Dynamic Deformation And Fault Locking of The Xianshuihe Fault Zone, Southeastern Tibetan Plateau: Implications For Seismic Hazards

Layue Li (✉ lilayue@126.com)

China Earthquake Administration <https://orcid.org/0000-0001-9117-2761>

Yanqiang Wu

China Earthquake Administration

Yujiang Li

National Institute of Natural Hazards <https://orcid.org/0000-0003-0246-9737>

Wei Zhan

China Earthquake Administration

Xinzhong Liu

China Earthquake Administration

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Abstract

The Xianshuihe Fault Zone is one of the most historically seismically active regions in mainland China. However, the seismicity along this fault zone has been quiescent for the past 40 years, since the Daofu $M_{6.9}$ earthquake in 1981. Understanding its current deformation patterns and fault coupling characteristics is of great significance to estimate the potential risk of strong earthquakes. In this study, we analyzed the dynamic deformation and fault coupling characteristics along the Xianshuihe Fault Zone using Global Positioning System (GPS) data for 1999–2007 and 2016–2020. The results show that the deformation pattern of the Xianshuihe fault zone underwent a dynamic adjustment after the Wenchuan and Lushan earthquakes, i.e., the maximum shear strain accumulation rates of the Luhuo and Daofu sections significantly decreased from $6.0 \times 10^{-8}/a$ to $3.2 \times 10^{-8}/a$, while that of the southeastern segment (i.e., Kangding and Moxi sections) increased from $4.5 \times 10^{-8}/a$ to $6.2 \times 10^{-8}/a$. Additionally, the slip rate and deformation width of the Xianshuihe Fault Zone also changed during these two periods. Combined with the near-field cross-fault observation data, we suggest that the surrounding strong earthquakes 2008 Wenchuan $M_w 7.9$ and 2013 Lushan $M_w 6.6$ had evident differential impacts on the deformation pattern of the Xianshuihe Fault Zone. The fault-coupling inversion results show that the locking degree of the Xianshuihe Fault Zone continued to increase after the $M_w 7.9$ Wenchuan and $M_w 6.6$ Lushan earthquakes, especially the Qianning and Moxi sections increased significantly, with an average coupling coefficient of greater than 0.9 and left-lateral slip-rate deficits of ~ 5 mm/a and ~ 8 mm/a, respectively. In contrast, the locking degree of the Kangding section decreased with almost no slip-rate deficit, which may be due to the partial energy release caused by the $M_w 5.9$ and $M_w 5.6$ Kangding earthquakes in 2014. The analysis of the recent rupture history and strain accumulation characteristics of the Xianshuihe Fault Zone indicates that both the Qianning and Moxi sections have a high seismic potential for the next strong earthquake in the Xianshuihe Fault Zone.

Introduction

The Xianshuihe Fault Zone, located in the southeastern margin of the Tibetan Plateau, is a block boundary fault that plays a significant role in accommodating the Late Cenozoic crustal deformation of the eastern Tibetan Plateau (Wang et al., 1998; Tapponnier et al., 1982; Avouac and Tapponnier, 1993). This fault is characterized by a high left-lateral strike-slip rate and frequent seismic activity. Neotectonic and geodetic studies have estimated that the left-lateral slip on the northwestern and southeastern segments of the Xianshuihe Fault are approximately 15 ± 5 mm/a and 5–9 mm/a (Allen et al., 1991; Gan et al., 2007; Wang et al., 2009; Wang and Shen, 2020; Ji et al., 2020). In the past ~ 300 years, at least eight $M \geq 7.0$ earthquakes and fifteen $M \geq 6.5$ earthquakes initiated in the Xianshuihe Fault Zone (Wen et al., 2008; Yi et al., 2015). However, the strong seismic activity on the Xianshuihe Fault Zone has been relatively quiescent for ~ 40 years, with only two moderate earthquakes, the $M_w 5.9$ and $M_w 5.6$ Kangding earthquakes in 2014. In contrast, a series of strong earthquakes have successively occurred along the other boundary faults around the Bayan Har Block, including the $M_w 7.8$ Kunlun earthquake in 2001, the $M_w 7.9$ Wenchuan earthquake in 2008, and the $M_w 6.9$ Yushu earthquake in 2010 (Deng et al., 2015).

Large earthquakes can modulate the crustal deformation, stress field, and strain accumulation of the surrounding faults (King et al., 1994; Stein, 2003; Nalbant and McCloskey, 2011; Wu et al., 2018). Therefore, the potential seismic hazard posed by the Xianshuihe Fault deserves additional attention.

