Seismic Activity Simulation and Detection of Wenchuan Earthquake Sequence

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Abstract

The Coulomb rate state model (CRS) based on rate state-dependent constitutive law simulates the seismic activity of three main earthquakes in Wenchuan earthquake sequence. The results show that the model considering the trigger source of secondary aftershocks is more in line with the observation. We come to the conclusion that the trigger of the main earthquake sequence is generated by the self-excitation of small earthquakes under the stress field dominated by Coulomb stress of the main earthquakes of adjacent faults, which is similar to the point process model of ETAS.

Keywords

Coulomb Stress Rate State Model (CRS); Main Earthquake Trigger; Secondary Aftershock Trigger.

1. Introduction

In the identification of abnormal seismic activity, most studies have given that ETAS statistical model based on epidemic aftershock sequence is more effective than CRS physical model based on Coulomb velocity state , but the performance of physical model considering uncertainty and secondary trigger is equivalent to ETAS[1]. In the process of CRS physical simulation, the key parameters of reference seismic activity rate, regional stress field and loading rate are involved, and the simulation results depend on various combinations of the above parameters. Various uncertainties, such as the difference of slip model, the direction of receiving fault and the choice of friction coefficient, have been discussed in detail[2] . On the basis of considering these uncertainties, we focused on the effect triggered by the second aftershock, and simulated the seismic activity in the region including the aftershock areas of Wenchuan earthquake, Lushan earthquake and Jiuzhaigou earthquake. The simulation calculation of the secondary aftershock source is added, which is similar to the cascade effect of the empirical statistical model ETAS. In this process, we try to understand the physical trigger mechanism of this complete sequence.

2. Research Methods and Data

2.1. Research Method

The change of Coulomb stress is closely related to the temporal and spatial distribution of seismic activity. According to Coulomb failure criterion, when an earthquake occurs, the shear stress needs to overcome the normal stress that prevents the fault from sliding, that is, static friction. The failure criterion of Coulomb stress is [3]:

$$\Delta\sigma_c = \Delta\tau - \mu\Delta\sigma_n \tag{1}$$

Where $\Delta\tau$ and $\Delta\sigma_n$ are the changes of shear stress and normal stress calculated along the sliding direction on the fault plane respectively, and μ is the friction coefficient. According to Equation 1-1, the increase of Coulomb stress will make the fault close to failure, on the contrary, the decrease will make the fault far away from failure. There are usually two models to describe

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the change of pore pressure in response to the applied stress. One is the apparent friction pore elasticity model, where $\mu' = \mu(1-B)$ is the apparent friction coefficient. The simulated seismicity rate R is a state variable, and it is a function of reference shear stress rate and background seismicity, which was put forward by Dieterich[4]. The basic idea is to model seismicity as a series of earthquake nucleation events, and the distribution of nucleation sources and stress history control the earthquake occurrence process. The model takes advantage of the rate-dependent fault properties obtained in the laboratory and assumes that the state of seismic activity rate changes due to external stress. The formula is:

$$R = \frac{r}{\gamma \dot{\tau}_r} \quad (2)$$

Where r is the reference seismic activity of the study area. Cattalli[5] defines it as the smooth result of the complete unclustered earthquake catalogue on the time window, and gives the relationship between the reference seismic activity rate and the stress rate, which reduces the calculated parameters to two.

At a constant stress rate, the state changes tend to a steady-state value.

$$\gamma_o = \frac{1}{\dot{\tau}_r} \quad (3)$$

State variables evolve by the following formula

$$\gamma_n = \gamma_{n-1} \exp\left(\frac{-\Delta CFF}{A\sigma}\right) \quad (4)$$

The evolution of coulomb stress is

$$\Delta CFF = \Delta\tau + (\mu - \alpha)\Delta\sigma_{\text{eff}} \quad (5)$$

Here α is the positive dimensionless parameter of the effective normal stress change of the constitutive law [6], so the friction coefficient is different from that usually assumed in Coulomb stress.

Coseismic stress disturbance makes the state variable γ decrease, which accelerates the fault slip and produces a high seismic slip rate.

2.2. Research Data

Wenchuan sequence in Longmenshan earthquake fault is selected to test the reliability of CRS model. The sequence includes Wenchuan earthquake of 7.9Mw on May 1, 2008, Lushan earthquake of Mw6.6 on April 20, 2013 and Jiuzhaigou earthquake of Mw6.5 on August 8, 2017. The longitude is 100-108 degrees, the longitude is 28-36 degrees, and the earthquake depth is 0.1-50 kilometers. This area completely covers the main earthquake area and aftershock area of the entire Wenchuan sequence.

