Effect of Poisson's ratio on stress state in the Wenchuan $M_S8.0$ earthquake fault*

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Abstract The Wenchuan $M_S8.0$ earthquake occurred on the Longmenshan fault which inclines at a dip angle exceeding 60 degrees. Since most thrust earthquakes occur on faults with dip angles of about 30 degrees, it is enigmatic why the Wenchuan earthquake occurred on such a steep fault. In this study we use a simple finite element model to investigate how the stress state in the fault changes with the variation of Poisson's ratio. The results show that, with the Poisson's ratio in the fault increasing, the magnitudes of the principal stresses increase and the maximum shear stress decrease, and, especially, the angle between the maximum principal stress and the fault plane decreases, which will enhance the driving force to overcome the frictional resistance on the fault. The increase of Poisson's ratio in the fault may be an important factor to affect the occurrence of the fault earthquakes with large angles between maximum principal stress and fault plane.

Key words: Wenchuan earthquake; steep fault; Poisson's ratio; stress state; stress rotation; finite element

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1 Introduction

Most thrust earthquakes occur on faults with dip angles of about 30 degrees. The seismogenic fault of the Wenchuan $M_S8.0$ earthquake, i.e., the Longmenshan fault, however, dips at an angle of 70°–80° adjoining the surface and turns to 30°–60° near the focus (15–19 km) (Zhang et al, 2009). Post-earthquake geological survey yields a dip angle of 62° (Fu et al, 2008). If the tectonic maximum principal stress σ_1 is horizontal in the Wenchuan area, the resulting normal stress on the fault must be high, implying a relatively high frictional strength. It is thus enigmatic why the Wenchuan earthquake occurred on such a steep fault.

A high Poisson's ratio was probed by seismic tomography in some large earthquakes (Zhao et al, 1996; Salah and Zhao, 2003), and it was also found in the focus zone of the 2008 Wenchuan earthquake (Wang et al, 2009). Can the high Poisson's ratio affect the stress state in the seismogenic fault? In a recent study, Faulkner et al (2006) showed that when the Poisson's ratio in a fault

zone increases, the principal stress directions show significant variations, while the differential stress decreases and the mean stress increases. In the present study, we analyze, using a simple 2D finite element model (FEM) with a thrust fault zone, how the stress state in the fault zone evolves with the variation of Poisson's ratio and how the Poisson's ratio variation affects the earthquake occurrence. We show that an increased Poisson's ratio in the fault zone causes the shear rupture plane to rotate close to the fault plane, allowing the occurrence of earthquakes on thrust faults with a steep dip angle.

High angle intersection between the maximum principal stress direction and the fault trace may also occur around the world. One well known example is the strike-slip San Andreas fault (SAF) in California, where the angle of intersection is 68°–85° in the region near the fault (Zoback et al, 1987; Scholz, 2000; Townend and Zoback, 2004). Thus the results of the present study may have global applications.

2 FEM model to study seismogenic stress field of the Wenchuan earthquake

It is commonly recognized that the fault of a large earthquake is a zone of fractured rock and fault gouge,

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rather than a geometric surface without thickness. For instance, the SAF is 100–200 m in southern California (Li et al, 1994; Li, 2003) and more than 1 km thick in central California (Wang, 1984; Wang et al, 1986). In this paper we use the term “fault” to mean a “fault belt” or a “fault zone” with a ‘core’ located at the center of the fault zone and a damage zone around the core (Chester et al, 1993; Faulkner et al, 2006).

For simplify, we use a two-dimensional plane strain model perpendicular to the strike of the Longmenshan fault trace (Figure 1). We suppose that the Longmenshan fault zone (the solid line AB in Figure 1) is 1 km thick and the fault-zone material is elastic. The fault reaches a depth of 15 km, as indicated by the aftershocks, with a dip angle of 62° .

For boundary conditions, we assume that the upper surface is free and the bottom of the model is supported on rollers (Figure 1). On the lateral boundaries, horizontal displacements are applied symmetrically on both boundaries toward the fault (Figure 1a), with a magnitude that increases linearly from 20 m on the model surface to 250 m at the depth of 35 km and is constant from 30 km to 50 km. The magnitude of the boundary displacement is chosen so as to provide a stress field in the model with a maximum principal stress in the horizontal direction.

The material properties in the model are estimated

on the basis of a one-dimensional P-wave velocity model for the Longmenshan area (Lei et al, 2009). Using this velocity model as a reference and the lateral variations of velocity from tomographic studies (Lei et al, 2009; Liu et al, 2009), we set the P-wave velocity at the hanging wall in Qinghai-Xizang (Tibet) plateau (the left area of line AC in Figure 1) to be higher by 5% between 0 and 20 km and lower by 5% between 20 km and 50 km in depth, and we did the same for the footwall in Sichuan basin (the right area of line AC in Figure 1). Finally, we assume that the P-wave velocity in the fault is lower than the reference velocity by 10% (Wang, 1984).

In the model, density ρ is taken from the preliminary reference Earth model (PREM), which is, in kg/m^3 ,

$$\rho = \begin{cases} 2650 & 0 \leq y < 35 \text{ km} \\ 2900 & 35 \text{ km} \leq y \leq 50 \text{ km} \end{cases} \quad (2)$$

For the Poisson's ratio, ν , we assume a value of 0.25 outside the fault zone and a range of values from 0.25 to 0.48 within the fault zone.

Given the above boundary conditions and material properties, we calculate the stress state in the fault zone using a finite element method. The model is divided into 27 000 quadrilateral elements and 27 331 nodes (Figure 1b). The meshes in the fault and within a width of 5 km from the fault are sufficiently dense to assure computational precision.

