Research Article

Rock Deformation Estimated by Groundwater-Level Monitoring: A Case Study at the Xianshuihe Fault, China

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Rock deformations induced by active faults is an important topic in earthquake studies. Such deformations are usually measured with crossfault measurements (CFM), which are time-consuming and labor-intensive. In this study, rock deformations induced by the famous Xianshuihe fault in Xialatuo of China were estimated by groundwater-level monitoring (GLM) and CFM for the period of January 1, 2016 to December 31, 2018. The pattern of the variations in areal strain estimated with GLM matches that from CFM well. The estimated strain by the GLM and CFM both changed from positive to negative with time, indicating that the fault plane switched from tensile to compressive. This indicates that the rate of rock deformation had slowed down during this period, which is consistent with the long-term creep rates obtained by CFM at the site, implying that the fault may have gradually entered the next reock state. The estimated strain changes using the GLM method lag slightly behind those of CFM, which is probably due to the diffusive effects of pore pressure propagation that is caused by the rock deformation under the crustal stress. This study demonstrates that GLM is a more convenient and efficient addition to traditional geophysical techniques and raises the possibility for the characterization of continuous rock deformations. The method may be used to obtain the changing regional strain field with a network of monitoring wells.

1. Introduction

Estimation of rock deformation and ground movement induced by active faults is an important task in earthquake studies [1–5]. Several techniques, e.g., satellite- and ground-based methods, are commonly used in the measurement of the ground displacement at the regional and local scales. Different measurement methods generally have different accuracies and resolutions. As a satellite-based method, GPS observation has been widely used in previous regional deformation and/or ground movement studies [1, 6–12]. GPS data can be used to analyze plate movement with a measurement accuracy of $10^{-8}$ and regional deformations with a measurement accuracy of $10^{-9}$ [2, 4]. GPS data can be further used to analyze the creep movement of faults, with its accuracy reaching $10^{-10}$ [2, 4]. The measurement accuracy is determined by the density of the GPS monitoring stations. The cost of building a GPS network is relatively high, especially in southwestern China where topography varies dramatically. Consequently, there are fewer GPS observation stations in this region than in other regions [13, 14]. Therefore, it is
difficult to accurately estimate local rock deformation and crustal movement based on the sparseness of the GPS stations in the southwestern region of China.

As a ground-based method, crossfault measurements (CFM) are usually carried out with conventional baseline and leveling arrays, alignment arrays, and trilateration networks to provide highly accurate observations for fault movement in the vertical, orthogonal, and oblique directions [15]. CFMs are reliable for measuring surface deformation and have been widely adopted to monitor fault activity [3, 5, 16–18]. The accuracy of this method is 10^{-6}–10^{-5} m, and the frequency of measurements can be daily to monthly [3, 19]. However, this method is time-consuming and labor-intensive and thus may not be an appropriate method for the analysis of active faults in remote areas, especially if frequent measurements are needed.

The changes in groundwater level, temperature, and chemical composition caused by the crustal movements, which reflect the interaction between tectonic activities and hydrological systems [20–37]. Such changes can be captured and observed by the physical and chemical parameters monitoring in the groundwater wells. Groundwater-level monitoring (GLM) can be used to obtain rock deformations, and the accuracy of the strain estimated with GLM can be as high as 10^{-9}–10^{-11} [21, 22], higher than the GPS and CFM methods mentioned above. Groundwater level oscillations in the deep well, responding to a pressure disturbance, can be caused by the earth tide dilatation of the aquifer [25, 28–30, 38, 39]. Responses of groundwater level to earth tides reflect the pore pressure changes that are closely related to the changes in crustal stress. Groundwater level monitoring (GLM) in the fault provides a way to obtain the changes of the rock properties in response to the fault activity and other tectonic movements [32, 33]. The hydraulic properties of fault zones responding to the pore pressure development are closely related to the fault stability [40–42]. Well water level responses to earth tides provide an effective method to monitor continuously in site properties of fault zone [2, 29, 33, 36, 43]. Previous research [44, 45] studied the tectonic stress field of north China using groundwater levels in deep wells while there is other data to prove the results. Despite a rich observation history of groundwater level changes in rock deformation, little is known regarding the temporal variations of groundwater level tidal response in rock deformation in regions with active faults [25]; furthermore, less is known whether the estimated deformation from the groundwater level tidal response is accordant with that obtained by traditional geophysical measurements, such as GPS or CFM, mainly because of the high costs of drilling and instrumenting geophysical facilities.

