Numerical simulation of fault slip and its dynamic source in the main fault zone of Taiyuan Basin

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Abstract: There are three earthquakes which magnitude over 6 have been recorded in Taiyuan Basin located Shanxi seismic belt which has high seismicity. The tectonic activity of Taiyuan basin is mainly controlled by the Jiaocheng fault and Taigu fault near Taiyuan city, So the potential seismic risk is concerned. The previous research results show that the fault slip rate is directly related to the magnitude of the earthquake, and the larger fault slip rate indicates higher seismic risk. In this research, geological and geophysical data are conclude to construct a finite element model of Taiyuan Basin to simulate the fault slip of Jiaocheng fault and Taigu fault after long term tectonic evolution, the stress field is simulated to compare with the focal mechanism of small earthquakes to analyze the dynamic source of Taiyuan basin tectonic activity. The results show that the extrusion of the Ordos block from west to East is the main source of tectonic activities in the Taiyuan basin. The extrusion of Ordos block is the main cause of stress in this area shows tensile property in the north-west direction and compressive property in the north-east direction in Taiyuan Basin. In addition, the slip state simulation results show that the Jiaocheng fault slip rate is higher than that of the Taigu fault, the slip rate of northern Jiaocheng fault is higher than that of southern Jiaocheng fault.

1 Introduction
The Shanxi seismic belt is on the border of Ordos and northern china block, The western side is pushing by Ordos block and the eastern side is blocked by northern china block, because of the severe tectonic activity, the earthquake is frequent in this area. Taiyuan basin is located in the middle of Shanxi seismic belt, there are three earthquakes magnitude over 6 recorded in the basin since 231 A.D. Compared with the whole Shanxi seismic belt, there are three earthquakes magnitude over 6 recorded in the basin since 231 A.D.

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risk in the basin through the simulation result of fault slip. To achieve the above objectives, we select a code named FAULTS[8] to do the research. FAULTS code incorporate friction mechanism of faults, faults occurrence, gravity, heat flow and so on to simulate the stress field, strain field, surface velocity and fault slip rate.

2 Method and Numerical Model

2.1 The governing equation

FAULTS code complies with dislocation-creep constitutive relationship when temperature is higher in lower crust. The rheology formula used in FAULTS to determine the lithosphere rheology strength is

\[(\sigma_i - \sigma_j) = 2A(e_i - e_j)(2\left(-e_1 e_2 e_3 e_1\right)^{1/2})\exp\left(B + Cz\right)\]

\(\sigma_i\) and \(e_i\) represent principle stress(tensile stress is positive) and strain rate, \(i, j = 1, 2, 3\); \(T\) and \(Z\) represent absolute temperature and depth of crust; \(A, B, C, n\) are the material parameters. When considering the fault strength of low temperature in the upper crust, Mohr-Coulomb-Navier frictional sliding law must be obeyed:

\[|\sigma_s| = f(-\sigma_n - \beta P_p) + \sigma_c\]

Where \(\sigma_s\) and \(\sigma_n\) represent the shear stress on the faults plane, and the stress which is perpendicular to faults plane; \(f, \beta, P_p, \sigma_c\) represents effective friction coefficient, Biot coefficient, pore pressure, Cohesion separately. The variation of fault strength with the depth shows as Figure. 1.

2.2 Finite element model and fault parameters

The purpose of this study is to simulate the fault slip state of main faults in Taiyuan basin, Therefore, only Jiaocheng, Taigu, Huoshan and Jiacun fault are selected, the fault surface trajectory is digitalize from China Active Faults map[9]. The model region is chosen much bigger than the region focused by our research to avoid boundary effect. The model is from 111° to 113°E, 36° to 38°N, and in the vertical direction, the region is from surface to Moho. The research region and faults geometry is shown in Figure. 2. The data of faults occurrence is get from Zhou (personal communication).

![Figure 1](image1.png)

**Figure. 1** the constitutive relationship of finite element model with the depth change

![Figure 2](image2.png)

**Figure. 2** the faults geometry of research region
2.3 Model parameters
The main parameters to determine the strength of rock and fault element is the friction coefficient and creep parameters, the friction coefficient determine the strength of upper crust, the creep parameters determine the strength of lower crust, the parameters setting is shown as Table 2. the average density of the crust is set as 2700 (kg/m$^3$), and the average density of the upper mantle is set to be about 3300 (kg/m$^3$)[10]. The elevation data is given by ETOPO2′×2′.

| Model     | Fault Coefficient | Creep Parameters |
|-----------|-------------------|------------------|
| Model 1   | 0.3               | 4E4              |
| Model 2   | 0.5               | 4E4              |
| Model 3   | 0.7               | 4E4              |
| Model 4   | 0.9               | 4E4              |
| Model 5   | 0.9               | 2E5              |

2.4 The boundary condition
The FAULTS finite element code uses displacement boundary, so we take the GPS observations (compared to the Eurasia plate)[11] as the boundary conditions of the model. If there is no GPS data at a point of boundaries, the value of this point is given by linear interpolation using neighboring GPS data.

