

Aftershock occurrence due to fluid migration in a fault zone

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Abstract

We have constructed a model for the occurrence of aftershocks and aftershock sequences. The aftershock occurrence is assumed to be dependent on the pore fluid pressure p through the Coulomb fracture criterion coupled to the principle of effective stress. The fluid is assumed to flow out of a localized high-pressure fluid zone with the occurrence of the main shock. Our aftershock source model explains the following seismological observations of aftershocks in a unified manner; the Omori law of aftershock activity, the Gutenberg-Richter magnitude-frequency relation, the occurrence of secondary aftershock sequences, and the migration of aftershock activity. It is also an attractive feature of our model that the model can simulate not only aftershocks but also a variety of earthquake sequences by changing the values of poroelastic model parameters .

Introduction

Because of their evident regularity, the statistics of aftershock sequence represent attractive phenomenological targets for modeling. Two statistical evidences are very well established. One of them is the Omori law (1894) for the temporal rate of aftershock occurrence,

$$n(t) = a / t^p, \quad (1)$$

which has been verified often (Utsu,1961); p is of the order of unity and t is measured from the main shock that triggered the aftershocks.

It is also well known that aftershocks have magnitude distributions that satisfy the Gutenberg-Richter magnitude-frequency law

$$\log n(M) = a - bM, \quad (2)$$

where $n(M)$ is the frequency of events that occur at a given magnitude M , and a and b are constants. Utsu(1961) showed, investigating many aftershock sequences, that b is in the range $0.6 < b < 1.5$, and that values $b=0.8$ to 2.3 are most common.

A number of theoretical studies have chosen to explain either the Omori formula or the Gutenberg-Richter relation. In this paper we present a unified model that successfully generates the above two distinctive features. Some type of inelasticity is needed to account for the time delays between the main shock and the aftershocks and between the aftershocks themselves. We assume fluids migrating in a fault zone as a mechanism to cause such time delays. Our model can also simulate a slow expansion of aftershock area and a tendency of the occurrence of large aftershocks near the edge of the fault. It is also shown that secondary aftershock sequences can occur in a fault zone with a low permeability; each sequence of secondary aftershocks is shown to satisfy the Omori law (1) with $p \sim 1$. Conspicuous secondary aftershock sequences are also caused by the rupture of discrete high-pressure fluid zones.

Model

It is now widely believed that fluids exert significant mechanical effects on earthquake faulting. In this paper we consider the reduction of the effective confining pressure by the zones of high pore fluid pressure. A localized high-pressure fluid source is assumed near the bottom of a sealed vertical strike-slip fault before the nucleation of ruptures (Fig.1). The sudden rupture of the high-pressure fluid zone is assumed to generate a main shock, and the fluid migrating in the fault zone generates a sequence of aftershocks.

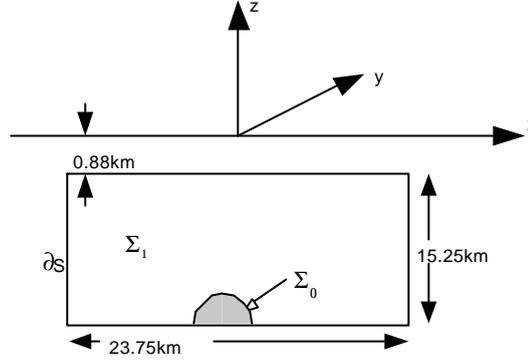


Figure 1. Elastic half space with vertical strike-slip fault. The plane $z=0$ corresponds to the free surface. High-pressure fluid is initially localized at Σ_0 ; the rest of the fault, Σ_1 , is under lower fluid pressure.

The rupture occurrence is assumed to be dependent on the pore fluid pressure p through the Coulomb fracture criterion coupled to the principle of effective stress

$$\tau = a + \mu(\sigma_n - p) \quad (3)$$

where τ is the static shear traction at fracture, μ is the coefficient of static friction, σ_n is the total normal traction on the fault, and a denotes a cohesive strength. The cohesive strength is assumed to decrease from a_0 to $(1-\gamma)a_0$ when a fault segment slips for the first time, where γ is in the range $0 < \gamma < 1.0$. This occurs because of the partial loss of the cohesion. The cohesive strength is kept constant during later slips there.