In short, the groundwater level tidal response might serve as an additional and economic method of characterizing the variations in rock deformation in remote areas where geophysical facilities are rare and continuous measurements are needed. As is well known, these different measurement methods have different accuracies and resolutions. Do the temporal variations of rock deformation estimated with GLM match those measured continuously by CFM in a region with an active fault? This question can be answered at a site where both GLM and CFM are available. The field site at the active Xianshuhe fault (XF) zone in southwest China, built in Xialatuo in 2015 and chosen for this study, is such a site. The rock deformation induced by the active fault was estimated by GLM and compared with that measured by CFM at the site. The results show that the pattern of the variations in the areal strain estimated with GLM matches well with that obtained by CFM. This demonstrates that GLM is a more convenient and economic method of estimating rock deformation with observed groundwater levels than CFM. The GLM method may be used to obtain the changing regional rock deformations and crustal movements with a network of monitoring wells. In the following, the field site and data collected are described first; then, the methodology and results and discussion are presented, and finally, some conclusions are drawn.

2. Field Site and Data Collection

2.1. Field Site. The field site is located in Xialatuo in the eastern Tibetan Plateau. This area belongs to the subhumid climate zone of the Qinghai-Tibet Plateau (Figure 1(a)). The annual average temperature and annual precipitation are 7.4°C and 572.5 mm, respectively. The site is situated in Xialatuo Basin, which is a pull-apart basin formed by the left-lateral strike-slip movements of the XF (red lines in Figure 1(b)). The XF is one of the most tectonically active intracontinental faults in China, and more than 20 earthquakes (M > 6.5) have occurred along this fault since 1700 [41]. Xialatuo Basin is located in the northwest XF, which strikes NNW-SSE and dips NE at approximately 85°, surrounded by a high mountainous region (Figures 1(b) and 1(e)). The formations in the XF region range from Neoproterozoic to Cenozoic, whereas Cretaceous and Jurassic formations are absent owing to the uplift and denudation that occurred in this region [46]. The formation outcropping in the Xialatuo is mainly Triassic, and some Permian formations also occur. Granite is mainly formed during the Himalayan tectonic movement. The study area is mainly covered by Quaternary sediments, which are underlain by the fractured slate rock of the Triassic, according to the well log at borehole ZK01 (Figure 1(c)).

2.2. Crossfault Measurements. In this study, CFMs of the XF (Figure 1(d)) are constructed by baseline and leveling measurements based on trilateral and quadrilateral networks, which provide an accurate accounting of the deformation in the area. A closed quadrilateral network of four stations labeled D, E, F, and G (Figure 1(d)) across the XF was built in December 2015 for the performance of ground deformation measurements. These stations form a measured network that includes six baselines and four leveling lines (white lines in Figure 1(d)). The baseline measurements of the changes in distance among the stations can be indicated by six baselines as in Figure 1(d) (white lines), in which lines EF and DG are orthogonal to the XF, lines DF and EG are oblique to the XF, and lines DE and FG are parallel to the XF. Baselines measurements conducted by Leica TM 50 Monitoring Station with a distance accuracy of 0.6 mm + 1
ppm (Leica Geosystems) are used to measure the horizontal displacements of the XF. Leveling measurements conducted by Leica DNA03 Digital Level Surveying with a distance accuracy of 0.3 mm (Leica Geosystems) are carried out to quantify the vertical displacement of the XF. Note that both F and G are located on the hanging wall block of the XF, while both D and E are located on the footwall block.