In order to get a better model comparison, I chose the slip model used by Jia[7]. There are three models for Wenchuan earthquake, two for Lushan and one for Jiuzhaigou. For focal mechanisms below magnitude 6, there is no slip model, so I adopted the empirical formula of Wells&Coppersmith[8] to synthesize the slip model. Earthquakes without focal mechanism but as stress sources are calculated by isotropic stress field.

The focal mechanism solution comes from 1491 earthquakes with magnitude 3.0 or above from May 2008 to December 2015 obtained by Yang[9] using full waveform inversion. I downloaded and supplemented the catalogue of historical focal mechanisms before 2008 from China Seismological Network Center, and used it as a stress source during inversion. The background catalag is obtained by declustering and smoothing the earthquake activities before May 11th, 2008.

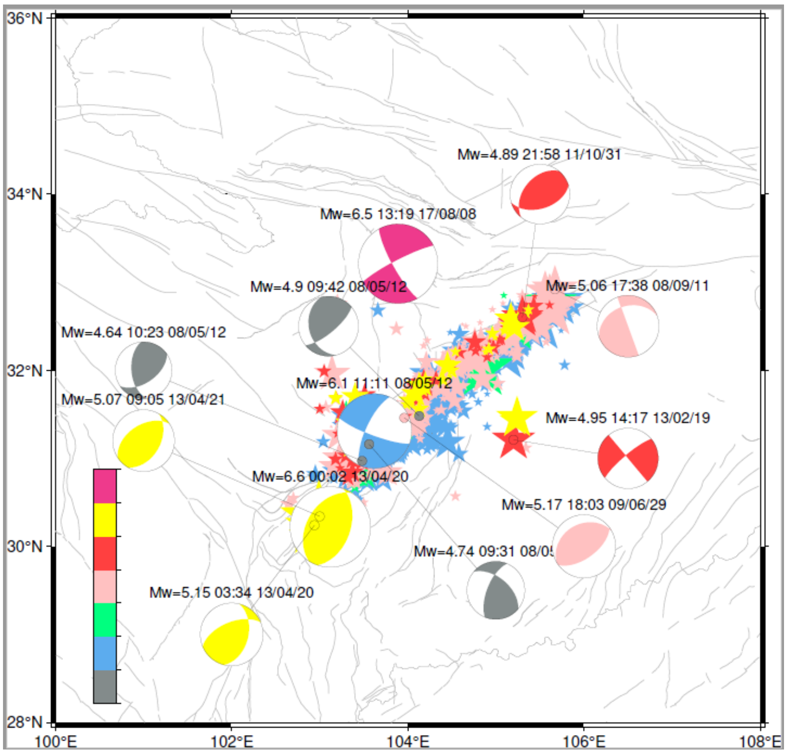

Fig 1. Tectonic environment of the study area

3. Results

Figure 2 shows the difference of the number of events between the main earthquake model and the earthquake with magnitude 4 or above as the stress source. It can be clearly seen that secondary aftershocks have been added, and the number of earthquakes per day has greatly increased. Compared with the model with only magnitude 7 as the main shock, the increase is 2-4 times. It is worth noting that the seismic activity during the Wenchuan-Lushan earthquake has increased by four times. The increase of Wenchuan and Wenchuan-Jiuzhaigou is relatively moderate, which may indicate that Lushan earthquake triggered more small earthquakes, because the magnitude is not considered here, only the number of triggers is considered. The triggering ability of different magnitudes is obviously different with different models. Only three main earthquakes, namely Wenchuan earthquake, Lushan earthquake and Jiuzhaigou earthquake, were considered for the magnitude 7 earthquake source, and there were only three models in Wenchuan stage. The results of the first model were similar to those of the third model, and the number of the second model was three times less. Wenchuan-Lushan stage and Wenchuan-Jiuzhaigou stage also showed randomness.

Considering that the situation of earthquake sources with magnitude 4 is very different, the number of events ranges from 75 in the highest model in Wenchuan stage to 125 in Wenchuan-Lushan stage, and then reduced to 100 in Wenchuan-Jiuzhaigou stage. We pay special attention to the process of secondary aftershocks, because it is more in line with the physical process, and it is also confirmed that the results contained are better fitted. The change of the number of earthquakes reflects the role of small earthquakes in the physical process.

Figure 3 shows the cumulative number of different stress sources in different models. However, with the addition of earthquakes of magnitude 6, it is still found that the model considering the secondary triggering of aftershocks triggered more earthquakes. Earthquakes of magnitude 6 include main earthquakes of magnitude 7, so the number of triggering events is more than that of earthquakes of magnitude 7, but most models are less than that of earthquakes of magnitude 4, with the exception of model 5. It is found that the number of triggering events of earthquakes

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of magnitude 6 even exceeds the source of earthquakes of magnitude 4. Check the model carefully, it is not caused by mistakes. In addition, it is noted that the number of models 6 is almost the same as that of models 7, even slightly lower. The robust slip model can be selected as input by comparing the cumulative numbers.