It will be reasonable to assume a much lower permeability in the high-pressure zone Σ_0 than in the surrounding low-pressure zone Σ_1 before the main shock occurrence because of the building-up of the fluid-pressure there. We therefore assume an idealized case $0 = c_0 < c_1 (< 1)$ in the simulations, where c_0 and c_1 are the nondimensional values of permeability in Σ_0 and Σ_1 respectively before the main shock occurrence. We also assume that the permeability increases suddenly with a rupture to the value 1. We use mathematical formula assumed in Yamashita (1999) for the analysis of rupture occurrence, fluid migration and coupling between them; however, the porosity change due to ruptures is neglected here. Only the permeability is assumed to be a poroelastic parameter dependent on ruptures.

Aftershock occurrence and its statistical properties

An example of the sequence of aftershocks is illustrated in Fig.2.

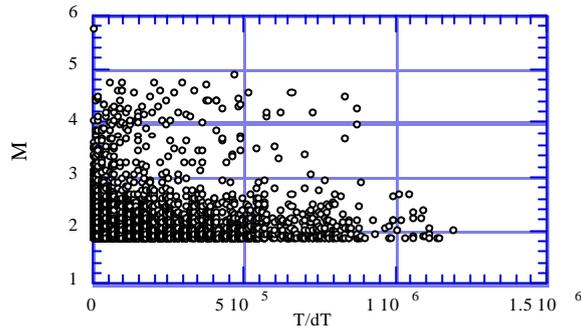


Figure 2: An example of sequence with $c_1=0.1$ and $\gamma=0.99$.

We assumed $c_1=0.1$ and $\gamma=0.99$ in this example and a_0 is assumed to be a random number distributed uniformly in a certain range. It is clearly observed in this figure that the rupture activity tends to decrease with time. This sequence satisfies both the Omori law and the Gutenberg-Richter relation very well (Figs.3 and 4).

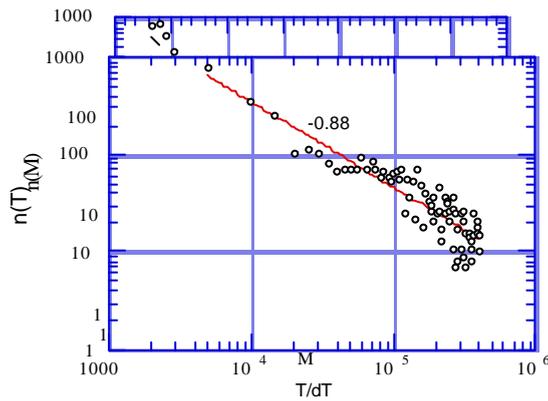


Figure 3: Frequency distribution of magnitudes for the sequence shown in Fig.2.

Figure 4: Temporal rate of aftershock occurrence for the sequence shown in Fig.2

We carried out a number of simulations changing the values of c_1 and γ . It is shown in the calculations that the b -value is almost independent of the assumption of these values. However, the deviation from the equation (1) is large for $c_1 \sim 0.0$ as exemplified in Fig.5.

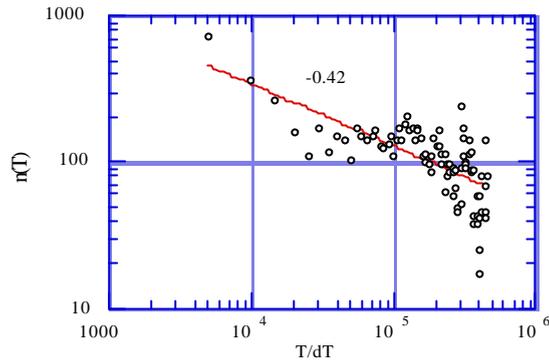
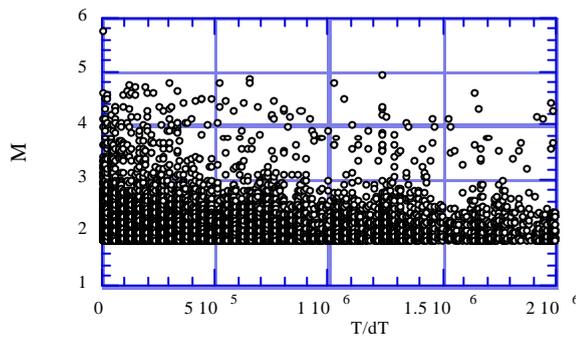


Figure 5: Temporal rate of aftershock occurrence for a sequence with $c_1=0.0$.

