcotte (1997) and others. Such models were further developed by Dragoni and Santini (2012), Dragoni and Piombo (2015) and Dragoni and Lorenzano (2015), who considered the fault as a discrete dynamical system made of two asperities. In these models, the fault is characterized by the average values of stress, friction and slip on each asperity. The fault

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http://dx.doi.org/10.1016/j.pepi.2016.05.014
0031-9201/

has three different slipping modes, corresponding to the asperities slipping one at a time or simultaneously. A seismic event generated by the fault is a sequence of such modes and very different source functions may result (Dragoni and Santini, 2014).

The analytical solution for this system in the presence of radiation has been given in Dragoni and Santini (2015). We base on this model in order to study the asperity dynamics during fault slip. The number of slipping modes involved in a seismic event is determined by the initial conditions of the fault. The simplest events are made of one or two slipping modes. In the first case, the event is due to the failure of a single asperity; in the second case, to the consecutive failure of the two asperities, with no simultaneous slip. These events occur for a particular subset of the admissible initial conditions.

In the present paper, we focus our interest on seismic events that are sequences of two or more slipping modes. In particular, we determine the initial conditions that may produce such complex events. We calculate the slip rates, the moment rates and the tangential tractions on the asperities as functions of time and investigate the relationships between these quantities during fault slip. We also calculate the seismic moments and spectra and consider how they change as functions of initial conditions. Finally, we model the moment rate function of the 1992 Landers, California, earthquake as a sequence of slipping modes of a fault with a highly heterogeneous friction and calculate the stress evolution on the fault during the earthquake.

2. The model

We consider a plane fault with two asperities of equal areas, that we name 1 and 2 respectively (Fig. 1). We assume that the fault is embedded in a shear zone that is a homogeneous and isotropic Hooke solid with rigidity μ. The shear zone is subject to a uniform strain rate $\dot{e}$ by the motion of two tectonic plates at constant relative velocity v.

We assume that fault dynamics coincides with the dynamics of the two asperities. Accordingly, we describe the state of the fault by the variables characterizing the asperities. Each asperity is treated as an entity that is either sticking or slipping. At each instant of time, an asperity is characterized by a single value of stress, friction and slip, that can be considered as average values on the asperity: these quantities change in time according to the governing equations of the dynamical system.

According to the concept of an asperity model, we assume that the region surrounding the asperities is a weaker region, with a negligible friction. Therefore, we assume that the slip of this region and its contribution to seismic moment are negligible.

Following Dragoni and Santini (2015), all quantities are expressed in nondimensional form. We describe the state of the fault by the slip deficits $X(T)$ and $Y(T)$ of the two asperities, where T is time. The slip deficit of an asperity increases when the asperity is stationary and decreases when the asperity slips. The fault dynamics has four modes: a sticking mode (00), corresponding to stationary asperities, and three slipping modes, corresponding to the motion of one asperity (modes 10 and 01) or to the simultaneous motion of both asperities (mode 11). Each seismic event is a sequence of n slipping modes (Table 1).

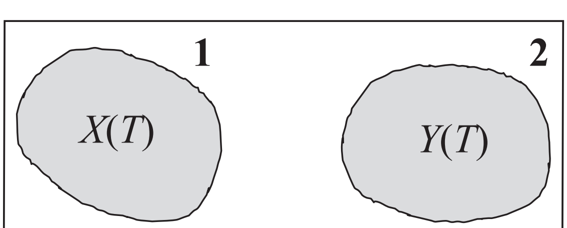

Fig. 1. Sketch of the fault model. The state of the fault is described by the slip deficits $X(T)$ and $Y(T)$ of the asperities.

The occurrence of seismic events is controlled by the tangential forces that are applied to the asperities in the sticking mode:

$$F_1 = -X - \alpha(X - Y), \qquad F_2 = -Y - \alpha(Y - X) \tag{1}$$

where α is the coupling constant of asperities. This constant is a measure of the stress transfer between asperities, depending on the asperity size and on the distance between them.

Fault slip is governed by friction. According to the premise, the constitutive equation of the fault (Ruina, 1983; Dieterich, 1994; Scholz, 1998) is assigned by assuming that asperities have constant static frictions and considering the average values of dynamic frictions during fault slip. We assume that the static friction of asperity 2 is a fraction β of that of asperity 1 and that dynamic frictions are a fraction ϵ of static frictions for both asperities.

In the slipping modes, the slip deficits evolve according to the equations

$$\ddot{X} + \gamma\dot{X} + (1 + \alpha)X - \alpha Y - \epsilon = 0 \tag{2}$$

$$\ddot{Y} + \gamma\dot{Y} + (1 + \alpha)Y - \alpha X - \beta\epsilon = 0 \tag{3}$$

where dots indicate differentiation with respect to T and γ is a parameter related to the seismic efficiency of the fault. Eqs. (2) and (3) can be solved analytically and the solutions were given in Dragoni and Santini (2015) for the three slipping modes.

The solution can be written in a general form if we introduce normal coordinates

$$W_1 = \frac{Y + X}{\sqrt{2}}, \quad W_2 = \frac{Y - X}{\sqrt{2}} \tag{4}$$

This change of variables is equivalent to a rotation of the coordinate system (X, Y) by an angle of 45° anticlockwise. Normal coordinates express respectively the sum and the difference of forces (1) applied to the fault in the sticking mode:

$$W_1 = -\frac{F_1 + F_2}{\sqrt{2}}, \quad W_2 = \frac{F_1 - F_2}{\sqrt{2}(1 + 2\alpha)} \tag{5}$$

The general solution for a mode starting at $T = 0$ is then

$$W_1(T) = \bar{W}_1 + (A_1 \sin\Omega_1 T + B_1 \cos\Omega_1 T)\, e^{-\frac{\gamma}{2}T} \tag{6}$$

$$W_2(T) = \bar{W}_2 + (A_2 \sin\Omega_2 T + B_2 \cos\Omega_2 T)\, e^{-\frac{\gamma}{2}T} \tag{7}$$

where $\bar{W}_1$, $\bar{W}_1$, A_1, B_1, A_2 and B_2 are constants depending on the particular mode and initial conditions. The frequencies Ω_1 and Ω_2 depend on the model parameters α and γ. All the following calculations are based on solutions (6) and (7).

3. Initial conditions

Since we describe the state of the fault by the couple (X, Y) of slip deficits, the plane XY can be taken as the state space of the system. The onset of seismic events is controlled by the values of forces (1) that are applied to the asperities. We assume a condition

Table 1
Dynamic modes of a two-asperity fault.

Dynamic mode	Symbol	Description
Sticking mode	00	Asperities are stationary
Slipping mode	10	Only asperity 1 slips
Slipping mode	01	Only asperity 2 slips
Slipping mode	11	Both asperities slip