Loading/Unloading Effect Analysis of Strong Earthquakes in Northern North China

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Abstract: Based on the numerical simulation method and Coulomb stress change, we calculate the stress change of strong earthquakes of Ms≥6.5 in northern North China, and discuss the loading/unloading effect of strong shock on the future event. The result shows regional stress state and seismic risk are affected and controlled by the interaction of fault system, strong seismic activity and inter-seismic tectonic loading.

Keywords-northern North China; Coulomb stress change; loading/unloading effect; simulation

1 Introduction

North China is one of the areas of intense seismic activities in China. There are several seismic activity belts and it is mainly a NW oriented active tectonic seismic belt named Zhangbo in northern North China. It starts from Zhangbei and Shangyi in the west, through Zhangjiakou to the southeast, goes along Huailai, Shunyi, Sanhe, Tianjin and other places, then through Bohai Sea to the Yellow Sea north of Penglai. It is of great scale and complex in structure and it intersects with NE oriented fault belts at multiple points with significant segmental activity properties. The feature of geology, landform and seismic activity of different areas are different, some even vary greatly [1]. It is characterized by high earthquake intensity, high frequency and serious damage. There were strong earthquakes like Bohai Ms7 in 1548, Sanhe-pinggu Ms8.0 in 1679, Huailai Ms6.8 in 1720, Bohai Ms7 in 1888, Bohai Ms7.4 in 1969, Tangshan Ms7.8 in 1976, and ZhangbeiMs6.2 in 1998, et al, along this seismic belt.

The gestation and occurrence of earthquake is the mechanical process of stress and strain energy accumulating, then entering the critical state and eventually being unstable of the pregnant shock body [2,3]. King, et al[4] found that the Landers shock was advanced by raising the Coulomb stress of Landers epicenter by several previous moderate shocks and it, in turn, raised the stress of future Ms6.5 Big Bear shock site. As a method to characterize the fault stress state, the Coulomb rupture stress has been widely used in analysis of strong shocks interactions and regional seismic hazard [5,6,7].

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In order to explore the interaction between strong seismic activities in northern North China, the numerical simulation method is adopted to analyze the loading/unloading effect of strong earthquakes on subsequent events based on the change of Coulomb stress here.

2 Method and model

2.1 Simulation method and research area overview

Numerical simulation is an important method to analyze the interaction and stress evolution between faults. The Zhangbo seismic belt in northern North China is taken as the target research area and the finite element software Ansys of the Institute of Geology of China Earthquake Administration is used to carry out the simulation analysis here. The seismic belt is about 700 km of length, and composed of more than 20 faults with different tendencies and steep inclination [8].The thickness of the crust below it varies greatly, reaching about 10km. It is thicker in the northwest than in the southeast. The thickest area is in Kangbao and Zhangbei with about 40km thickness. The direction of the principle compressive stress field in this region is near the EW direction. The seismic activities and observation results of modern crust deformation show generally active property of normal fault mainly with left-handed strike-slip.

2.2 3D fault model

Based on seismic geology, geophysics, deep medium structure, geodesy and other multidisciplinary research results, a 3D geological model ranging from 113°E -123°E and 36° N-42°N is constructed. On basis of it, a 3D viscoelastic model including nearly 30 different active faults is established (see Figure 1). The thickness of the model is 60km and the medium parameters and the model layers are determined according to the crustal structure and the rheological properties of the deep medium [9](see Table 1), There are has five layers in the model: upper part of upper crust, lower part of upper crust, middle crust, lower crust and upper mantle. The faults are discontinuous contact surfaces following the Coulomb friction criterion. The numbers of nodes and elements of the 3D discrete model are 124561 and 614158, respectively.