The strain rate accumulation, fault coupling, and slip-rate deficit provide insights into the seismic hazard assessment on faults (Miura et al., 2002; McCaffrey et al., 2002; Ader et al., 2012; Riguzzi et al., 2012; Jiang et al., 2015; Dogru et al., 2018). Based on joint inversions of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data, Jiang et al. (2015) inverted the distribution of the interseismic fault locking of the Xianshuihe–Zemuhe Fault system and found that a potential asperity exists in the Qianning–Kangding section. Using GPS data from 1999 to 2017, Guo et al. (2018) inverted the slip rate and the locking degree of the Xianshuihe Fault Zone based on a screw dislocation model (Weertman et al., 1966; Wang et al., 2009) and suggested that the Daofu–Kangding section is at high risk for M_w 6.6 or greater earthquakes in the future. Using GPS data from 2004 to 2017, Li et al. (2020) also inverted the slip deficit rate and locking degree of the Xianshuihe Fault Zone based on a two-dimensional elastic dislocation model (Savage et al., 1999; Segall, 2010). Their results revealed that the Daofu–Qianning section is experiencing creep at the surface, and it will not be able to generate earthquakes with magnitudes of larger than 7.0 in the near future. Moreover, they determined that the Selaha Fault is most likely to generate a $M_w > 7$ earthquake. Based on 2014–2019 InSAR images, Qiao et al. (2021) estimated the deformation field and determined the slip distribution of the Xianshuihe Fault Zone. They concluded that the Qianning section is capable of generating a M_w 6.6 earthquake. Although these studies agree that the Xianshuihe Fault Zone presents a high seismic hazard, the potential location of the strong earthquakes in the Xianshuihe Fault Zone remains controversial.

The dynamic changes in the crustal movement obtained via geodetic observations not only respond to the rupture process of great earthquakes but also reflect the seismogenic processes of strong earthquakes and the adjustment process after an earthquake, which is an essential information for determining the subsequent seismic potentials of large earthquakes (Jiang et al., 2009; Zou et al., 2015; Wu et al., 2018; Zhao et al., 2020). In this study, we focused on the dynamic deformation characteristics of the Xianshuihe Fault Zone using two periods of GPS observations and estimated the potential seismic hazards it poses. First, we analyzed the characteristics of the historical seismic activity along the Xianshuihe Fault Zone, and then, we analyzed the dynamic deformation characteristics by calculating the strain rate fields and GPS velocity profiles. Finally, based on the negative dislocation model, we inverted the fault coupling and slip-rate deficit distribution to provide a detailed estimation of the potential seismic hazards posed by the Xianshuihe Fault Zone.

Tectonic Setting And Seismicity

2.1 Tectonic setting

The Xianshuihe Fault Zone is a highly active left-lateral strike-slip boundary fault between the Bayan Har Block and the Sichuan-Yunnan Block within the eastern Tibetan Plateau (Zhang et al., 2003). The

Xianshuihe Fault is approximately 400 km long, strikes 40°N–50°W, and has a steep dip angle. It extends from Donggu, Ganzi County in the northwest through Luhuo County, Daofu County, and Kangding County to Shimian County in the south (Qian et al., 1988; Wen et al., 1989; Xu et al., 2003). The Xianshuihe Fault Zone is divided into northwestern and southeastern segments by a geometric discontinuity near the Qianning Basin (Qian et al., 1988). The northwestern segment has a simple fault geometry and consists of the Luhuo, Daofu, and Qianning sections, whereas the structure of the southeastern segment is relatively complicated (Bai et al., 2018). The Kangding section, which extends from the Qianning Basin to Kangding County, consists of three nearly parallel secondary faults, the Yala River, Selaha, and Zheduotang branches. The Moxi section extends from south of Kangding to Shimian, and the surface trace of this fault is distinct (Fig. 1). The detailed geometry of each fault section is presented in Table 1.

Table 1
Segmentation and geometric parameters of the Xianshuihe Fault Zone

Number	Fault section	Strike	Dip
S1	Luhuo	N45°W	NE80°
S2	Daofu	N45°W	NE80°
S3	Qianning	N40°W	NE80°
S4	Kangding	N30°W	NE70°
S5	Moxi	N20°W	NE70°