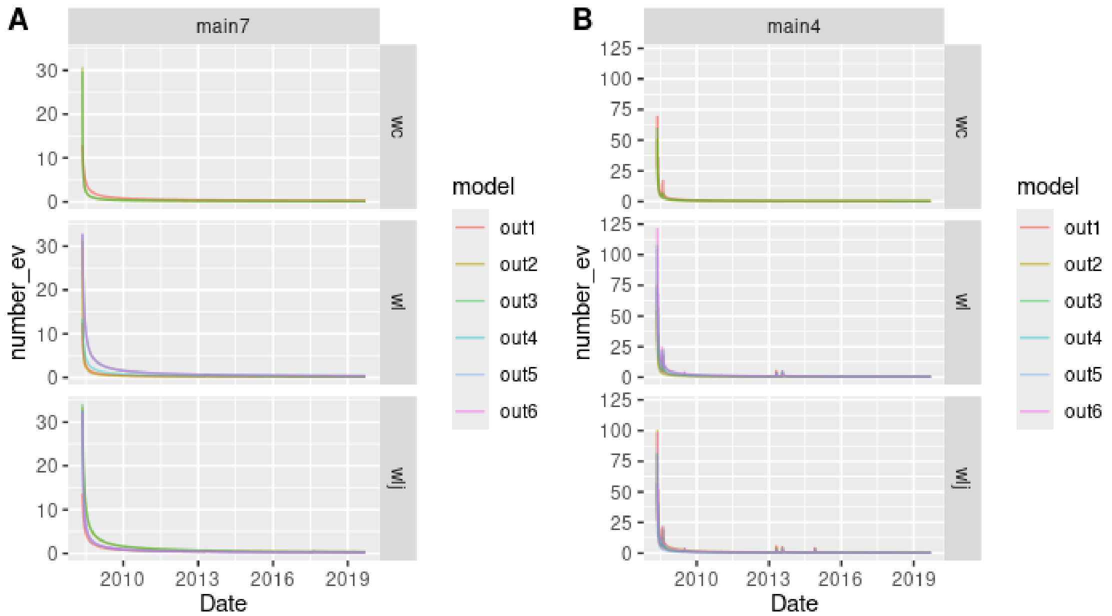

Fig 2. The simulation results triggered by the main earthquake and the secondary aftershock are adopted. Where ou1-out6 is a combination of different slip models. Main7 is an earthquake of magnitude 7, which is the simulation result of only three main earthquakes; Main4 is an earthquake of magnitude 4, and also participates in the simulation calculation of seismic activity as a stress source

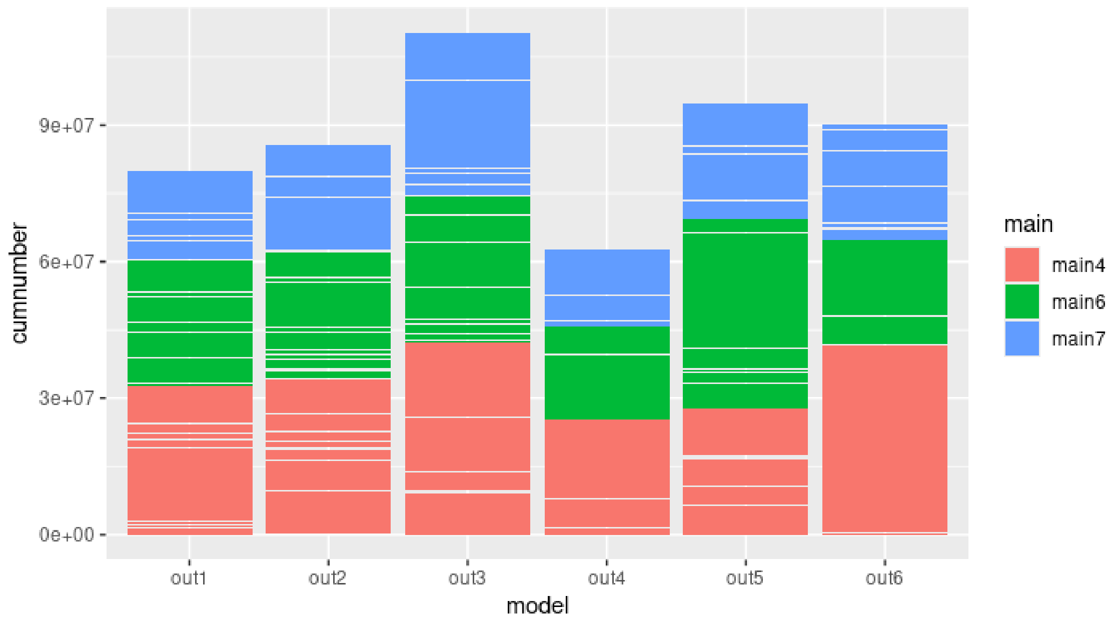

Fig 3. Cumulative number of earthquakes simulated by different models and different main earthquake stress sources.