Leveling measurements among the four stations (D, E, F, and G) were conducted daily from January 1, 2016 to December 31, 2018. The elevation variations of station D relative to station E and station F relative to station G were defined as $h_{DE}$ and $h_{FG}$, respectively. A total of 1095 pairs of $h_{DE}$ and $h_{FG}$ were obtained. The leveling change of the hanging wall relative to the footwall block of the XF was defined as $h_{DE} - h_{FG}$, and the temporal variation of $h_{DE} - h_{FG}$ is presented in Figure 2(a), which shows that the hanging wall block was uplifted relative to the footwall block during the measurement period. Specifically, this uplift (decrease in slope of $h_{DE} - h_{FG}$ with time is not shown in the paper) decreased from January of 2016 to December of 2018, and several factors, such as atmospheric pressure, earth tides, were responsible for producing the annual variations in $h_{DE} - h_{FG}$ (Figure 2(a)). The baseline measurements among the four stations (D, E, F, and G) were conducted every 5 (from January of 2016 to December of 2017) or 10 days (from January of 2017 to December of 2018) during the
same period as the leveling measurements. The baseline changes between stations D and F, F and G, and D and G were defined as $d_{DF}$, $d_{FG}$, and $d_{DG}$, respectively. A total of 144 groups data were obtained, and the temporal variations of $d_{DF}$, $d_{FG}$, and $d_{DG}$ are displayed in Figure 2(b).

Specifically, the minus sign describes the fact that $d_{DG}$ and $d_{FG}$ generally decrease relative to the displacements on January 1, 2016, meaning that the displacement between D and G and F and G continued to decrease during the measurement period. The plus sign means that $d_{DF}$ increases relative to the displacements on January 1, 2016, indicating that the deformation between stations D and F continued to increase during the measurement period. This showed that the deformation tends to be compressed along the orthogonal direction of XF, while the deformation along the strike of XF is stretched.

2.3. Observed Groundwater Levels. A monitoring well (ZK01) was installed near the centre of the site at E100°45′7.28″ and N31°17′34.18″ (Figure 1(d)), and the ground elevation was 3140 m. The well is about 200 m deep and open to the aquifers at depths from 110 to 128 m and 145 to 173 m (Figure 1(d)). It was drilled approximately 15 m north of the XF, intersecting the fault at a depth of approximately 95 m (Figure 1(c)). The well is open to fluid flow in the formation below 110 m and provides a unique opportunity to directly measure the fault activities over time. The water table was 14-17 m below the ground. Daily precipitations (Figure 3(a)) were recorded by the local meteorological station approximately several hundred meters away from the well. The groundwater levels (Figure 3(b)) were observed using the Diver logger with the accuracy of ±0.5 cm H$_2$O from January 1, 2016 to December 31, 2018 with 15 min sample interval. To evaluate the effects of the barometric pressure on groundwater levels (Figure 3(c)), the barometric pressure was observed by a Baro Diver logger with the accuracy of ±0.06 cm H$_2$O during the same period. In the end of 2017, a new Diver logger was deployed to measure pressure 6.5 m higher than the old one (Figure 3(c)). The logger recorded the barometric pressures was temporarily jammed; so, there were no recorded barometric pressure fluctuations during two periods; otherwise, the time series are uninterrupted for three years period (Figure 3(b)). One mysterious feature of the data is the change of water pressure that occurred during April-July 2017. These water pressure abnormal fluctuations were not related to any local earthquakes, quarry blast events, or surface hydrological events according to the local investigations. The cause of these water pressure fluctuations was not clear, which requires further and more data to evaluate. Therefore, the study of these abnormal fluctuations is beyond the scope of this paper. The tidal response analysis pursued here
focused on a specific harmonic and is therefore unaffected by these abnormal fluctuations and the resulting errors displayed by the error bars of the tidal analysis (Figure 4).

The water pressure fluctuates in a seasonal pattern, such that it increases from March to October and decreases after October. Furthermore, the water pressure does not respond to local precipitation (Figure 3(d)). This is demonstrated by the fact that if local precipitation recharged an aquifer, one would expect an increase in the water pressure with increasing local precipitation, rather than the uncorrelated patterns shown in Figure 3(d). Thus, the annual change in the water pressure in the well is likely due to the seasonal recharge (well located in the basin that is surrounded by mountainous region) [48]. The water pressure data were resampled to hourly intervals for tidal analysis, revealing that the water level in the well recorded a clear tidal signal and showed a strong response to earth tides (Figure 3(c) and Figure 5(a)).

