Interpretation of the coseismic surface deformation of Wenchuan earthquake based on the theory of disclination and dislocation

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Abstract. A combination model of disclination-dislocation which can describe the three-dimensional translational and rotational motion of the fault is given. We used the combined model and the dislocation model to calculate the coseismic horizontal displacement of 102 points of Wenchuan earthquake respectively. The result indicates that the horizontal displacements calculated by the two models are generally in agreement with the GPS observations both in magnitude and direction, but there are some differences in some points. When the magnitudes of horizontal displacements by the two models are close to each other, we calculate their direction residuals by taking the direction of the GPS observations as the true value. It is found that the directions residuals calculated by the two models are concentrated between [-20°, 20°], and the number of points accounts for 84.3% of the total in this interval. In the interval where the direction residuals is smaller, the percentage of the number of the points calculated by the combined model is greater than that calculated by the dislocation model, indicating that the combined model can better explain the surface deformation observation.

1. Introduction
On May 12, 2008, a Mw8.0 earthquake occurred in the Longmenshan range between the Qinghai-Tibet Plateau and the Sichuan basin. The landslides and geological disasters caused huge casualties and economic losses. The earthquake is the most intense earthquake in China’s mainland in recent years. The study of the movement of the fault plane of the earthquake will be of great significance for the interpretation seismic mechanism and the prediction of strong earthquakes. After the Wenchuan earthquake, many geophysicists used seismic wave and geodetic data to retrieve the rupture process of the earthquake. However, the slip maxima given by scholars is different, such as 9m (Ji, 2008), 12m (Wang et al.,2008), 6.7m(Chen et al.,2013), 12-12.5m(Chen et al.,2009). At the same time, many scholars have used rectangular dislocation model (Okada, 1985; Okada, 1992) together with the conseismic GPS data, INSAR data of Wenchuan earthquake to study the fault slip distribution; Wang et al. (2011) calculated the maximum slip value of 12-13m in the shallow fault of the Beichuan area, which is close to the calculation of 5-13m by Tong et al. (2010). Shen et al. (2009) concluded a result of the moving average value 5m of the slip distribution on the Beichuan fault, being the peak value of 5.8m close to the surface. Wen et al. (2014) and Xu et al. (2010) used the INSAR data and the GPS data to obtain a maximum slip amount of 10.7 m of the Hongkou section at the
eastern end. The dislocation theory is widely applied for the interpretation of the geodetic deformation by geodesists and geophysicists. In fact, the spatial motion of the fault should include two modes, namely the translational mode and rotational mode. However, the dislocation theory describing the translational mode of faults ignores the rotational mode. To some extent, the fault model which is given by the above scholars can explain the horizontal displacement of the surface well, but ignores the case of fault rotation.

The fault rotation is widespread in fact, such as S type, anti-S type, and spiral structure. Many scholars have preliminarily studied the fault rotation phenomenon (Lee, 1929; Ho, 1953; Ding et al., 1987; Xie, 2004). The fault disclination theory can be used to overcome the limitations of existing dislocation theory models that cannot describe fault rotation. Considering the continuity of the three-dimensional motion of the fault, it should be more reasonable to interpret the surface deformation from the combination of the translational and rotational modes of the fault space.

The disclination theory model (Yang, 2000) describes the relationship between the deformations caused by non-deformable rotation in the two planes in an infinite elastic medium. Fressengeas et al. (2011) put forward the elastoplastic linear theory of disclination, which represents the defect of continuous crystalline solid. So far, the theory of the disclination is still in the initial stage in the application of the macro crustal deformation. Some scholars adopted the numerical simulation to study the relationship between the fault rotation, the surface deformation and the surface gravity in the homogeneous medium of the elastic half space (Wang et al., 2016, Matsuo and Heki, 2011, Duan et al., 2015). In the study of the fault rotation, one of the key points is the determination of the rotation datum point and the rotation axis. Wang et al. (2016) and Duan et al. (2015, 2016) set the rotation datum point at the bottom of the fault. Assuming that the torsional mode (W2) of the fault dislocation occurs, the movement of the fault is undoubtedly the largest at the ground. Considering the absorption of the medium, this view is not consistent with the theory of energy propagation.