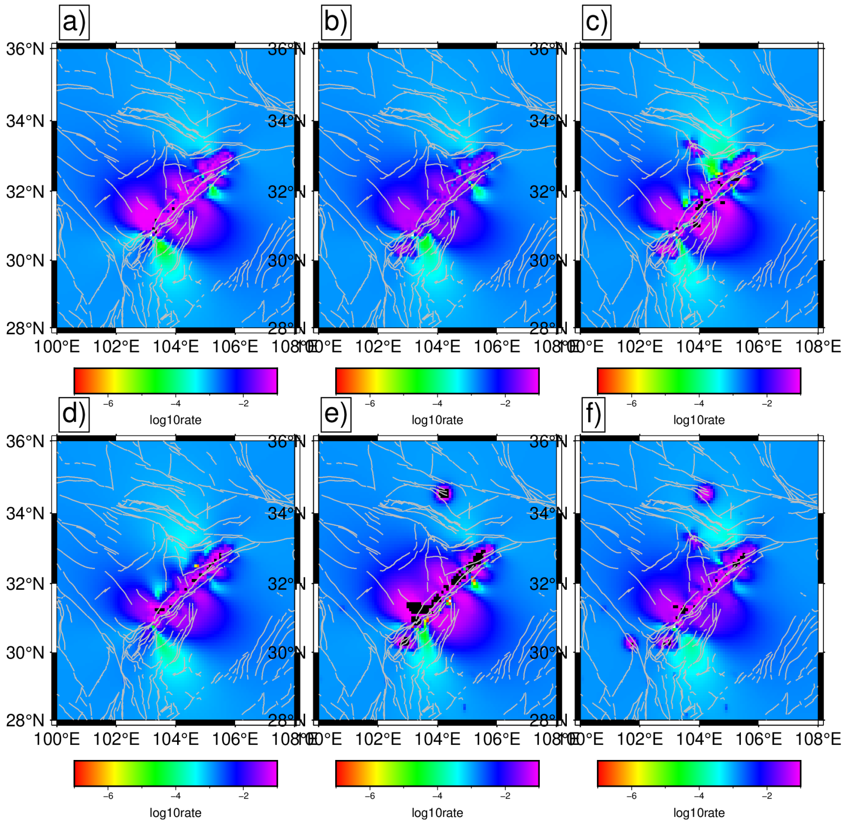

Fig 4. shows the spatial distribution of seismic activity simulated by stress sources of earthquakes with magnitude 7 and above 4.

Fig. 4 Spatial distribution of seismic activity simulated by different stress sources in three main earthquake stages of Wenchuan sequence. a), b) and c) are the simulation results of seismic activity rate of Wenchuan earthquake, Lushan earthquake and Jiuzhaigou using main earthquake stress source. d), e) and f) are the results of earthquake simulation with magnitude 4 or above.

4. Discussion and Conclusion

The temporal and spatial clustering of earthquakes reflects the interaction between earthquakes. In this paper, the Coulomb rate state model is used to study the triggering effect of coseismic Coulomb stress on adjacent faults, focusing on the performance of different model combinations in different stages of earthquake triggering. It is found that the seismic activity considering the secondary triggering process of the earthquake with magnitude 4 is more consistent with the triggering mechanism. In the ETAS model, every earthquake, regardless of its magnitude, participates in self-excitation. In the CRS model here, earthquakes with magnitude above 4 are selected as the stress trigger source. Compared with the results of 7-magnitude main earthquakes, including 6-magnitude main earthquakes as stress sources, the simulation results with moderate earthquake trigger sources perform well in most models, which proves that the trigger of earthquakes not only depends on Coulomb stress caused by coseismic sliding of large earthquakes, but also plays a role in small earthquakes. In the critical state of the fault, small stress changes can change the cementation state of the fault, resulting in stick-slip instability. Aftershocks themselves are another source of post-earthquake stress.

Lushan earthquake and Jiuzhaigou earthquake are similar in magnitude, but different in focal mechanism. The assumed uniform regional stress and background rate do not exist, which may explain the difference between the two earthquakes. The Wenchuan earthquake destroyed the

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surrounding faults, including the Lushan earthquake source area. The broken faults may enlarge the surrounding inhomogeneity and produce more small earthquakes, and finally rupture the longer faults, leading to the Jiuzhaigou earthquake.

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