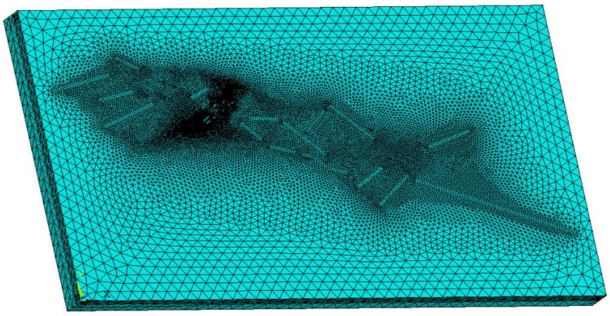

Figure 1. 3D nonlinear finite element model of northern North China

2.3 Coulomb stress change equation

The static Coulomb stress change, ΔCFS, caused by a main-shock with simplifying assumptions to account for pore pressure effects[10,11,12,13] is

$$\Delta CFS = \Delta\tau + \mu'\Delta\sigma_n \qquad (1)$$

In (1), $\Delta\tau$ is the shear stress change on a given fault plane(positive in the direction of fault slip) and $\Delta\sigma_n$ is the fault-normal stress change (positive when unclamped), and μ' is the effective coefficient of friction (which implicitly includes the unknown pore pressure change on the fault). Here μ' is 0.4. Based on the stress tensor obtained from the simulation, we can calculate the Coulomb stress. The Coulomb hypothesis holds that earthquakes are promoted when ΔCFS is positive, and they are inhibited when ΔCFS is negative.

3 Boundary conditions and hypocenter parameters of strong shocks

In numerical simulation, reasonable model boundary constraints conditions are very important to modeling. Here, we determine the internal and external dynamic boundary conditions of the model based on the research results of regional geophysical observations, seismic activity and their source parameters in the research area.

3.1 Boundarty conditons

In the model, the vertical displacement of the bottom is constrained the upper surface is free. The four lateral surfaces are constrained by observation results of modern crust deformation [14].

3.2 Source parameters of earthquakes

Hypocenter parameters of strong shocks are important parameters affecting the results of the Coulomb stress calculation. Many scholars have carried out systematic analysis of the strong seismic parameters in north China based on the multidisciplinary data. Combined with $Ms \geq 6.5$ earthquakes of Zhangbo seismic belt (see Table 2) since the third active period [15], here we simulate the long period evolution process of fault stress considering the effect of co-seismic, after-seismic viscoelastic relaxation and inter-seismic tectonic loading.

4 Results and discussion

According to the calculation results of Coulomb stress change caused by previous $Ms \geq 6.5$ earthquakes on subsequent events, we can obtain the impact of loading/unloading effect of strong earthquakes on subsequent events. Here we calculate not only the co-seismic effects of 15 strong earthquakes, but also the effects of inter-seismic tectonic loading considering the post-seismic viscoelastic relaxation.

4.1 Impact of previous earthquake on subsequent event

Limited to the space, Here only gives the contour map of co-seismic coulomb stress change (Figure 2) on Dongbeiwang-xiaotangshan (abbreviation as D-x) fault, on which the Ms6.5 earthquake of Haidian, Beijing occurred on September 30,1730, caused by the Ms6.8 earthquake of Shacheng, Hebei occurred on Xinbaoan-shacheng fault on July 12,1720, and change considering co-seismic, post-seismic viscoelastic relaxation and the inter-seismic tectonic loading (Figure 3). It shows that Ms6.8 earthquake of Shacheng, Hebei in 1720 has loading effect on Ms6.5 earthquake of Haidian, Beijing in 1730.

Figure 2 shows the coulomb stress change on Dongbeiwang-xiaotangshan (abbreviation as D-x) fault caused by Ms6.8 earthquake of Shacheng, Hebei occurred on Xinbaoan-shacheng fault in 1720. We can know that the coulomb stress change on the fault caused by the co-seismic effect is mostly positive except in the near SW end of the fault.