2.2 Historic seismic activity

The Xianshuihe Fault Zone has experienced numerous historic strong earthquakes. Here, we compiled a catalog of the $M \geq 6.0$ earthquakes during 1700–2020 from two sources, including records of historical earthquakes in China and data from the China National Seismic Network. Earthquake rupture data from Wen et al. (2008) were also collected. The magnitude–time frequency diagram and spatiotemporal distribution of the strong earthquake ($M \geq 6.0$) ruptures in the Xianshuihe Fault Zone are shown in Fig. 2. We identified two seismically active periods, 1700–1816 and 1893–present (Fig. 2a). During 1700–1816, at least nine $M \geq 6.0$ earthquakes occurred in the Xianshuihe Fault Zone, including three $M \geq 7.0$ earthquakes, which led to the rupture of most of the sections of the Xianshuihe Fault Zone (Fig. 2b). During the second active period, i.e., since 1893, seven $M \geq 6.5$ earthquakes occurred in the Xianshuihe Fault Zone, including five $M \geq 7.0$ earthquakes. However, most of these earthquakes occurred in the northwestern segment. Only the $M 7.5$ Zheduotang earthquake in 1955 occurred in the Kangding section, and the seismicity in the southeastern segment was sparse. Although the $M_w 5.9$ and $M_w 5.6$ Kangding earthquakes occurred in 2014, their rupture scales were small, only about 30 km long (Yi et al., 2015). In addition, there have been no strong earthquakes in the Moxi section since 1786, and 234 years have passed since the last earthquake. Thus, the seismicity of this section is also worthy of attention.

Data And Methods

3.1 Data collection and processing

The GPS data used in this study were collected from the Crustal Movement Observation Network of China (CMONOC I) and the Tectonic and Environmental Observation Network of Mainland China (CMONOC II). Most of the stations have operated for over a 10-year span or have had at least five observational campaigns with the campaign sites being observed for 4 days during each campaign, which allowed us to obtain high-accuracy velocities. In general, the crustal deformation recorded by the GPS stations contains information about the steady block motion and the post-seismic effects. It should be noted that three moderate-strong earthquakes, including the M_w 7.9 Wenchuan earthquake in 2008, the M_w 6.6 Lushan earthquake in 2013, and the M_w 5.9 and M_w 5.6 Kangding earthquake in 2014, occurred in the study area. We divided the GPS data into two periods, 1999–2007 and 2016–2020, corresponding to the periods before and after these three moderate-strong earthquakes to obtain the regional dynamic deformation characteristics. The first period mainly consists of the data from the campaign stations, which were collected in 1999, 2001, 2004, and 2007. The second period includes continuous and campaign stations and the campaign stations' data were collected in 2016, 2017, 2018, 2019, and 2020.

We processed the GPS data using GAMIT/GLOBK (version 10.61) (Herring et al., 2015a, 2015b). The process mainly included three steps. (1) We processed the original observation data using GAMIT to obtain the loosely constrained daily solutions and satellite orbits. (2) Then, we performed the joint adjustment of the loosely constrained daily solutions of all the stations to obtain their position time series and estimations of the velocities in ITRF2014 using the software GLOCK10.61. For the details of the method used, refer to Liang et al. (2018, 2021) and Su and Zhan (2021). (3) We transformed the velocity solutions into a fixed-Eurasian reference frame (Fig. 3) using the Euler vector for Eurasia with respect to the International Terrestrial Reference System (Altamimi et al., 2017).

3.2 Methods and model

3.2.1 Strain rate calculations

The strain rate field is an important indicator for describing the regional deformation. It is not affected by the reference frame and can reflect the crustal deformation characteristics on different spatial scales (Ward, 1994; Reddy et al., 2000; Jin and Park, 2006; Zhang and Sagiya, 2017). Considering the observation errors of the actual observation data, we used the least-squares collocation method (Wu et al., 2009, 2011) to derive the strain rate fields, which has a relatively good robustness. In this method, the functional relationship between the GPS velocity field and the station locations is constructed, and then, the partial derivative function of the displacement and strain are used to directly obtain the strain rate tensors ϵ_λ , ϵ_ϕ , and $\epsilon_{\lambda\phi}$ of any grid point. The details of the calculation process have been described by Wu et al. (2011).

$$\begin{cases} \varepsilon_{\varphi} = \frac{1}{R} \frac{\partial u_{\varphi}}{\partial \varphi} \\ \varepsilon_{\lambda} = \frac{1}{R \cos \varphi} \frac{\partial u_{\lambda}}{\partial \lambda} - \frac{u_{\varphi}}{R} \tan \varphi \\ \varepsilon_{\lambda\varphi} = \frac{1}{2} \left[\frac{1}{R \cos \varphi} \frac{\partial u_{\varphi}}{\partial \lambda} + \frac{u_{\lambda}}{R} \tan \varphi + \frac{1}{R} \frac{\partial u_{\lambda}}{\partial \varphi} \right] \end{cases} .(1)$$

Then, using Eq. (2), additional strain rate vectors can be calculated.

$$\begin{aligned} \varepsilon_{1,2} &= \frac{1}{2}(\varepsilon_{\lambda} + \varepsilon_{\varphi}) \pm \frac{1}{2}(4\varepsilon_{\lambda\varphi}^2 + (\varepsilon_{\lambda} - \varepsilon_{\varphi})^2)^{\frac{1}{2}} \\ \gamma_{\max} &= \frac{1}{2}(\varepsilon_1 - \varepsilon_2) \quad \varepsilon_{\text{surface}} = \varepsilon_{\lambda} + \varepsilon_{\varphi} \end{aligned} , (2)$$

where ε_1 is the principal tensional strain rate, ε_2 is the principal compressive strain rate, $\gamma_{\max}$ is the maximum shear strain rate, and $\varepsilon_{\text{surface}}$ is the surface strain rate.