3. Methodology

3.1. Tidal Analysis. The main work of tidal analysis is to estimate the tidal factors and phase shifts of the measured groundwater levels. The tidal factor is defined as the ratio of amplitudes of the groundwater levels induced by earth tides to that of the theoretical earth tides, and the phase shift is defined as the time lag between earth tides and water level, which is caused by the time required for water to flow into and out of the well. Both the tidal factor and phase shift are commonly used to represent responses of aquifer systems to earth tides. Variations in both the tidal factor and phase shift imply changes of aquifer parameters and/or force
sources. In this study, the tidal signals were extracted from the groundwater level using Baytap08, a modified version of the Bayesian Analysis Program-Grouping Model program (BAYTAP-G), which is a popular software package for tidal analysis [31, 33, 35, 49–51]. Baytap08 assumes that a signal $y_i$ can be decomposed into the following parts:

$$y_i = \sum_{m=1}^{M} (A_mC_m + B_mS_m) + d_i + \sum_{k=0}^{K} b_kx_{i-k} + e_i,$$  \hspace{1cm} (1)

where $\sum_{m=1}^{M} (A_mC_m + B_mS_m)$ is the tidal component, $M$ is the number of tidal waves in the tidal group, $C_m$ and $S_m$ are the summation of the cosine and sine parts of the theoretical values of different tidal components, respectively, $A_m$ and $B_m$ are the tidal constants, $d_i$ is the long-term trend; $\sum_{k=0}^{K} b_kx_{i-k}$ is the local barometric response component in which $b_k$ is the response coefficient, $x_{i-k}$ is the observed barometric pressure, $K$ is the lag time between the groundwater level response and barometric pressure, and $e_i$ is the noise. This software package incorporates a Bayesian inversion process that allows the parameters $A_m$ and $B_m$ to be evaluated by minimising Akaike’s Bayesian Information Criterion, which is formulated by Equation (1).

Several possible causes of water level fluctuation in the well include periodic effects of the earth tides, the barometric tide, ocean tidal loading and seismic waves and aperiodic effects related to seasonal aquifer recharge or discharge,
and pumping from nearby wells [31, 37, 52]. The observation well in this study are situated where the effects of ocean tidal loading and pumping can be neglected. The impacts of seismic waves can also be neglected as their periods (0.1–100 s) are much shorter than that of the earth tide. The barometric pressure includes periodic and aperiodic signals accounting for approximately 10% of the total tidal signals [53], which was eliminated by Baytap08 as well. If the aquifer is imperfectly confined, rainfall can contribute to aperiodic water level changes.

The periodic and aperiodic fluctuations, which are evident in the records in Figure 3, can be separated by well-known tidal harmonic analysis method of Baytap08. This method requires at least 28-day tide record [53]. The tidal factors and phase shifts of the constituents of the well tide were obtained from harmonic analyses of the periodic fluctuations. Some features of the spectrum of tidal harmonic constituents are revealed by the normalized fast Fourier transform spectrum analysis of the periodic water pressure data (Figure 5(b)). Note that the earth tides include 386 tidal groups with different periods [54]. The $O_1$, $K_1$, $M_2$, $S_2$, and $N_2$ tides account for 95% of all earth tides, and $M_2$ is more stable with a larger amplitude and is less disturbed by external perturbations [38, 53]. Therefore, $M_2$ has been widely used in the tidal analysis for aquifer system in previous studies [31, 34, 37, 48, 52, 55–57]. The $M_2$ tide is also adopted for the tidal analysis in this study, and responses of the groundwater level to the $M_2$ tide are very distinct from the normalized fast Fourier transform spectrum analysis (Figure 5(b)). In the analysis of the observed period, a time interval of 720 hour (30 days) with a sliding window of a half-month (15 days) was adopted to extract the various tidal parameters in a full time series and obtained time-dependent tidal parameters, such as the tidal factors, phase shifts, and amplitudes of the tidal constituents, from the output of Baytap08. The average value of the tidal factor was used in the subsequent calculation. Both the $M_2$ phase shift and tidal amplitude are at least twice as large as their root mean square error (RMSE), which were presented in Figure 6.