Considering the dynamic source of this region, the boundary condition of the model set as two possible cases, one is the four boundaries of model were applied to the displacement boundary, that is to consider the research area both thrust by Ordos block, but also suffer from the tension of the Northern China block; another is to consider only the thrust from Ordos block, that is to apply the boundary condition in the west and south of the model, the other two boundaries is set as free condition in the horizontal direction. Under the above two kinds of boundary conditions, the simulated stress field and the actual stress field are compared to determine the more reasonable boundary conditions, then we can analyze the dynamic source of this region.
3 The main dynamic source of research region

The model 2 parameters is selected to simulate the stress field, fault slip rate and fault dislocation form under the above two boundary condition. The simulation result is given as Figure 3. The first column is the result under boundary condition a, the second column is the result under the boundary condition b. From the simulation result we can find that the dislocation form is thrust in all the main faults in this region, which is not consistent with the tensile properties of the Taiyuan basin and Linfen basin[12], also is not consistent with the other researcher’s(personal communication of Zhou S Y) simulation result of fault dislocation form under boundary condition a. Zhou’s simulation shows all the faults are normal fault, the fault slip rate of Jiaocheng fault is higher than that of Taigu fault, the fault slip rate of northern Jiaocheng fault is higher that of southern segment. These features are simulated under the boundary condition b by us, meanwhile the simulation results show that the maximum principal stress is compressive stress the direction is NE-SW, the second principal stress is tensile stress the direction is NNW-SSE, which is consistent with the result obtained by focal mechanism[13]. This stress field can explain why the focal mechanism of earthquakes which magnitude over M L 2.5 are mainly strike slip and normal very well in this region. If we use the boundary condition a, the stress field is totally different the northern China stress field[14]. From the analysis of the above results, we believe that the main dynamic source of research area is the extrusion from Ordos block, which is consistent with the results of Xu’s result[15] from the analysis of the geological and seismic data. In the following study, the main dynamic source is the extrusion from Ordos block.
The strength of fault depends on the friction coefficient and creep parameters in FAULTS code. When the coefficient of friction and creep parameters are large enough, the fault is locked, and with the decrease of creep strength and friction strength, the fault begins to slip. In this study, we adopt the method of reducing the fault strength to simulate the fault slip state. First, the fault strength is set to be extremely high(Model 5), the most faults in research area are locked, but Taigu fault slip very slowly, it is in a state of creep, then we reduce the creep strength without changing the friction coefficient(Model 4), the simulation result shows the Jiaocheng fault begin to slip, the dislocation form is normal, then we reduce friction coefficient to 0.7 without changing the creep strength(Model 3), the Jiaocheng fault slip more, but Taigu fault still slip very slowly. With the decreasing of friction coefficient(Model 2,1), the Jiaocheng fault slip more tense, however the Taigu fault don’t change its slip state. From the result we also can found the slip rate of northern Jiaocheng fault is higher than that of southern Jiaocheng fault. This result illustrate that the Jiaocheng fault is easy to occur earthquake than Taigu fault, especially the northern Jiaocheng fault is much easier under this dynamic and geological tectonic background. This conclusion is consistent with the small earthquake location result(Fang L H’s personal communication), is also consistent with the Song’s conclusion that the seismicity of northern Jiaocheng fault is the highest[16]. A part of small earthquakes located between Jiaocheng and Taigu fault, probably because the Jiaocheng fault is a lower detachment fault.
In summary, we believe that the Jiaocheng fault more easily occur earthquakes because of the sudden decrease of fault strength than Taigu fault in our research area.

![Figure. 5. The simulation result of fault slip. The pink means it is normal fault, the width of pink means the size of slip rate.](image)

5 Conclusion

In this research, geological and geophysical data are conclude to construct a finite element model of Taiyuan Basin to simulate the fault slip state of Jiaocheng fault and Taigu fault after long term tectonic evolution, the stress field is simulated to analyze the dynamic source of Taiyuan basin tectonic activity. The results show that the extrusion of the Ordos block from west to East is the main source of tectonic activities in the Taiyuan basin. The extrusion of Ordos block is the main reason why stress in this area shows tensile property in the north-west direction and compressive property in the north-east direction in Taiyuan Basin, this may be the reason of Jiaocheng fault and Taigu earthquake focal mechanism is mainly strike slip fault and normal fault. In addition, the slip state simulation results show that the Jiaocheng fault slip rate is higher than that of the Taigu fault, the slip rate of northern Jiaocheng fault is higher than that of southern Jiaocheng fault, that means the higher seismicity in northern Jiaocheng fault which is consistent with the earthquake location result. Moreover, the Jiaocheng fault may generate great earthquake because of its high fault slip rate.
Figure 6. The distribution of earthquakes in research area.

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