Earthquake nucleation and its relationship to earthquake clustering

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Abstract

Earthquake clustering phenomena such as aftershocks, foreshocks, and pairing of mainshocks are prominent and characteristic features of earthquake occurrence. Because the earthquake nucleation process controls the time and place of occurrence of earthquakes, non-linear dependence of nucleation times on stress changes can strongly affect the spatial and temporal patterns of earthquake occurrence. Earthquake nucleation on faults with rate- and state-dependent fault properties has this characteristic, and appears to quantitatively represent the details and broad statistical patterns of earthquake clustering.

Introduction

Earthquake clustering phenomena such as aftershocks, foreshocks, swarms, and pairing of mainshocks are conspicuous and pervasive characteristics of earthquake occurrence. Indeed, aftershocks generally comprise significant portions of the events in earthquake catalogues and earthquake rates during the early stages of an aftershock sequence are often 10^3, or more, times the pre-mainshock rates. The prevalence of earthquake clustering and its strong imprint on spatial and temporal patterns of seismicity, provide convincing arguments, I believe, for the inclusion of reliably depicted earthquake clustering as one of the primary goals of any comprehensive program to develop computational models of earthquake processes.

Earthquake nucleation

It is proposed that various clustering phenomena have common origins rooted in time- and stress-dependent earthquake nucleation. A theory of the earthquake nucleation based on laboratory observations of fault properties (Dieterich, 1994[1]) has been used to quantitatively model earthquake clustering effects. The nucleation model is based on observations of rate- and state-dependent constitutive properties which are ubiquitous in laboratory experiments and it has been quantitatively confirmed in large scale laboratory experiments (Dieterich and Kilgore, 1996[4]). Extrapolated to tectonic stressing rates, the nucleation process is predicted to be preceded by a long interval (months to years) of slowly accelerating slip on a fault patch of finite dimensions. Once nucleation is underway, perturbation of the time of the onset of the earthquake instability is highly sensitive to both the magnitude of the stress perturbation and the unperturbed time remaining to instability. It is proposed that earthquake clustering arises from this sensitivity of nucleation times to stress changes induced by prior earthquakes. Two different approaches have been used to investigate these effects.

Formulation for earthquake rates

The first approach employs a constitutive formulation for rate of earthquake activity derived from the nucleation solutions (Dieterich, 1994[2]). The formulation yields earthquake rates as a function of time for a stressing history. Solutions for the changes of earthquake arising from the changes in stress caused by a prior earthquake are then compared with various clustering phenomena. In its original form, the stresses driving the earthquake process are expressed in terms of shear stress and effective normal stress acting on the causative faults. Assuming stress perturbations are small with respect to total stresses, the formulation can be simplified to a single scalar stress variable (Coulomb stress function) which is more convenient than the original form for many applications. The rate of earthquake occurrence *R* in some magnitude interval is

$$R = \frac{r}{\gamma \, \dot{S}_r}, \tag{1}$$

where r and $\dot{S}_r$ are normalizing constants and γ is a state variable that evolves with time and stress. R is the earthquake rate in some magnitude interval and r is the steady-state rate for the reference Coulomb stressing rate $\dot{S}_r$ acting on the causative faults. Evolution of γ is given by

$$d\gamma = \frac{1}{A\sigma}\left[dt - \gamma dS\right], \tag{2}$$

where A is the rate constitutive parameter in the rate- and state-dependent formulation, which generally has values in the range .005 to .015, and σ is effective normal stress. In this approximation the term $A\sigma$ is assumed constant. S is the Coulomb stress function which is defined from

$$dS = d\tau - \mu d\sigma\ , \tag{3}$$

where, τ is fault shear stress, and μ is the coefficient of friction. For the nucleation solutions, μ is an apparent coefficient defined as

$$\mu = \frac{\tau}{\sigma} - \alpha \cdot \tag{4}$$

a is a positive dimensionless constant with value of about 0.25 (see Linker and Dieterich, 1992[5]). Recall additionally that σ is defined as the effective normal stress.

Solutions for seismicity rate following stress steps yield the characteristic Omori aftershock decay law and provide quantitative interpretation of aftershock parameters in terms of stressing rates and stress changes at the time of the mainshock[2]. Data on aftershock duration confirm a fundamental prediction of the model: aftershock duration is inversely proportional to stressing rate [2]. This observation appears to exclude aftershock models based on fluid diffusion or viscoelastic stress transfer. The solutions also predict spread of aftershocks with time, and an average value of the aftershock decay exponent p~0.8, both of which appear to be consist with aftershock observations.

Two mechanisms for foreshocks are proposed [4]. In the preferred model, foreshocks are taken to have essentially the same mechanism as aftershocks and the frequency of mainshock-foreshock pairs is obtained by extrapolating of the aftershock rate solutions to events larger than the mainshock. With the alternative model, premonitory creep for mainshock nucleation triggers the foreshocks. Equations (1) and (2) are solved for a stressing prescribed by the nucleation solutions. The second model requires mainshock nucleation zones that are comparable in size or larger than the foreshock sources. Both models appear to adequately describe the observed frequency of foreshock-mainshock pairs by time and magnitude.

Numerical simulations

The second approach for investigation of the role of nucleation processes on earthquake occurrence is based on direct numerical simulations of earthquake sequences that incorporate the time- and stress-dependencies of the nucleation process. This effort is at an early stage. Preliminary investigations [3] employ a model of a planar fault surface which is periodic in both the x- and y-directions. Elastic interactions among fault elements are represented by a rectangular array of elastic dislocations. Approximate solutions are used to represent the dynamics of earthquake slip and the healing and nucleation processes inherent in the rate- and state-dependent. Simplifications are introduced which allow the computations to proceed in steps that are determined by the transitions from one sliding state to the next. The three sliding states of the model are no-slip, nucleating slip, and dynamic slip. The transition-driven time stepping and avoidance of the need to solve large systems of simultaneous equations permit very efficient simulation of large sequences of earthquake events on computers of modest capacity, while preserving characteristics of the nucleation and rupture propagation process evident in more detailed models.

The most noteworthy feature of the earthquake sequences simulated with this model is a strong clustering of events. Initial results yield earthquake catalogs with foreshocks, aftershocks, event-pairs, and multiple-event earthquakes. The simulated aftershocks decay according to the Omori aftershock decay law, and the aftershock sequences have a characteristic duration that agrees with the earlier predictions derived from the rate formulation described above. Foreshocks tend to occur adjacent to the nucleation point of the mainshocks. In many, but not all, cases the mainshock re-ruptures the foreshock zone. Aftershocks generally occur around the edges of the mainshock rupture.

The frequencies of foreshocks and aftershocks relative to mainshocks in the simulations can by matched to earthquake data for western United States by adjusting the constitutive parameter *A*. Generally, the best agreement is obtained with values of *A* that are significantly less than laboratory observations of this parameter. This discrepancy is believed to be an artifact of the simplified computational procedure and will be examined further.

References

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