Effect of an outer-rise earthquake on seismic cycle of large interplate earthquakes estimated from an instability model based on friction mechanics

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Abstract

A numerical simulation study is conducted to examine the effect of a large outer-rise earthquake on seismic cycle of large interplate earthquakes in a subduction zone. A model of 2D uniform elastic half-space is set up to exactly evaluate static elastic interactions. The frictional force acting on a plate interface is assumed to obey a laboratory-derived rate- and state-dependent friction law. The simulation result indicates that a large tensional outer-rise earthquake tend to advance the occurrence time and reduce the magnitude of the next interplate earthquake.

Introduction

Earthquake occurrences are affected by stress perturbation due to nearby earthquakes. Since the interaction among faults is considered to be a possible cause of complicated aperiodicity in an earthquake sequence, it has theoretically been investigated by many researchers [1]. However, existing models neglect the effect of time-dependence of fault strength and the occurrence of aseismic sliding. We present a more realistic model for fault interaction by taking account of the time-dependent property of rock friction.

In this study, we consider the effect of a large outer-rise earthquake on seismic cycles of large interplate earthquakes in a subduction zone. This situation can be relatively well approximated by a two-dimensional model, and the effect is important for long-term forecasting of a destructive large interplate earthquake. We perform a numerical simulation, bearing in mind the Sanriku region along the Japan trench, where the Pacific plate subducts beneath the northern Honshu. In 1933, a large tensional outer-rise earthquake occurred in the Sanriku region. From seismological data, Kanamori [2] indicated that the faulting took place over the entire thickness of the lithosphere.

Model and simulation method

Figure 1 shows a 2-D model of uniform elastic half-space for the Sanriku subduction zone. First, we construct a model for a seismic cycle of interplate earthquakes similar to those of Tse and Rice [3] for strike-slip faults and Stuart [4] for thrust faults. The straight thrust fault in Figure 1 is regarded as the boundary between a continental plate and a subducting oceanic plate. Stable sliding is assumed to take place on a deeper part of the plate interface, where the rate of relative plate motion is 9 cm/year. On a shallower part of the plate interface, we assume the frictional force obeying a rate- and state-dependent friction law developed by Dieterich [5] and Ruina [6] from laboratory experiments. We further assume the occurrence of a tensional outer-rise earthquake. The friction law is not assumed on the fault plane of the outer-rise event. We artificially generate uniform slip on the fault plane at the occurrence of the earthquake. The source parameters of the outer-rise earthquake are taken from Kanamori [2] estimated for the 1933 Sanriku outer-rise event.

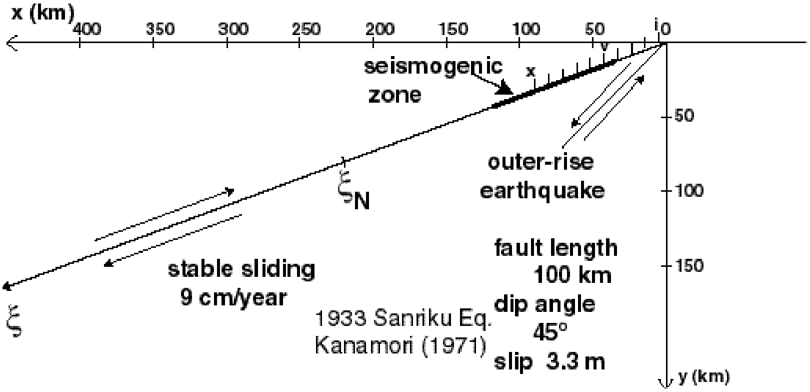


Figure 1: A 2D model for a subduction zone used in the present numerical simulation. The frictional force obeying the slowness version of rate- and state-dependent friction law is assumed to act on the plate interface shallower than x_N. A thick-line on the plate interface denotes the seismogenic zone (a-b< 0). A pair of arrows indicates the assumed stable sliding on the plate interface deeper than x_N. Uniform slip is assumed to take place on the fault plane of an outer-rise earthquake.