3.2. Estimations of Areal Strains Using GLM. For a confined aquifer, the period of earth tide is much shorter than that of discharge or recharge of the aquifer, and the fluctuations of the groundwater level caused by the dilatations or contractions of the aquifer can be approximated as being done under the undrained condition [35, 37, 57–59]. Strictly speaking, it is ideal that an aquifer is completely confined, and an aquifer in fact is generally the combination of confined and unconfined state. In this study, we just focus on the ideal case. In such a case, the relationship between the groundwater level in the deep well and volumetric strain induced by the dilation or contraction of the aquifer can be described by the following equation [21, 58, 60].

$$\delta = \frac{-\Delta H}{\varepsilon_v}, \quad (2)$$

where $\delta$ is the tidal factor (mm/10^{-6}), which represents the variation of water levels (L) per volumetric strain of 10^{-6}, and it can be obtained directly from the tidal analysis of Baytap08, $\varepsilon_v$ is the volumetric strain of the aquifer (-), and $\Delta H$ is the changes of groundwater levels in the well (L). Based on Equation (2), the volumetric strain can be calculated using the tidal factors and the change of the groundwater level.

The areal strain and volumetric strain model were set up under the plane stress $(\sigma_1, \sigma_2)$ based on the Evertson theory [61] and later improved by Pan [62] and Zhang [63, 64] under the condition of the shallow crust, $\varepsilon_a = (2k - \mu) (\sigma_1 + \sigma_2)/E_1$ (is the elastic modulus of rock) and $\varepsilon_v = 2k (\sigma_1 + \sigma_2)/E_v$. Therefore, the relationship between the areal strain and volumetric strain in the shallow crust of the earth can be written as

$$\varepsilon_a = \frac{(2k - \mu)}{2k} \varepsilon_v, \quad (3)$$

where $\varepsilon_a$ is the areal strain, and $\mu$ is the Poisson ratio of the host rock. The typical value of the drained Poisson ratio of rocks is approximately 0.25, which was widely adopted in previous studies [52, 65, 66]. Therefore, this typical value is adopted in this study. Meanwhile, $k$ is the ratio of the areal strain of the inner wall of the strain instrument probe to that of the borehole rock and is usually equal to 1, inferred from the elastic modulus of rock [61, 63, 64].

3.3. Elimination of Annual Periodic Variation from Baseline Measurements. The CFM is a geodetic measurement that conducted on the ground surface, which are sensitive to a variety of surface noises like anthropogenic and natural factors [67–69]. Effect of human activities on the measurements can be negligible because there are no any human activities like pumping or large buildings constructing in the site. Therefore, only the effect of natural noises like temperature, barometric pressure, and solid tidal effect influences the CFM [4, 70]. The baseline measurements among the four stations ($D$, $E$, $F$, and $G$) were conducted every 5 (from January of 2016 to December of 2017) or 10 days (from January of 2017 to December of 2018) from January 1, 2016 to December 31, 2018; thus, we just focus on the elimination of annual periodic variations rather than the daily variations in this study.

For the annual periodic variation caused by the nontectonic movements during the crossfault measurements, the generalized analysis shows that it is a combined result of several factors like temperature, barometric pressure, and solid earth tides that results from the rotation of the earth around the sun [63, 64, 67]. In order to extract the annual periodic variation of baselines from CFM, Empirical Mode Decomposition (EMD) is employed. The raw data is decomposed into different group data with different frequencies by EMD, and the data with frequency of one year can be extracted from the raw data. EMD, a very powerful and efficient tool for the analysis of nonstationary and nonlinear time series data [71], has been widely used for different geophysical data.
analyses, such as seismic waves [72, 73], river tides [74], and oceanic waves [75, 76].

If a real signal $X_{\text{real}}(t)$ is contaminated by a noise $n(t)$, then the raw measured signal $X_{\text{raw}}(t) = X_{\text{real}}(t) + n(t)$. The shifting process first determines the mean $m_1(t) = U(t) + L(t)/2$, where $U(t)$ and $L(t)$ are the upper and lower envelopes of $X_{\text{raw}}(t)$, obtained from a cubic spline function fitting. Subtracting $m_1(t)$ from $X_{\text{raw}}(t)$ yields the first intrinsic mode function (IMF) component $h_1(t) = X_{\text{raw}}(t) - m_1(t)$, and the shifting process needs to be iterated several times using the equation $h_{ik}(t) = h_{i(k-1)}(t) - m_{ik}(t)$, where $k$ denotes the number of iterations until $C_{ik}(t) = h_{ik}(t)$ which satisfies the definition of IMF. The function $C_i(t)$ is the first IMF with the highest instantaneous frequency and can be separated from $X_{\text{raw}}(t)$ by $R_1(t) = X_{\text{raw}}(t) - C_1(t)$. The shifting process is again conducted on the residual $R_1(t)$ to extract the second IMF. This process is continued until either the residual is a constant value or it becomes a monotonic function. Finally, $X_{\text{raw}}(t) = \sum_{i=1}^{N} C_i(t) + R_N(t)$ where $R_N(t)$ is the trend function, $n$ is the number of IMFs, and $C_i(t)$ is the $i^{th}$ IMF. The decomposed IMFs are orthogonal to one another and thus can be used as the basis to represent the raw measured signal. From the above, a time series of the baseline measurements data $X_{\text{raw}}(t)$ can be decomposed into different groups with different frequencies.