3.2.2 GPS profiles and fault slip rates

The GPS profile can be used to reveal the differential movements and the relationship between the displacement distribution and faults, and it is widely used in the analysis of fault deformation characteristics (Jiang et al., 2009; Maurin et al., 2010; Zhang, 2008). First, we selected the GPS stations within a certain range on both sides of the fault zone. Then, we directly projected the GPS velocities onto the directions perpendicular and parallel to the fault, and thus, the velocity component was obtained. In addition, we used an elastic dislocation model (Savage and Burford, 1973) to estimate the long-term slip rate.

3.2.3 DEFNODE negative dislocation inversion

We used the elastic block model (McCaffrey et al., 2002). This modeling was implemented using the open source DEFNODE program, and it has mostly been used to estimate fault slip deficit. The model combines block rotation, uniform block strain, and Okada dislocations (Eq. 1), and it can simultaneously estimate the Block's Euler poles, the fault slip rate, and the fault-locking coefficient to provide the best fit of the geodetic, geologic, and seismic data. In this approach, the spatial variability of the fault coupling is defined by the parameter Phi (the coupling coefficient). If Phi = 0, the fault is fully creeping or decoupled for a long-term slip rate. If Phi = 1, the fault is completely locked. A value of Phi between 0 and 1 indicates that the fault is partially locked. The slip rate deficit on the fault plane was derived by multiplying the fault slip vector by Phi, which provides the elastic deformation around the fault.

$$\bar{V}_{sf} = \bar{V}_{br} + \bar{V}_{is} + \bar{V}_{fs}, \quad (3)$$

where V_{sf} is the observed surface velocity, V_{br} is the velocity caused by the rotation of the block, V_{is} is the velocity caused by the internal strain of the block, and V_{fs} is the velocity caused by the negative dislocation of the fault locking.

Compared with general inversion programs of the same type, the DEFNODE program increases the inversion of the permanent strain inside the block, and the permanent strain inside the block can replace the partial postseismic viscoelastic relaxation effect. This program can be used for related inversions after the earthquake (Zhao et al., 2018).

3.2.4 Inversion model

The study area is divided into three tectonic blocks: the Bayan Har Block, the Sichuan-Yunnan Block, and the South China Block (Zhang et al., 2003). The Xianshuihe Fault Zone, the Longmenshan Fault Zone, and the Anninghe–Xiaojiang fault system were included in our inversion. The block properties (rigid body or elasticity) need to be set before the inversion. Based on previous studies (Zhao et al., 2015), we defined the Sichuan-Yunnan and Bayan Har Blocks as elastic during the inversion, which means that the locking degree (locking coefficient), the Euler vector of the block motion, and the uniform strain tensor inside the block are inverted simultaneously. The interior of the South China Block is relatively stable with weak deformation, and thus, it was modeled as rigid and the components of the strain rate were not calculated in the inversion.

Eleven nodes were set along the fault's strike, and the average distance between these nodes was approximately 35–40 km. The depth of the fault model was set to 20 km based on the results of the following previous studies. Zhu et al. (2005) relocated the small earthquakes that occurred in western Sichuan and found that 90% of the small earthquake events in the Xianshuihe Fault Zone occurred in the upper crust at depths of 0–15 km. Liu et al. (2014) concluded that the stress concentration was generally within 20 km of the upper crust based on joint inversion of P-wave receiver functions and background noise. The details of the models structure are shown in Fig. 4.

Results

4.1 Strain rate fields

Since the differences in the station spacing during 1999–2007 and 2016–2020 would have a certain effect on the strain rate fields, we selected the data for the same GPS station in both time periods and used the least-squares collocation method to calculate the dynamic strain rate fields, which covered the Xianshuihe Fault Zone. The calculation results are shown in Fig. 5.