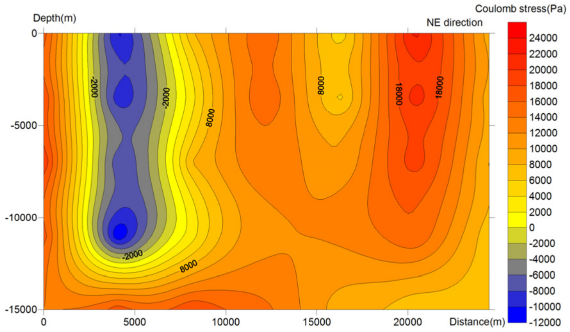

Figure 2. Co-seismic coulomb stress change on D-x fault

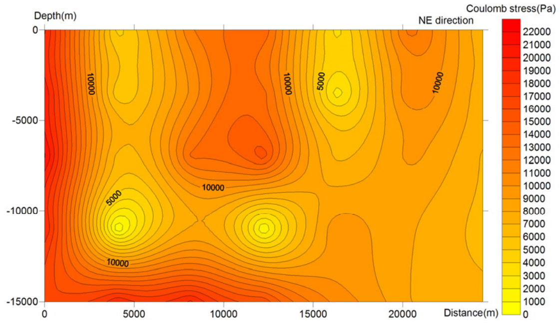

Figure 3. Combined coulomb stress change on D-x fault

Figure 3 shows the combined coulomb stress change on Dongbeiwang-xiaotangshan (abbreviation as D-x) fault accumulated during the period from the time Ms6.8 earthquake of Shacheng, Hebei occurred on Xinbaoan-shacheng fault in 1720 to the time before Ms6.5 earthquake of Haidian, Beijing in 1730.It means that this stress change is the joint effects of co-seismic, post-seismic viscoelastic relaxation and inter-seismic tectonic loading. We can know that the coulomb stress changes throughout the fault surface are positive, indicating loading effect.

4.2 Loading/unloading effect of strong shocks

Using the stress tensor of fault surface caused by each historical strong earthquake simulated in this study, the coulomb stress change of fault surface is calculated by (1). Then the promoting or delay effect of strong events on its subsequent shock is judged by analyzing the contour map of coulomb stress changes caused by every historical strong earthquakes, that is the loading/unloading effects of Ms≥6.5 earthquakes (15 in total) on its subsequent event. The results are summarized in Table 3.

Table 1 Medium parameters of Finite element model

Layers	Depth (km)	Thickness (km)	Density (kg/m3)	Young's modulus(Pa)	Poisson ratio	Viscosity coefficient(Pa·s)
Upper layer of Upper crust	7	7	2700	7.71e10	0.25	1.0e22
Lower layer of upper crust	15	8	2700	7.71e10	0.25	1.0e22
Middle crust	22	7	2800	9.41e10	0.25	1.0e21
Lower crust	39	17	3000	1.21e11	0.25	7.1e18
Upper mantle	60	21	3300	1.85e11	0.33	2.1e19

Table 2 Source parameters of Ms≥6.5 earthquakes (regardless of aftershocks) in simulation

Date	Lon. (°)	Lat. (°)	Magnitude	Epicenter	Strike (°)	Dip (°)	Rake (°)	Length (km)	Interface (km)
1484.2.7	116.08	40.50	6.8	Juyongguan, Beijing	50	70	175.6	40.8	5-15
1548.9.22	120.80	38.20	7.0	Bohai	290	85	-0.1	118.7	8-20
1597.10.6	120.00	38.50	7.0	Bohai	205	85	-170.9	48.5	10-25
1624.4.17	118.80	39.50	6.5	Luanxi, Hebei	135	80	3.2	34.3	5-15
1628.10.7	114.18	40.60	6.5	Huaian, Hebei	80	75	-33.2	34.3	5-15
1665.4.16	116.58	39.90	6.5	Chaoyang, Beijing	305	70	32.7	34.3	5-15
1679.9.2	117.00	40.00	8.0	Sanhe-pinggu	45	85	-175.7	148.6	8-25
1720.7.12	115.50	40.40	6.8	Shacheng, Hebei	110	70	-4.4	63.2	5-20
1730.9.30	116.18	40.00	6.5	Haidian, Beijing	235	69	-174.6	47.6	5-15
1888.6.13	119.00	38.50	7.5	Bohai	50	85	171.9	68.6	10-25
1922.9.29	120.50	39.20	6.5	Bohai	50	85	-177.6	34.3	10-25
1969.7.18	119.40	38.20	7.4	Bohai	45	80	172.7	60.0	15-30
1976.7.28	118.00	39.40	7.8	Tangshan, Hebei	210	80	180	80	5-25
1976.7.28	118.50	39.70	7.1	Luanxian, Hebei	25	60	175.5	46	5-20
1976.11.15	117.70	39.40	6.9	Ninghe, Tianjin	330	60	76.9	21	8-25