Because of the observation periods of baseline measurements are not the same, the baseline measurements were conducted every 5 days from January of 2016 to December of 2017 and every 10 days from January of 2017 to December of 2018. Thus, the first thing for the raw data before decomposed by EMD is to preprocess the raw data with the three spline interpolation to obtain a value of the baseline measurements every 5 days. Annual periodic variations (the red star line shown in Figure 6) of baseline DF, DG, and FG extracted from EMD are eliminated from the raw data (the solid line shown in Figure 6). The standard deviations (STD) of the residuals between the raw data and the residual data (the dotted line shown in Figure 6) without the annual periodic variations are 0.2668, 0.2321, and 0.2154, respectively. The residual data without the annual periodic variations are applied to estimate the areal strain.

The effect of hydrological processes with period ranges from a few days to annual period on the rock deformation. The original raw data is probably the most reliable if interference information like the hydrological processes for the strain is excluded with significant uncertainties; thus, in this study, we did not exclude the effect of hydrological processes caused by precipitations on the strain estimated by both groundwater level monitoring and crossfault measurements. Therefore, the study of hydrological processes caused by precipitations on the rock deformation is the next research plan, which is beyond the scope of this paper.

3.4. Estimations of Areal Strains Using CFM. Deformation in a local place can be conventionally obtained by CFM, a method proposed by Jaeger [77] that calculates the main strain, shear strain, and areal strain from variations of the baseline lengths in two or more measurements:

$$\frac{\Delta S}{S} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\varepsilon_x - \varepsilon_y}{2} \cos 2\alpha + \frac{\gamma_{xy}}{2} \sin 2\alpha,$$

where $S$ is the baseline length, i.e., the distance between two observation stations (L), $\Delta S$ is the variations of baseline length relative to that at the beginning of the measurement, i.e., change in the distance between two stations (L), $\varepsilon_x$ is the strain in the direction parallel to the strike of the fault, $\varepsilon_y$ is the strain in the direction perpendicular to the fault, $\gamma_{xy}$ is the shear strain, and $\alpha$ is the angle between the baseline and the fault. Angles between the DF, DG, and FG baselines

Figure 6: The raw data, annual periodic variation, and the long-term trend of over more than one year for (a) $d_{DF}$, (b) $d_{DG}$, and (c) $d_{FG}$ from 2016/01/01 to 2018/12/31.
and the fault are $\alpha_1 = 35.6^\circ$, $\alpha_2 = 89.65^\circ$, and $\alpha_3 = 3.02^\circ$, respectively. The strains can be obtained by

$$\begin{bmatrix}
\frac{\Delta S_{03}}{S_{03}} \\
\frac{\Delta S_{02}}{S_{02}} \\
\frac{\Delta S_{01}}{S_{01}}
\end{bmatrix} = \begin{bmatrix}
\frac{1 + \cos 2\alpha_1}{2} & \frac{1 - \cos 2\alpha_1}{2} & \frac{\sin 2\alpha_1}{2} \\
\frac{1 + \cos 2\alpha_2}{2} & \frac{1 - \cos 2\alpha_2}{2} & \frac{\sin 2\alpha_2}{2} \\
\frac{1 + \cos 2\alpha_3}{2} & \frac{1 - \cos 2\alpha_3}{2} & \frac{\sin 2\alpha_3}{2}
\end{bmatrix} \begin{bmatrix}
\varepsilon_x \\
\varepsilon_y \\
\gamma_{xy}
\end{bmatrix}.$$  

(5)

And the areal strain $\varepsilon_a$ can be obtained by

$$\varepsilon_a = \varepsilon_x + \varepsilon_y.$$  

(6)

In order to help readers better understand the analysis steps, a flowchart shown in Figure 7 showing the connection of different physical processes.