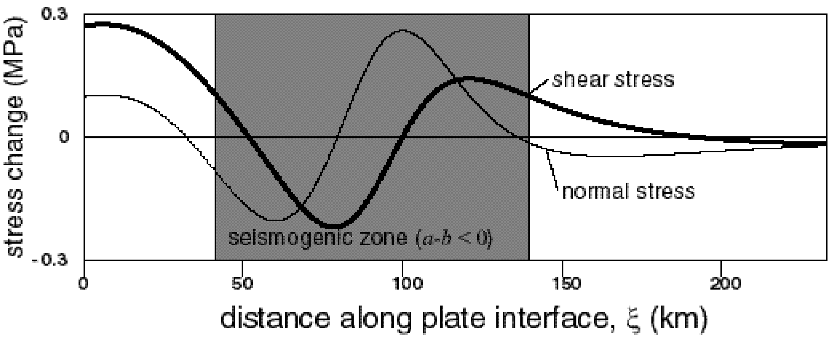


Figure 2: Changes in shear (thick line) and normal (thin line) stresses on the plate interface due to the occurrence of a tensional outer-rise earthquake.

The method of numerical simulation is essentially the same as that of Kato and Hirasawa [7]. Taking account of the experimental results on the environmental dependence of friction parameters, we assume the variations of friction parameters with depth. We found that the simulation results of the recurrence interval of large interplate earthquakes and the seismic slip amount depend on the values of friction parameters. We select appropriate values of friction parameters to represent the seismic cycle in the Sanriku subduction zone. In the numerical simulation, large earthquakes repeatedly occur at a constant time interval on a shallower part of plate interface, and aseismic sliding occurs on a deeper part before the occurrence of an outer-rise earthquake. The recurrence interval of large earthquakes is 84.5 years. The average slip amount is 3.5 m. These values are reasonable for a large interplate earthquake. Note that we do not exactly evaluate elastodynamic equations. We simply define the seismic slip by slip with slip rate equal to or greater than 1 cm/s for comparing the amplitude of seismic slip with that of aseismic sliding [7].

Figure 2 shows static stress changes on the plate interface due to the occurrence of the tensional outer-rise earthquake. Since the stress distributions are complicated, we cannot easily conclude whether the outer-rise earthquake promotes an interplate earthquake or not.

We define some parameters to quantitatively examine the simulation results. Figure 3 schematically shows a slip history of a plate interface. EQ0 and EQ1 are large earthquakes before the occurrence of the outer-rise earthquake. T_r^1 is the time interval between EQ0 and EQ1. u_{seis}^0 and u_{seis}^1 are the average slip amounts of EQ0 and EQ1. u_{seis}^0 equals to u_{seis}^1, because interplate earthquakes of the same magnitude repeatedly occur before the outer-rise event. At the time of T_{or} from EQ1, the outer- rise event takes place. EQ2 is the next interplate earthquake. T_r^2 is the time interval between EQ1 and EQ2, and u_{seis}^2 is the average slip amount of EQ2. EQ3 is the next interplate earthquake after EQ2, and T_r^3 and u_{seis}^3 are defined in similar ways.

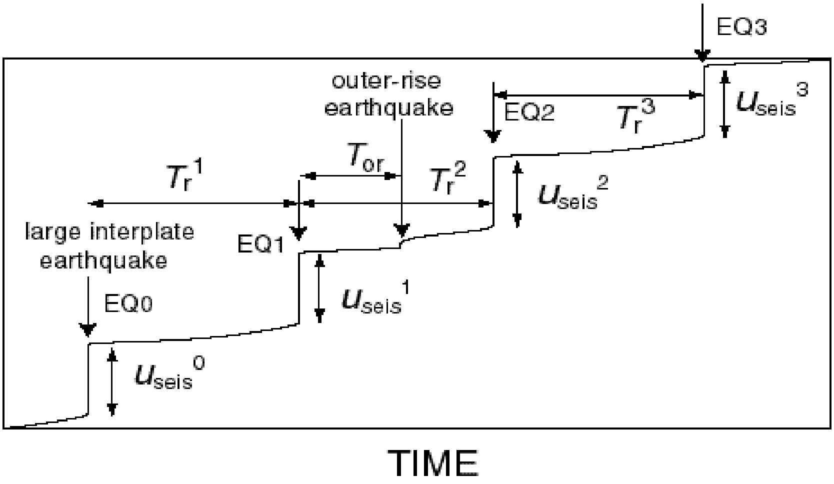


Figure 3: Schematic diagram of slip history of a plate interface to show the definitions of the quantities used in the text.

