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A two-asperity fault model with wave radiation

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ABSTRACT

We study the dynamics of a fault containing two asperities having different strengths and subject to a constant strain rate. The fault is modeled by a discrete dynamical system with two degrees of freedom that are the slip deficits of the asperities. The radiation of elastic waves during the slipping modes is taken into account by introducing a term proportional to slip rate in the equations of motion. We give a complete analytical solution of the four dynamic modes of the system. Any seismic event can be expressed as a sequence of modes, for which the moment rate, the spectrum and the total seismic moment can be calculated. We consider the energy budget of the event and calculate the seismic efficiency. The presence of radiation may remarkably change the evolution of the system from a given state, since it moves the boundaries between the different subsets of the sticking region. In addition, the slip amplitude in a seismic event is smaller, while the slip duration is longer in the presence of radiation. The shape of the moment rate function depends on the seismic efficiency and the seismic moment decreases with increasing efficiency, at constant radiated energy. As an application of the model, we consider the 1964 Great Alaska earthquake and calculate the mode durations, the slip distribution, the moment rate function and the seismic moment of the earthquake, obtaining values that are consistent with observations.

1. Introduction

Faults are heterogeneous surfaces, with a complex distribution of friction that can be represented in terms of asperity models. Stress accumulation on each asperity, fault slip at asperities and stress transfers between asperities play a key role in fault mechanics. Therefore the evolution of a fault can be fruitfully investigated by means of discrete dynamical systems where the basic elements are asperities (Ruff, 1992; Rice, 1993; Turcotte, 1997). An advantage is that the evolution of the system can be followed in the phase space, providing a deeper understanding of the behavior of the system.

Several large and medium-size earthquakes occurred in the last decades have been the result of the failure of two asperities, such as the 1992 Landers earthquake (Kanamori et al., 1992), the 1995 Kobe earthquake (Kikuchi and Kanamori, 1996), the 2004 Parkfield earthquake (Johanson et al., 2006) and the 2010 Maule, Chile, earthquake (Delouis et al., 2010). The first event for which a two-asperity structure was recognized is probably the 1964 Great Alaska earthquake (Christensen and Beck, 1994).

A discrete model describing a fault with two asperities was originally proposed by Nussbaum and Ruina (1987) and further investigated by Huang and Turcotte (1990), McCloskey and Bean (1992), Turcotte (1997) and others. The dynamics of the system has four different modes, corresponding to stationary asperities, motion of one asperity and simultaneous motion of the two asperities. Complete analytical solutions for such modes were given in Dragoni and Santini (2010, 2011) for the symmetric case and in Dragoni and Santini (2012, 2014) for the asymmetric case.

In general, previous models do not include the radiation of elastic waves: the reason is that the seismic efficiency of a fault is relatively small. In this case, all the elastic energy accumulated during the sticking mode is dissipated into heat during the asperity failure. Radiation can be taken into account by introducing in the equation of motion a damping term, proportional to slip rate (Rice, 1993). Bizzarri (2012) considered a single block model including radiation damping and concluded that radiation significantly affects the evolution of the system.

In the present paper, radiation of elastic waves during the slipping modes of a two-asperity fault is considered. The aim is to find out how the dynamics of the system is changed in the presence of radiation and to provide a better representation of seismic sources by discrete models. As an example, the model is applied to the 1964 Great Alaska earthquake.

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2. The model

We consider a plane fault with area A_0 containing two asperities (named 1 and 2) with equal areas A (Fig. 1). Let ℓ be the distance between the asperities. The fault is embedded in a shear zone of width d, placed between two tectonic plates moving at relative velocity v. The shear zone is assumed to be a homogeneous and isotropic Hooke solid with rigidity μ and is subject to a uniform strain rate, that is determined by the values of d and v.

In order to describe the state of the fault, we do not determine stress, friction and slip at every point of the fault but, instead, the average values of these quantities on each asperity. In particular, we assume that asperity slip is uniform over the asperity area: hence the asperity undergoes a rigid body (or Volterra) dislocation, as is frequently used in seismic source modeling (e.g. Okada, 1992).

At any time t, each asperity can be characterized by its slip deficit, i.e. the slip that the asperity should undergo in order to recover the relative plate displacement occurred up to time t. The slip deficit increases when the asperity is stationary and decreases when the asperity slips. We describe the state of the fault by the slip deficits $x(t)$ and $y(t)$ of the two asperities.

The asperity dynamics has four modes: a sticking mode, corresponding to stationary asperities, and three slipping modes, corresponding to the motion of one asperity or to the simultaneous motion of both asperities. Since the asperities move as rigid bodies, it is simpler to use forces instead of tractions. The asperity motion is controlled by friction and by the forces that are exerted by the surrounding medium.

The rate-and-state friction laws (Ruina, 1983; Dieterich, 1994) have been found to be effective in reproducing many aspects of earthquakes and seismicity. For our purposes, we use a simpler friction law, assuming that asperities 1 and 2 are characterized respectively by static frictions f_{s1} and f_{s2} and by dynamic frictions f_{d1} and f_{d2} that are the average values of friction during fault slip. We assume $f_{s1} \geqslant f_{s2}$ and $f_{d1} \geqslant f_{d2}$.