**4. Results and Discussion**

Both tidal factors (Figure 4(a)) and phase shifts (Figure 4(b)) are time-dependent parameters, and they range from 0.1255 to 0.3681 and 12.181 to 64.411°, respectively. The blue error bars indicate the RMSE of the tidal analysis. Theoretically, the periodical fluctuations of the tidal factor and phase shift are mainly caused by the elastic deformation of an aquifer forced by the earth tides [78]. In this study, the abnormal jumps in both tidal factors and phase shifts are consistent with the abnormal fluctuations in the observed groundwater level during the April-July 2017. Specifically, the tidal factors and phase shifts changed little with time except those from April to July 2017, in which the abnormal groundwater level fluctuations result from some reasons that require further and more data to evaluate. Therefore, a large RMSE resulted for both the phase shifts and tidal factors during the time.

According to Hsieh’s model, a single, homogeneous, isotropic, laterally extensive, and confined aquifer in which the water table drainage effect is negligible, and the phase shifts should be negative [34, 59, 79]. However, if the phase shifts are positive which may be caused by the vertical drainage of the water table and the aquifer is unconfined [39, 80], sometimes, the phase shift of an aquifer can be switched from negative to positive under strong ground movements, such as earthquakes, the water table drainage happened through the reopening of vertical fractures during earthquakes, and the water table drainage is ignored as vertical fractures resealed over time after earthquakes [2, 29, 34]. As shown in Figure 4(b), the phase shifts in this study are positive, indicating that the connection between the aquifer and the water table is strong, and the vertical drainage of the water table cannot be ignored. It seems like that ZK01 is an unconfined aquifer, and the connection with water table is important, which will be discussed further later.

The temporal variation of the areal strain estimated with the GLM method is presented in Figure 8 (the green stars). It should be noted that the estimated strain was defined as the relative strain, which is calculated with respect to the reference on January 1, 2016. Positive strain means that the rock becomes tensile with respect to the reference, and negative strain means that the rock becomes compressive with respect to the reference. The strain was positive in the early time and then became negative after June 1, 2016, and the slope of the linear regression analysis is negative (not shown in the article), meaning that the rock around the well switched from tensile to compressive state relative to the reference, resulting from the local crustal stress redistribution under the crustal movement. Figure 8 shows that the estimated areal strain significantly oscillated over time, which may be induced by the dynamic responses of the groundwater level to the crust movement and precipitation infiltrations, similar oscillations also exist in the strain estimated by the CFM method.

The temporal variation of the estimated areal strain calculated by the CFM method was also presented in Figure 8 (solid curve with blue dots). The strain, similar to that by the GLM method, also was the relative strain with respect to the reference on January 1, 2016. It shows that the areal
strain estimated by the CFM method was positive early and became negative after April 1, 2016, and the slope of the linear regression analysis is negative (not shown in the article), meaning that the rock switched from tensile to compressive state relative to the reference as time progressed. The areal strain fluctuated dramatically over time as well. The reason is the same as that of the estimated strain using the GLM method mentioned above.

Comparison of the areal strains estimated by different methods in the study area during the period of January 1, 2016 to December 31, 2018 was shown in Figure 8. It shows that the pattern of the strain variations estimated by the GLM method matches well with that obtained by the CFM method. The fluctuations of the areal strain during the period of January 1, 2016 to December 31, 2016 are weaker than those during the period of January 1, 2017 to December 31, 2018, which is probably caused by the precipitation loading in the rainy season, i.e., the precipitation of 2016, 2017, and 2018 was 508 mm, 572 mm, and 800 mm, respectively, and rain falls mainly in the rainy season. Although with different maximum areal strain values, the interannual variation of the estimated strain appeared near January 2016, January 2017, and January 2018 is apparently. This interannual characteristic of the estimated strain occurs in both methods, which is likely caused by annual infiltration loading [48]. The temporal variations in the estimated strains using both GLM and CFM method show that XF switched from tensile to compressive state relative to the reference on January 1, 2016, owing to the areal strain changed from positive with time relative to the reference on January 1, 2016.