The strain rate fields show that (Fig. 5a) before the Wenchuan earthquake, the maximum shear strain rate was relatively high in the Luhuo and Daofu sections in the northwestern segment of the Xianshuihe Fault Zone, with maximum values of $6.0 \times 10^{-8}/a$ and $5.7 \times 10^{-8}/a$, respectively, which was significantly higher than that of the southeastern section (Table 2). However, after the Wenchuan and Lushan earthquakes, the maximum shear strain rates of the Luhuo and Daofu sections decreased significantly (Fig. 5b), while that of the southeastern segment (Kangding and Moxi sections) increased, that is, the maximum shear strain accumulation rate increased from $4.5 \times 10^{-8}/a$ to $6.2 \times 10^{-8}/a$ (Table 2), reflecting the shear deformation pattern of the Luhuo and Daofu section underwent a dynamic adjustment after the

Wenchuan and Lushan earthquakes. In addition, the Qianning section also deserves special attention, because the shear strain accumulation rate of this section remained unchanged during the two periods, indicating that this section tends to be locked.

Table 2
Maximum shear strain rates on each segment of the Xianshuihe Fault Zone

Number	Fault section	1999–2007		2016–2020	
		value (a^{-1})	error	value (a^{-1})	error
S1	Luhuo	6.0×10^{-8}	0.34	5.0×10^{-8}	0.18
S2	Daofu	5.7×10^{-8}	0.29	3.2×10^{-8}	0.20
S3	Qianning	4.3×10^{-8}	0.34	3.2×10^{-8}	0.19
S4	Kangding	4.5×10^{-8}	0.33	6.2×10^{-8}	0.21
S5	Moxi	4.5×10^{-8}	0.39	6.2×10^{-8}	0.20

The principal strain rates calculated for 1999–2007 and 2016–2020 (Fig. 5) demonstrate that the roughly E–W directed compression and N–S directed extension were dominant in the northwestern segment of the Xianshuihe Fault, and from NW to SE along the strike of the Xianshuihe Fault, the compression gradually transitioned to NW–SE directed and the extension transitioned to NE–SW directed. Furthermore, we noted that the values of the principal strain rates in the northwestern segment were larger than those in the southeastern segment during 1999–2007. However, after the Wenchuan and Lushan earthquakes, the values of the principal strain rate in the northwestern segment decreased, while the values in the southeastern segment significantly increased, indicating that the tectonic stress on the southeastern section enhanced

4.2 GPS velocity profile

We created two velocity profiles (A and B) across the Xianshuihe Fault Zone. The locations of profiles are shown in Fig. 3. The profiles are 400 km long and 130 km (A) and 110 km (B) wide.

The velocity profile results in Fig. 6 show that an obvious left-lateral strike deformation characteristics dominates in the Xianshuihe Fault Zone. Before the M_w 7.9 Wenchuan earthquake, the left-lateral strike-slip rate of the northwestern segment of the Xianshuihe Fault Zone was ~ 11.5 mm/a, but it decreased to ~ 7.8 mm/a after the Wenchuan and Lushan earthquakes. Moreover, the near-field deformation width of the fault was about 125 km before the Wenchuan earthquake, but it decreased to within the vicinity of the fault (~ 50 km) after the earthquake.

The velocity profile results (Figs. 6c, 6d) show that before the M_w 7.9 Wenchuan earthquake, the left-lateral strike-slip rate of the southeastern segment of the Xianshuihe Fault Zone was ~ 11 mm/a, but it

hardly decreased after the M_w 6.6 Lushan and M_w 5.9 Kangding earthquakes, kept a left-lateral strike-slip rate of ~ 10.8 mm/a. Moreover, the near-field deformation width of the fault almost unchanged during the two periods.

4.3 Fault locking

Based on the fault model above, we obtained the optimal model parameters through multiple calculations. Figure 7 shows the GPS velocity residuals for the two time periods for the best-fit model. The predicted velocities fit the GPS velocities well without systematic error. The majority of the residuals are within the error range, and the directions of the residuals are stochastic throughout the entire study area. Only the residuals near the Zemuhe Fault Zone are slightly larger. 7

The inversion results show that before the Wenchuan earthquake (Fig. 8a), the Luhuo section of the Xianshuihe Fault Zone was coupled, with a maximum fault-locking depth of ~ 16 km, and the average fault-coupling coefficient was greater than 0.85 at depths of 0–16 km. The Daofu section was shallowly coupled at depths of < 5 km and the Qianning section was coupled only at the surface. Moreover, the southeastern segment of the Xianshuihe Fault Zone exhibited a high degree of locking, especially in the Kangding section, which was locked to a depth of ~ 16 km. The locking depth in the southeastern segment gradually weakened from northwest to southeast. However, after the Wenchuan and Lushan earthquakes (Fig. 8b), the locking degree of the Kangding section greatly decreased, and it became almost completely decoupled and freely crept. In contrast, the locking degrees of the Daofu, Qianning, and Moxi sections increased, with average coupling coefficients of greater than 0.9 at depths 8 km, 8 km and 16 km, respectively. The details are shown in Fig. 8b.