Simulation results

From numerical simulation, we find the occurrence time of EQ2 is advanced and its amplitude tends to be reduced due to the effect of the outer-rise event. To understand why the occurrence time of EQ2 is advanced, we examine the spatiotemporal variations of slip and friction coefficient on the plate interface due to the occurrence of the outer-rise event as shown in Figure 4. At the occurrence time of the outer-rise event, aseismic sliding occurs at the top of the plate interface and it propagates into a deeper part of the plate interface. This is because shear stress is increased in these regions by the occurrence of the outer-rise event and because the normal stress is small at shallow depths. Although this aseismic siding is arrested in the seismogenic zone, the shear stress is increased there due to the aseismic sliding on the shallower part of the plate interface. This stress increase promotes the occurrence of interplate earthquake. At the occurrence time of EQ2, the strain energy accumulated in the source volume is smaller, because the occurrence time is earlier than usual. Accordingly, the magnitude of EQ2 is smaller than EQ1.

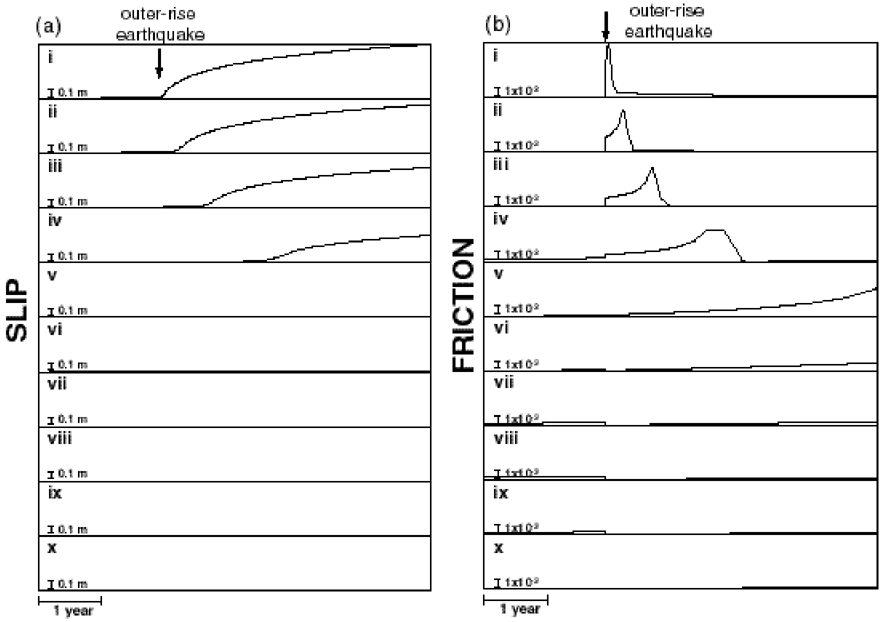
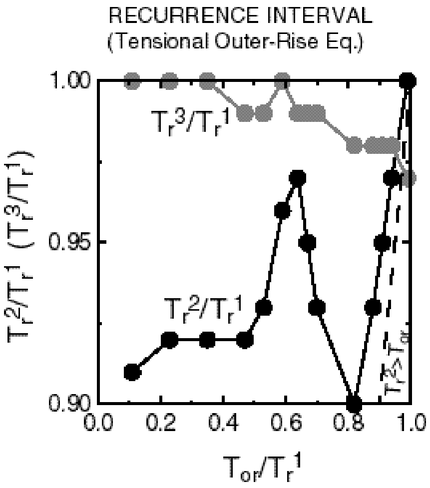


Figure 4: (a) Slip histories at 10 points on the plate interface, which are affected by the occurrence of a large outer-rise earthquake. (b) Histories of friction coefficient at 10 points on the plate interface. The time interval is the same as that in (a). See Figure 1 for the locations of points i to x on the plate interface.