Table 3 The loading/unloading effect of previous strong earthquakes (Ms≥6.5) on subsequent event

Number	**Date**	**Event**	**Effect on subsequent event**		
			Loading	**Unloading**	**negligible**
1	1484.2.7	Juyongguan,Beijing M6.8			√
2	1548.9.22	Bohai M7.0	√		
3	1597.10.6	Bohai M7.0	√		
4	1624.4.17	Luanxian,Hebei M6.5	√		
5	1628.10.7	Huai'an,Hebei M6.5		√	
6	1665.4.16	Chaoyang,Beijing M6.5	√		
7	1679.9.2	Sanhe-pinggu M8.0	√		
8	1720.7.12	Shacheng,Hebei M6.8	√		
9	1730.9.30	Haidian,Beijing M6.5			√
10	1888.6.13	Bohai M7.5		√	
11	1922.9.29	Bohai M6.5	√		
12	1969.7.18	Bohai M7.4		√	
13	1976.7.28	Tangshan,Hebei M7.8	√		
14	1976.7.28	Luanxian,Hebei M7.1	√		
15	1976.11.5	Ninghe,Tianjin M6.9	-	-	-

We simulate the stress evolution process with time since the third active period of Zhangbo seismic belt in northern of North China, starting from the Ms6.8 earthquake of Juyongguan, Beijing on February 7, 1484 and obtain the coulomb stress changes caused by previous strong earthquakes on subsequent seismic events. It indicates loading effect when the Coulomb stress change is positive, otherwise unloading effect when negative. It can be seen from Table 1, except for the 15th strong earthquake (Ms6.9 earthquake of Ninghe, Tianjin on November 5, 1976), the other 14 strong earthquakes show the stress impact on seismogenic fault of subsequent events, including 9 events of loading effect by the previous strong earthquake, accounting for 64.3%, 3 events of unloading effects, accounting for 21.4%, and 2 events of negligible effects, accounting for 14.3%.

The Coulomb stress change obtained by simulation here is stress change value on fault surface obtained by deducting the regional background stress field, which can provide reference for understanding the acceleration or deceleration of the fault stress accumulation process. If we want to judge the regional seismic risk, a comprehensive analysis should also be combined with the background tectonic stress state.

5 Conclusions

Based on the 3D nonlinear fault model of northern North China, which takes Zhangbo seismic belt as main target research area, we simulate the stress evolution process of Ms≥6.5 earthquakes in the seismic belt since the third seismic active period. And we obtain the Coulomb stress change caused by co-seismic, post-seismic viscoelastic relaxation and inter-seismic tectonic loading. So we can get the loading/unloading effect of previous earthquakes on subsequent event and find that the stress impact of strong earthquake on region and fault surface is an important factor in the future seismic activity trend, which could provide us some reference for the analysis of seismic risk and seismic trend in the future.

At the same time, it should be noted that the analysis of regional seismic risk needs to consider the joint effect of strong seismic activity, post-earthquake viscoelastic relaxation and inter-seismic tectonic loading, and also to combine the state of the regional background tectonic stress field. Background stress field is difficult to obtain at present. In numerical simulation, it is often approximated as background tectonic stress field with a long historical period (such as 100,000 years, even millions of years, etc.) tectonic loading, as well as in this study. It will be the difficulty we need to face in our future research work. In addition, the different mechanical properties of faults in the numerical simulation will have some influence on the results, and the closer to the actual dynamic parameters and boundary conditions will improve the reliability of the simulation results. Of course, the heat, fluid movement and pore pressure of underground media are also factors affecting seismic activities. It can be seen that seismic prediction is a comprehensive, complex scientific problem and still has long way to go, which requires us to explore and advance step by step.

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