The fault-parallel slip-rate deficit demonstrates that the Xianshuihe Fault Zone experienced a left-lateral slip-rate deficit (positive value) (Fig. 9). Before the Wenchuan earthquake, the left-lateral slip-rate deficit of the Luhuo and Daofu sections was the highest (8–10 mm/a), followed by the Moxi section (6–8 mm/a). After the Wenchuan and Lushan earthquakes, the left-lateral slip-rate deficit decreased to 2–6 mm/a in the Luhuo, Daofu, and Qianning sections. After the Wenchuan and Lushan earthquakes, the Kangding section exhibited almost no left-lateral slip-rate deficit, and that of the northern tip of the Moxi section remained at approximately 6–8 mm/a.

Discussion

The spatial pattern and rate of the strain accumulation during the interseismic phase are very important for interpreting the mechanisms of earthquakes and for evaluating the seismic potentials of faults (Navarro et al., 2003; Fialko, 2006; Moreno et al., 2010).

5.1 Different impacts of major earthquakes on the Xianshuihe Fault Zone

The current deformation characteristics of the Xianshuihe Fault Zone can be described by the strain rate field, the fault slip across the block boundaries, and the fault coupling based on geodetic data (Zhao et al., 2018; Li et al., 2019; Wang and Shen, 2020). Our results show that the high shear strain rates were concentrated in the Xianshuihe Fault Zone, and the values in the northwestern section were significantly larger than those in the southeastern section before the Wenchuan earthquake, indicating that the strain accumulation rate in the northern section is larger than that in the southern section, which is consistent with the high slip rate in the northwestern section and the relative low slip rate in the southeastern section (Meade, 2007; Qu et al., 2018; Zhang et al., 2019), exhibiting the basic features of the block-like tectonic extrusion model (Avouac and Tapponnier, 1993; Tapponnier et al., 1982).

After the strong Wenchuan and Lushan earthquakes, the shear strain rate in the Luhuo and Daofu sections significantly decreased. The left-lateral slip-rate and the slip-rate deficit in these sections also decreased (Figs. 6b, 9b). We conclude that these variations were mainly caused by the large-scale decoupling of the central and southern sections of the Longmenshan Fault Zone accompanied by the Wenchuan and Lushan earthquakes. After the Wenchuan earthquake, the extrusion rate of the Bayan Har Block toward the Sichuan Basin accelerated which decreased the far-field left-lateral strike-slip rate and the fault slip-rate deficit and increased the tensile movement of the northwestern section of the Xianshuihe Fault. These major earthquakes may have alleviated the strain accumulation rate in the northwestern segment of the Xianshuihe Fault Zone.

To further verify the impacts of the Wenchuan earthquake and the other regional strong earthquakes on the Xianshuihe Fault Zone; we also collected near-field cross-fault short-baseline observational data for the northwestern segment of the Xianshuihe Fault Zone from 1982 to 2018. The distributions of the fault-crossing sites are shown in Fig. 3. Fault-crossing deformation observations can directly reflect the local tectonic deformation and changes in the stress state of active faults, and they have been used to analyze near-field fault activity (Bo et al., 1998; Li et al., 2016; Li et al., 2017). In this study, the calculation method of Bo et al. (1998) was used to quantitatively calculate the horizontal strike-slip component and the horizontal tension and compression components. The positive slope of the curve indicates right-lateral and tension movements (Fig. 10).

The results of the fault activity analysis (Fig. 10) reveal that the northwestern segment of the Xianshuihe Fault Zone has predominantly experienced left-lateral strike-slip movement (the slope of the curve was negative), with a low tension and compression rate, before the Wenchuan earthquake. However, after the Wenchuan earthquake, and especially after the Lushan earthquake, the tensile activity in the northwestern segment of the Xianshuihe Fault Zone increased significantly. Furthermore, it was found that the near-field left-lateral strike-slip movement at some of the sites, such as Zhuwo, Goupu, and Laoqianning, decreased slightly. Therefore, the results of the near-field cross-fault observations also indicate that the Wenchuan and Lushan earthquakes affected the movement features and strain accumulation rate of the northwestern section of the Xianshuihe Fault Zone.