This will occur because the sequence consists of a number of secondary aftershock sequences as illustrated in Fig.6. This figure shows that a large aftershock is generally followed by secondary



aftershocks.

Figure 6: An example of sequence with $c_1=0.0$ and $\gamma=0.99$.

Each sequence of secondary aftershocks satisfies the Omori law with $p \sim 1$ (see Fig.7).

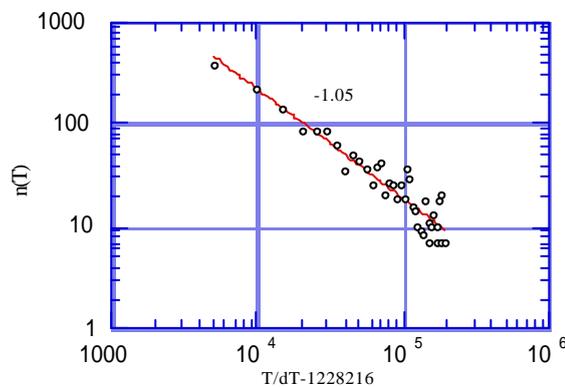


Figure 7: Temporal rate of secondary aftershock occurrence beginning at $T/dT=1228216$.

Our calculations also show that conspicuous secondary aftershock sequences are simulated if we assume discrete high-pressure fluid zones before the main shock; the rupture of a high-pressure fluid zone corresponds to a secondary aftershock sequence.

It is shown in our calculation that large aftershocks tend to occur near the advancing edge of the fault; such events are associated with the slip of newly fractured fault segments. Since the sudden advancement of the fault edge causes a large perturbation in fluid flow, many aftershocks are generated there. Small events are in most cases caused by repeated slips of fractured fault segments.

Discussion and conclusions

The coupling between the rupture occurrence and fluid-migration in a fault zone was shown to give rise to an aftershock sequence satisfying both the Omori-law and the Gutenberg-Richter relation. Aftershock zone generally expands with time due to gradual fluid migration. Small events can occur anywhere on the fault, while large events generally occur near the fault edge. These are consistent with seismological observations (e.g., Takeo and Mikami, 1990; Hirata et al., 1996).

A number of mechanisms for developing time delays between main shocks and aftershocks have been proposed. At least both the Omori law and the Gutenberg-Richter relation must be predicted by reasonable models. However, it is not enough for the validation of one mechanism over another. It may be that the ability to discriminate between one mechanism and another becomes clearer when the statistical properties of the spatial distributions are introduced as targets for modeling. Yamashita and Knopoff (1987) took a fracture mechanics approach with an assumption of stress corrosion cracking at fault tips, and proposed two models for aftershock occurrence. Their two models correctly predict the Omori law as well as the Gutenberg-Richter relation (Reuschle, 1990). Reuschle (1990) argued that the discrimination between these two models is possible by considering the time distribution of aftershock magnitudes. As shown above, our model can also explain the time distribution of aftershock magnitudes. In addition, spatial distribution of simulated aftershocks is consistent with seismological observations, and our model can explain the occurrence of secondary aftershock sequences. This does not mean that stress corrosion cracking has little effect on aftershock occurrence since stress corrosion cracking is activated in the presence of fluids. It is likely that both mechanical effects of fluid migration, studied here, and stress corrosion cracking equally affect the aftershock occurrence in actual aftershock sequences. However, it is an attractive feature of our model that a variety of earthquake sequences can be simulated by considering fluid migration in a fault zone; for example, earthquake swarm can be simulated by slight changes in the values of model parameters associated with poroelasticity (Yamashita, 1999).

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