The long-term creep rates of the site with CFM were measured by the Survey Engineering Institute of Sichuan Earthquake Administration (SEISEA) (Figure 9). The creep rate is negative in the vertical direction of XF (blue line with diamonds) and decreases quickly before 1992; then, it decreases slowly in the remaining period of the measurements. The creep rate that oblique with XF (red line with squares) was positive and approximately constant before 2015, then decreased significantly, and became negative after 2016. The creep rate that orthogonal to XF (green line with triangles) has decreased significantly after 1980. The temporal variations of the creep rates in the three directions implied that the left-lateral creep rate of XF at this segment has decreased gradually since 1980.

For the period of this study, specifically, the creep rate that oblique with XF (red line with squares) is negative with respect to the reference of the creep rate on January 1, 2016, owing to the creep rate in the opposite direction kept increasing since 2016. It illustrates that XF changed from the stretched state (before 2016) to the compressed state (after 2016) in the direction that oblique with XF with respect to the state on January 1, 2016. Besides, the creep rate that orthogonal to XF (green line with triangles) is also negative relative to the creep rate on January 1, 2016, owing to the creep rate that orthogonal to XF kept decreasing since 1980s. It also illustrates that the fault had a tendency from the stretched state to the compressed state in the direction that orthogonal to XF with respect to the state on January 1, 2016. The vertical creep rate of XF also decreased gradually since 1980s. Above all, it can be concluded that the fault has tended to the compressed state from the stretched state.

Moreover, previous studies on XF [5, 68, 81] have indicated that the fault at this segment behaved as tensional creeping in the first few years following the 1973 Luhuo earthquake; however, the creep rate has slowed down since 1980, speculating that the fault has gradually entered the relock state (a state in the seismic cycle described from Du et al., 2010) before the next earthquake happen. This deformation pattern is consistent with the areal strain state of the study area using both GLM and CFM, proving the reliability of the estimated strain in this study.

It is recognized that there are some discrepancies in the estimated strains using the two methods. First, the magnitude of the estimated strain using the CFM method is smaller than that of the GLM method. The reason is that the estimated strain using the CFM method mainly represents the ground deformation, whereas the estimated strain using the GLM method mainly represents the rock deformation at a depth of 200 m. Second, the strain changes
estimated by the GLM method lag slightly behind that of the CFM method. This lag is probably owing to the diffusive effects of pore pressure propagation caused by the rock deformation under crustal stress. Besides, the CFM method only considers the surface rock deformation. Thus the change of the strain estimated using CFM is a little earlier than that obtained by GLM. A comparison of the two methods indicates that the readily available groundwater level monitoring data provide a convenient and economic tool to investigate the rock deformation. The GLM method can be used to obtain the regional strain field or crustal movement with a network of monitoring wells, which is the next study we intend to conduct.

5. Conclusions

In this study, rock deformation at the Xianshuihe fault in Xialatuo, China, was estimated using GLM and compared with that of using CFM. Groundwater levels were measured with two dataloggers in a monitoring well installed in the center of the study area from Jan 1, 2016 to Dec 31, 2018. The baseline and leveling measurements have been conducted in this study area since 1980s.

The conclusions were drawn from this study as follows.

(1) The pattern of the areal strain variations estimated using the GLM method matches well with that obtained by the CFM method.

(2) The strains estimated by the GLM and the CFM method both changed from positive to negative, indicating that the fault switched from tensile to compressive, which is consistent with the long-term creep rates measurements of the fault.

(3) The strain estimated by the GLM method lag slightly behind that of the CFM method, which is probably owing to the diffusive effects of pore pressure propagation caused by rock deformations under the crustal stress.

(4) GLM is an additional method that is effective at characterizing variations in rock deformation in remote areas where geophysical facilities are rare while continuous measurements are needed.

Data Availability

The data used in the study can be found at the documentary called “original data” on the [https://github.com/2019Yuqing/HESS/blob/master/originaldata.xlsx](https://github.com/2019Yuqing/HESS/blob/master/originaldata.xlsx).

Conflicts of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors’ Contributions

Y.-K. Zhang, Y.Q. Zhao, X.Y. Liang, and other co-authors conceived the idea and designed the experiments based on weekly workshops and discussions. Y.L. Yang and F.F. Li conducted the field experiments in the Xialatuo study area. Y.Q. Zhao analyzed the field data and wrote the first draft of the paper.

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