In addition, we noted that the shear strain rates of the southeastern section of the Xianshuihe Fault increased after the series of earthquakes (Fig. 5b). The Kangding section has almost no left-lateral slip-rate deficit (Fig. 9b) and still has a high left-lateral slip-rate, while the Moxi section remains strongly coupled, with a high left-lateral slip-rate deficit of 8 mm/a in the second period (Figs. 8b, 9b). This is consistent with the latest InSAR results (Qiao et al., 2021), which also indicate a high shallow slip rate (16.3–19.8 mm/a) in the western Kangding section during 2014–2019, and a locking depth of 18.5 km in the Moxi section. The southeastern section of the Xianshuihe Fault Zone is located in the triple junction area where the three major fault zones interact and restrict one another. The Wenchuan and Lushan earthquakes occurred in the central northern segment and southern segment of the Longmenshan Fault Zone, respectively. The post-seismic geological survey and precise aftershock positioning results reveal that the ruptures of the Lushan earthquake and the Wenchuan earthquake did not pass through, and the Lushan earthquake did not cause the entire southern section of the Longmenshan fault to decouple (Fang et al., 2013; Gao et al., 2014; Xu et al., 2013). The triple junction area is still in a strong compressional deformation environment. More than a year after the Lushan earthquake, the M_w 5.9 and M_w 5.6 Kangding earthquakes on November 22, 2014, occurred on the Selaha fault between the Kangding and Qianning sections of the Xianshuihe Fault Zone, which also confirms that this area had a high level of stress accumulation after the Wenchuan and Lushan earthquakes. However, owing to the small-scale rupture and the limited energy released by the M_w 5.9 Kangding earthquake, the event was not sufficient to significantly change the strain throughout the entire triple junction area. Therefore, the southeastern section of the Xianshuihe Fault still had a high strain accumulation rate after the series of earthquakes. All of these results indicate that the surrounding strong earthquakes, i.e., the M_w 7.9 Wenchuan earthquake in 2008 and the M_w 6.6 Lushan earthquake in 2013, had evident differential impacts on the strain accumulation pattern of the Xianshuihe Fault Zone.

5.2 Seismic hazard analysis

The seismic gaps, locking degree, low b-value section of the background seismic activity, and Coulomb stress changes are effective indicators for determining the locations where strong earthquakes may occur in the future (Hubert-Ferrari et al., 2000; Nalbant et al., 1998; Shan et al., 2015; Stein et al., 1997; Wen et al., 2008; Yi et al., 2008).

The spatial and temporal distributions of the earthquake ruptures caused by the major earthquakes along the Xianshuihe Fault Zone reveal that no strong earthquakes have occurred in the Qianning section since the M 7.0 Qianning earthquake in 1893, and the elapsed time exceeds the recurrence interval of the historic strong earthquakes, indicating that this seismic gap is a potential location for strong earthquakes in the future. Following the Wenchuan and Lushan earthquakes, the locking degree and locking depth of the Qianning section increased. In addition, the GPS-derived strain rates show that the Qianning section is an invariant deformation adjustment zone. These results indicate that the Qianning section is in a coupled state with little deformation. Yi et al. (2008) calculated the b-value from seismic data (from the China Seismic Network and Sichuan Regional Seismic Network) for 1976–2006 and found a large-scale asperity with a low b-value from Daofu to Qianning (defined as the Qianning section here) of the

Xianshuihe Fault Zone. The weak deformation of this section may be related to the large-scale asperity. In addition, the Coulomb stress change shows that the occurrences of the Wenchuan and Lushan earthquakes caused increased stress in the Qianning section (Li et al., 2012; Luo and Liu, 2018; Parsons et al., 2008; Shan et al., 2013; Toda et al., 2008; Wan and Shen, 2010), which is consistent with our inversion results. Therefore, we suggest that the Qianning section may be a potential seismogenic source for a future strong earthquake.

Another potential seismogenic source of a strong future earthquake is the Moxi section, which is located at the triple junction of the Xianshuihe Fault Zone, the Anninghe Fault Zone, and the Longmenshan Fault Zone. The tectonics of this area are especially complex. It has been over 200 years since the $M7.75$ Kangding-Moxi earthquake occurred in 1786 in the Moxi section (Wen et al., 2008). Owing to the influence of long-term tectonic loading, this section already has a high strain accumulation (Wang et al., 2016). In addition, our fault-coupling inversion results show that this section has a high degree of fault-locking and a high left-lateral rate deficit. Moreover, the Coulomb stress change in this section has been enhanced by historical strong earthquakes (Li et al., 2020; Shao et al., 2016). Therefore, the risk of future strong earthquakes in this area also requires more attention. In contrast, the locking degree of the Kangding section has almost no slip-rate deficit. This may be related to moderate $M_w5.9$ and $M_w5.6$ Kangding earthquakes in 2014, which caused part of the energy in the Kangding section to be released. High-resolution InSAR velocity maps have been used to identify postseismic afterslip near the 2014 Kangding earthquake rupture (Qiao and Zhou, 2021; Li and Bürgmann, 2021). However, owing to a lack of high precision, near-field, intensive geodetic observations of the study area, we cannot clearly determine the deformation mechanism.