Figure 1 Numerical model and boundary conditions. (a) Model geometry and boundary conditions. The horizontal boundary displacements applied on both sides increase linearly from 20 m on the model surface to 250 m at the depth of 35 km and are constant from 30 km to 50 km; (b) Finite element grid used in the computation.

3 Numerical results

For convenience, we choose a profile AB (Figure 2) in the fault to represent the direction of the fault and

define an angle ψ as the angle from the fault plane to the direction of σ_1 . $\psi > 0$ when it is clockwise. The smaller the value of ψ is, the closer the direction of σ_1 to the fault plane.

Figure 2 Definition of the angle ψ with respect to the mid-plane of the fault zone.

The following figures show the numerical results of the analysis on the stress in the fault zone when the Poisson's ratio in the fault zone increases from 0.25 to 0.48. Figure 3 shows that the magnitudes of the maxi-

mum and minimum principal stresses, σ_1 and σ_3 , change with the variation of Poisson's ratio at different depths. Figure 3a shows that σ_1 and σ_3 increase and the difference between σ_1 and σ_3 decreases correspondingly with the increase of Poisson's ratio ν . The variations of the minimum principal stress are larger than those of the maximum principal stress. Figure 4 shows that ψ changes with Poisson's ratio. The curve $\psi_{\nu=0.25}$ shows how the angle ψ changes with depth, given $\nu=0.25$. The magnitude of ψ decreases with increasing Poisson's ratio, which means that the direction of the maximum principal stress rotates toward the fault plane. This rotation is also expressed in the same figure by the curve $(\psi_{\nu=0.48}-\psi_{\nu=0.25})$. In the figure, negative value denotes the reduction of the angle, and the amount of rotation reaches a maximum of 21 degrees at a depth of 12 km and then decreases sharply with depth.

Figure 3 Changes of σ_1 and σ_3 at different depths with different Poisson's ratio ν .

Since the principal stresses and their rotation are the focus of this study, we express the Coulomb failure criterion (CFC) in the following equivalent form:

$$\frac{\sigma_1 - \sigma_3}{2} = \frac{S_0 + \mu \sigma_3}{(1 - \mu \tan \psi) \sin 2\psi}, \quad (3)$$

where the expression on the left hand side is the critical maximum shear stress, S_0 is the cohesion of the fault and μ the equivalent (or apparent) frictional coefficient.

When the maximum shear stress in a fault is less than the critical value, the fault is stable; when it exceeds the critical value, instability occurs that may lead to an earthquake. As Figure 3 shows, the calculated values of both σ_1 and σ_3 depend on the depth and on the Poisson's ratio. For a given pair of σ_1 and σ_3 , the value of μ is evaluated from the Coulomb criteria for $S_0=5$ MPa. Given these parameters and the above relationship, we plot in Figure 5 the critical maximum shear stress as a

Figure 4 Variation of angle ψ with different Poisson's ratios.

Figure 5 Critical maximum shear stresses $(\sigma_1 - \sigma_3)/2$ predicted by equation (3) as functions of ψ , and the maximum shear stresses in the fault at a depth of 13 km calculated from the present model, with an assumed Poisson's ratio of 0.25, 0.35, 0.45 and 0.48, respectively, in the fault zone.

4 Discussion and conclusions

Increases in the Poisson's ratio may be a common phenomenon in seismogenic processes, as suggested by rock mechanical experiments (Faulkner et al, 2006; Barton, 2007) and inclusion of fluid in the focus zone (Zhao et al, 1996, 2000; Salah and Zhao, 2003; Wang et al, 2009). An estimation from field observation, laboratory experiments and numerical modeling showed that Poisson's ratio in the fault core would increase and exceed 0.45 (Faulkner, 2006). A study on the Wenchuan earthquake by seismic tomography with 200 000 local travel time data shows that the focus zone of the Longmenshan earthquake fault is in the region with high Poisson's ratio (Wang et al, 2009).

function of ψ at Poisson's ratios of 0.25, 0.35, 0.45 and 0.48 at a depth of 13 km, i.e., the focal depth of the Wenchuan earthquake (Lu et al, 2008).

The maximum shear stress in the fault and the corresponding value of ψ at a depth of 13 km may be estimated from Figures 3 and 4, respectively, for different Poisson's ratios; these are plotted in Figure 5 in solid symbols. It is clear that at Poisson's ratios of 0.25 and 0.35, the maximum shear stresses in the fault fall below the corresponding critical values required for fault rupture. On the other hand, at Poisson's ratios of 0.45 and 0.48, the maximum shear stresses in the fault are equal to, or even fall below, the corresponding critical values.

In the present study we showed that increases in the Poisson's ratio may reduce the angle between the maximum principal stress and the fault. For a given Poisson's ratio, the principal stress direction changes much more at depths than that near the surface. We also find that an increased Poisson's ratio in the fault zone causes the shear rupture plane to rotate closer toward the fault plane. The rotation amount of the maximum principal stress direction reaches a maximum of 21 degrees at a depth of 12 km when Poisson's ratio ν increases from 0.25 to 0.48, which makes the Longmenshan fault with steep dip angle slip more easily than other Poisson's ratios at the same depth. The depth is close to the focus.

The present study focuses on the stress field and provides an explanation for the occurrence of earthquakes on thrust faults with steep angles. The conceptual model adopted here may be overly simplified. In reality, the dip angle of a fault may change with depth, which will change the stress state in the fault zone. The Poisson's ratio may also be heterogeneous in the fault. These factors will affect the stress state in the Longmenshan fault, both in its magnitude and direction. Further studies to consider these factors are needed.

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