In this paper, on the basis of USGS dislocation model, we divided the faults into south, middle and north segments according to the focal mechanism solution. The surface location of the north of each segment is selected as the rotation base point of the disclination. The direction passing the base point along the strike of fault is acted as the axis of rotation. Thus, the coseismic fault model of the Wenchuan earthquake is constructed. The results calculated by the model and compared with the GPS observations prove the existence of the W2 component of the fault disclination motion and determine that the disclination is near 5.0” . In addition, taking the GPS observations as the true value, the statistical analysis of the directions residuals of the horizontal displacement calculated by two models be carried out. The results confirm the superiority of the combined model which provide a new theoretical model reference for the interpretation of the surface displacement.

2. Relationship between the disclination model and the surface displacement
In semi space, the relationship between the translational motion and the rotation of the fault and the ground deformation is derived in accordance with the elastic mechanics geometry equation, the elastic medium constitutive relation and the stress balance differential equation. In general cases, the movement of faults in space may be formed by the way of the spatial translation vector \( b \) of the hanging wall vs the footwall or by the way of the rotation angle \( W \). Such a linear combination not only has the characteristics of dislocation, but also has the characteristics of disclination. When the fault rotates (the fault disclination occurs), the discontinuity of the rotation vector \( \Omega \) of the hanging wall vs the footwall and that of the displacement vector \( u \) can be expressed as:

\[
\Omega^+ - \Omega^- = W
\]

\[
u^+ - \nu^- = b + W \times r
\]

Where \( b \) is translation vector , \( W \) is rotation angle, and \( r \) is the radial distance of the rotational.

2.1. The disclination model
The translation vector \( b \) of the fault surface motion can be expressed by the orthogonal and
complete $U_1 \hat{e}_1, U_2 \hat{e}_2, U_3 \hat{e}_3$ coordinate basis. The disclination of the fault has an important feature (Note: the disclination of the fault in this paper refers to the relative rotation of the fault, rather than the overall rotation of the fault). The spatial location of the rotation axis of the disclination must be strictly regulated. In this paper, as shown in Fig.1, the orientation of the fault is defined as the X axis, the direction perpendicular to the fault orientation is defined as the Y axis, and the Z axis is perpendicular to the XY plane. Downward a local space right angle coordinate system is established. The space rotation $W$ of the fault is represented by the mutually orthogonal rotation vector $W_1 \hat{e}_1$, the torsional rotation vector $W_2 \hat{e}_2$, and the twisting rotation vector $W_3 \hat{e}_3$. As shown in Fig. 1, $W_1, W_2, W_3$ are rotation angles for the three rotation components respectively.

The red trapezoidal shape in Fig.1 (a) refers to the footwall of the fault, while the blue trapezoidal shape stands for the hanging wall of the fault. The adjacent place at the connection is the fault plane. $W_1$ model is relatively open in the XY plane, which is rotated at one end of the fault, passes the end and is parallel to the Z axis. $W_2$ model is the reverse of the rotation axis in the normal direction of the fault plane. One end of the fault is acted as the rotating base point and the rotation axis is defined by passing the end point and being vertical to the fault plane direction, warping relatively to the XY plane, to structure $W_3$ model.

2.2. Ground displacement due to fault disclination

The theory of dislocations is well known and will not be described here. Assume that the three kinds of rotational components of the fault are, respectively, $W_1, W_2, W_3$ and suppose $r_1, r_2, r_3$ are the distance from a point on the fault plane to the corresponding rotating axis. Then the relation of the related functions of the strike slip component $U_1$, the dip-slip component $U_2$, and the tension component $U_3$ of the point caused by the rotation of the fault can be expressed by (Fressengeas et al.,2011):

$$
\begin{align*}
U_1 &= r_1 (1 - \cos W_3) + r_1 (1 - \cos W_2) \\
U_2 &= r_3 \sin W_3 + r_2 (1 - \cos W_2) \\
U_3 &= r_1 \sin W_1 + r_2 \sin W_2
\end{align*}
$$

(3)
Fig. 1 The disclination described by the trapezoid body model
(a) the upper plate and the footwall of the fault; (b) Tension of disclination \( W_1 \)
(c) Twist of disclination \( W_2 \); (d) Raise of disclination \( W_3 \)

Similar to the point source dislocation theory, the coordinate of the dislocation source in the local coordinate system is assumed as \( \xi = 0, \eta = 0 \). The three-dimensional displacement field on the ground generated by fault disclination can be obtained through the formula (4).