Conclusions

In this study, we focus on exploiting the dynamic deformation characteristics of the Xianshuihe Fault Zone and its potential risk of strong earthquakes occurring using GPS data for 1999–2007 and 2016–2020. The main conclusions drawn are as follows.

- 1) The high shear strain rate was mainly concentrated in the Xianshuihe Fault Zone, and the values of the northwestern section were greater than those of the southeastern section before the Wenchuan earthquake, which is consistent with the spatial differences in the slip rate.
- 2) The deformation mode of the Xianshuihe Fault Zone underwent a dynamic adjustment after the Wenchuan and Lushan earthquakes. The shear strain accumulation rates of the Luhuo and Daofu sections decreased from $6.0 \times 10^{-8}/a$ to $5.0 \times 10^{-8}/a$ and from $5.7 \times 10^{-8}/a$ to $3.2 \times 10^{-8}/a$, respectively, while that of the southeastern segment increased from $4.5 \times 10^{-8}/a$ to $6.2 \times 10^{-8}/a$. The slip rate and deformation width of the Xianshuihe Fault Zone also changed during these two periods, reflecting the differential impacts of the surrounding major earthquakes on the deformation pattern of the Xianshuihe Fault Zone.

3) The locking degree of the Qianning and Moxi sections increased significantly after the Wenchuan earthquakes, while no slip-rate deficit occurred in the Kangding section, which is probably because part of the energy was released by the M_w 5.9 and M_w 5.6 Kangding earthquakes in 2014. Strain accumulation characteristics and recent rupture history of the Xianshuihe Fault Zone suggest that both the Qianning and Moxi sections have a high potential for future strong earthquakes.

Abbreviations

GPS: Global positioning system; InSAR: Interferometric Synthetic Aperture Radar; CMONOC I: Crustal Movement Observation Network of China; CMONOC II: Tectonic and Environmental Observation Network of Mainland China.

Declarations

Availability of data and materials

The horizontal GPS velocity data used in this study can be accessed at <ftp://60.30.77.19>.

Competing Interest

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. We have read and understood your journal's policies, and we believe that neither the manuscript nor the study violates any of them. There are no conflicts of interest to declare.

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Author Contributions

Layue Li, Yanqiang Wu, and Yujiang Li designed the research, analyzed the results and wrote the manuscript. Wei Zhan and Xinzhong Liu performed the GPS data processing and participated in the creation of the graphics. All authors have read and agreed to the published version of the manuscript.

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Figures

Figure 1

Tectonic setting and historic seismicity in the eastern Tibetan Plateau. S1–S5 represent the Luhuo, Daofu, Qianning, Kangding, and Moxi sections, respectively. The gray circles represent $M \geq 6.5$ earthquakes since 1970, and the beach balls represent the focal mechanisms of the $M \geq 6.7$ strong earthquakes since 1900 (data source: Xu et al. (2013)).

Figure 2

Historical seismicity of the Xianshuihe Fault Zone. (a) $M \geq 6.0$ earthquakes in the Xianshuihe Fault Zone since 1700. (b) Ruptures of $M \geq 6.0$ earthquakes in the Xianshuihe Fault Zone since 1300 (modified from Wen et al. (2008)).

Figure 3

GPS velocity fields and profiles across the Xianshuihe Fault Zone. (a) and (b) The 1999–2007 and 2016–2020 GPS velocities relative to the stable Eurasian Plate. The black triangles represent the fault-crossing observation sites. The black polygons denote the profiles plotted in Fig. 6.

Figure 4

Three-dimensional fault structure and node setting of the Xianshuihe Fault Zone.

Figure 5

Maximum shear strain rate fields around the Xianshuihe Fault Zone. (a) and (b) The maximum shear strain rate fields during 1999–2007 and 2016–2020. The black arrows represent the principal strain rates; and the background contours represent the maximum shear strain rate.

Figure 6

GPS velocity profiles across the Xianshuihe Fault Zone. (a) and (b) The velocity parallel to the northwestern section of the Xianshuihe Fault Zone during 1999–2007 and 2016–2020; and (c) and (d) the velocity parallel to the southeastern section of the Xianshuihe Fault Zone during 1999–2007 and 2016–2020.

Figure 7

Velocity residuals for the two time periods for the best-fit model.

Figure 8

Locking degree in the Xianshuihe Fault Zone. (a) and (b) The locking degrees of the Xianshuihe Fault Zone in 1999–2007 and 2016–2020.

Figure 9

Fault-parallel slip-rate deficit in the Xianshuihe Fault Zone. (a) and (b) The fault-parallel slip-rate deficits in 1999–2007 and 2016–2020.

Figure 10

Time series curves of the activity parameters of the Xianshuihe Fault Zone. The red line denotes the horizontal strike-slip component, and the blue line denotes the horizontal tension and compression components.

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