Let s be the tangential traction per unit moment that a slipping asperity imposes to the other asperity, calculated at the center of the asperity. Since asperity slip is uniform in the model, s can be calculated from the formulae for a rectangular dislocation in an elastic half-space collected by Okada (1992). However, if $\ell > 1.5\sqrt{A}$, the traction of a finite dislocation source is virtually indistinguishable from that of a point-like double-couple source in an unbounded medium and the latter simpler formula can be used.

Accordingly, the asperities are subject to tangential forces

$$f_1 = -Kx - K_c(x-y), \qquad f_2 = -Ky - K_c(y-x) \tag{1}$$

where

$$K = \frac{\mu A}{d}, \qquad K_c = \mu A^2 s \tag{2}$$

The two terms in f_1 and f_2 describe respectively the tectonic loading and the coupling between the asperities. The interaction of asperities is limited to static stress transfer. We do not consider the possibility of dynamic loading of the asperities during seismic events.

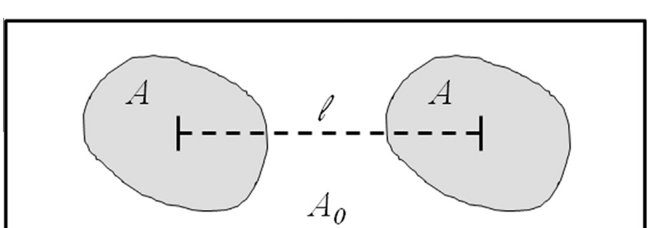

Fig. 1. The fault model with two asperities of area A. The total fault area is A_0.

The contribution of dynamic stress changes in triggering fault slip has been the subject of several studies (a review is given in Steacy et al., 2005) and such changes may have a role in seismic events with two or more slipping modes.

During the slipping modes, the sliding asperities are subject to the additional forces

$$f_{\imath 1} = -\imath\dot{x}, \qquad f_{\imath 2} = -\imath\dot{y} \tag{3}$$

due to radiation of elastic waves, where $\imath$ is an impedance. Therefore the equations of motion in the sticking mode are

$$\ddot{x} = 0, \qquad \ddot{y} = 0 \tag{4}$$

and the equations in the slipping modes are

$$m\ddot{x} + \imath\dot{x} + Kx + K_c(x-y) - f_{d1} = 0 \tag{5}$$

$$m\ddot{y} + \imath\dot{y} + Ky + K_c(y-x) - f_{d2} = 0 \tag{6}$$

where m is the mass associated with each asperity. The system is described by five nondimensional parameters defined as

$$\alpha = \frac{K_c}{K} = Ads, \quad \beta = \frac{f_{s2}}{f_{s1}} = \frac{f_{d2}}{f_{d1}}, \quad \gamma = \frac{\imath}{\sqrt{Km}} \tag{7}$$

$$\epsilon = \frac{f_{d1}}{f_{s1}} = \frac{f_{d2}}{f_{s2}}, \quad V = \frac{\sqrt{Km}}{f_{s1}} v \tag{8}$$

with $\alpha \geqslant 0, 0 < \beta \leqslant 1, \gamma \geqslant 0, 0 < \epsilon < 1, V > 0$. We introduce nondimensional variables and time

$$X = \frac{Kx}{f_{s1}}, \quad Y = \frac{Ky}{f_{s1}}, \quad T = \sqrt{\frac{K}{m}}t \tag{9}$$

If ω is the angular frequency of the emitted waves, we define a nondimensional frequency

$$\Omega = \sqrt{\frac{m}{K}}\omega \tag{10}$$

Hence Eq. (4) for the sticking mode becomes

$$\ddot{X} = 0 \tag{11}$$

$$\ddot{Y} = 0 \tag{12}$$

and Eqs. (5) and (6) for the slipping modes become

$$\ddot{X} + \gamma\dot{X} + (1+\alpha)X - \alpha Y - \epsilon = 0 \tag{13}$$

$$\ddot{Y} + \gamma\dot{Y} + (1+\alpha)Y - \alpha X - \beta\epsilon = 0 \tag{14}$$

where dots indicate differentiation with respect to T. The transition between dynamic modes is controlled by the values of forces (1). We define nondimensional forces

$$F_1 = \frac{f_1}{f_{s1}}, \qquad F_2 = \frac{f_2}{f_{s1}} \tag{15}$$

that can be written in terms of the model variables as

$$F_1 = -X - \alpha(X-Y), \qquad F_2 = -Y - \alpha(Y-X) \tag{16}$$

The conditions for the failure of asperities 1 and 2 are respectively

$$F_1 = -1, \qquad F_2 = -\beta \tag{17}$$

If we use (16), conditions (17) yield the equations of two lines in the plane XY,

$$Y = \frac{1+\alpha}{\alpha}X - \frac{1}{\alpha} \tag{18}$$

$$Y = \frac{\alpha}{1+\alpha}X + \frac{\beta}{1+\alpha} \tag{19}$$