The characteristics of EQ2 may depend on T_{or} because the frictional strength is time-dependent. We examine the effect of the outer-rise event by varying T_{or}-value. Figure 5 shows T_r^2 and T_r^3 normalized by T_r^1 plotted against T_{or}/T_r^1. T_r^2 rapidly increases for $T_{or} > 0.8T_r^1$. This is physically meaningless because T_r^2 must be larger than T_{or} by the definition. T_r^2 is always smaller than T_r^1, and the value of T_r^2/T_r^1 depends on T_{or}. We cannot easily explain why T_r^2 depends on T_{or}, because the occurrence of an interplate earthquake is controlled by the aseismic sliding on a shallower part of plate interface, the stress decrease in the seismigenic zone, aseismic sliding in the deeper aseismic zone, and the nonlinear characteristics of rock riction. T_r^3 also depends on T_{or}. However, the difference between T_r^3 and T_r^1 is less than 3%. The outer-rise earthquake strongly affects only the occurrence time of the next interplate earthquake.



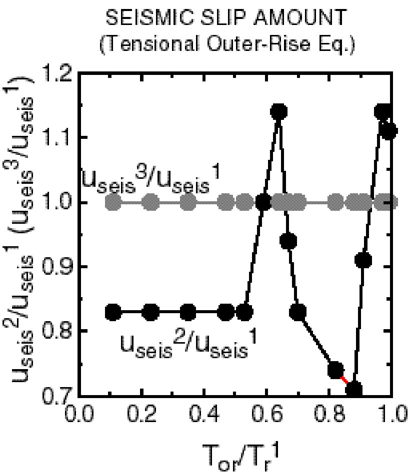


Figure 5 (left): The time interval between successive large interplate earthquakes, T_r^2 (black) and T_r^3 (gray), normalized by T_r^1 versus the occurrence time of a tensional outer-rise earthquake, T_{or}, normalized by T_r^1, where T_r^1, T_r^2, T_r^3 and T_{or} are defined in Figure 3. Figure 6 (right): The average seismic slip amounts, u_{seis}^2 (black) and u_{seis}^3 (gray), of EQ2 and EQ3 normalized by u_{seis}^1 versus the occurrence time of a tensional outer-rise earthquake, T_{or}, normalized by T_r^1, where u_{seis}^1, u_{seis}^2, u_{seis}^3 and T_{or} are defined in Figure 3.

Figure 6 shows the average seismic slip amounts of EQ2 and EQ3 normalized by that of EQ1 plotted against T_{or}/T_r^1. u_{seis}^2 is generally smaller than u_{seis}^1 except that T_{or} is nearly equal to $0.6T_r^1$ or T_r^1. We find a positive correlation between T_r^2 and u_{seis}^2. u_{seis}^3 is nearly equal to u_{seis}^1 for all the tested values of T_{or}.

Conclusion

From numerical simulation, we find that the stress perturbation due to a large outer-rise earthquake affects the occurrence time and the magnitude of large interplate earthquakes. In the case of a tensional outer-rise earthquake, it generally advances the occurrence time and reduces the magnitude of the next interplate earthquake. The effect of an outer-rise earthquake depends on its occurrence time in a seismic cycle of interplate earthquakes because the friction strength is time dependent. A large outer-rise earthquake strongly affects only the next interplate earthquake.

We examined a very simple case of fault interaction in the present study. Large interplate earthquakes in neighboring regions along a trench axis should significantly perturb stresses on a plate interface, though it is difficult to investigate by our simple 2-D model. Fault interaction is important to understand the complicated aperiodicity of an earthquake sequence.

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