\[
\begin{align*}
\delta_x' &= \frac{U_1}{2\pi} \left[ \frac{3\nu y}{R^2} + I_x^\gamma \sin \delta \right] \Delta \Sigma \\
\delta_y' &= \frac{U_1}{2\pi} \left[ \frac{3\nu x}{R^2} + I_y^\gamma \sin \delta \right] \Delta \Sigma \\
\delta_z' &= \frac{U_1}{2\pi} \left[ \frac{3\nu_0}{R^2} + I_z^\gamma \sin \delta \right] \Delta \Sigma \\
\end{align*}
\]

The surface displacement caused by the three dimensional rotation of the fault can be obtained by formula (5) through the numerical integration of the whole fault plane:

\[
\begin{align*}
\delta_x &= \delta_x^1 + \delta_x^2 + \delta_x^3 \\
\delta_y &= \delta_y^1 + \delta_y^2 + \delta_y^3 \\
\delta_z &= \delta_z^1 + \delta_z^2 + \delta_z^3
\end{align*}
\]

2.3 Ground displacement due to fault disclination and dislocation
The ground displacement can be expressed by the sum of the vectors of the displacement caused by the dislocation-disclination. The displacement caused by the transition motion of the fault can be determined by the classical dislocation theory. The slippage on the fault plane caused by disclination is characterized with uneven distribution. Thus, the commonly used finite element method can be used to
divide the fault plane into finite fault elements without gap and overlapping to determine the amount of each sliding unit. To meet the requirements of the point source dislocation, the distance from the point to the unit surface of the fault must be far greater than the element length of the fault. Each component of ground surface displacement caused by the disclination can be calculated by formula (3), (4), and (5). The ground displacement caused by the dislocation-disclination of the fault can be calculated by formula (6):

\[ u = u_1 + u_2 \]

Where, \( u_1 \) refers to the displacement caused by the dislocation and \( u_2 \) is the displacement caused by the disclination.

3. Data and methods

3.1. Data

The Longmenshan fault zone is located in the eastern margin of the Qinghai-Tibetan Plateau and the middle section of the North-South seismic belt. It is mainly composed of the Wenchuan-Maoxian fault (back mountain fault F3), the Yingxiu-Beichuan fault (central fault F2), and the Pengxian-Guanxian fault (front mountain fault F1). These three faults are nearly parallel to each other. The belt is approximately 30-40km wide and 500km long. The overall trend is NE (N40º -50º E). The inclination goes towards North West but the dip angle is uncertain.

In this paper, the data are selected from the actual measured GPS data of the Major National Science and Engineering "Crustal Movement Observation Network of China (CMONOC)" project group. The last observation before the earthquake was completed during the period of April-July of 2007. After the earthquake, China Earthquake Administration carried out a retest of these GPS points at the first time. Every point was observed for 2-3 days. The GPS station data sampling were taken with the intervals of 30s and 24h was defined as a period.

The double difference mode was adopted to get the regional velocity field of the crustal movement against the Eurasian plate by the GAMIT/GLOBK software. The result is shown in Fig.2, in which the black line means the geological surface trajectory of the fault. The red line is a simplified fault model based on the seismic activity. The red ball is from the GCMT catalog. The blue arrow stands for the GPS observations, with the pointing orientation as the direction and the length as the magnitude. The red real point signifies the city location.

3.2.1. Establishment of the fault model

USGS merges the Yingxiu-Beichuan fault, the Wenchuan-Maoxian fault and the Guanxian-Jiangyou fault into one which is represented by an equivalent fault. The fault parameters are set as follows: the starting point of the geodetic coordinate is B=32.5224 º, L=105.4260 º, trend taf=229.00 º, dip angle dt=33 º, length =315km, width =40km, the depth from the surface Depth=0.7411km. The seismogenic fault surface (315 km×40 km) is divided into m×n (21columns×5rows) rectangular sub-faults (15 km × 8 km).
3.2.2 The disclination model of the fault. We added the disclination model on the basis of the fault dislocation model given by USGS to achieve a disclination-dislocation model. By analysis of the surface GPS observation results, it is known that the Longmenshan fault movement is similar to the W2 model. The value of W2 is specified here. When the hanging wall and the foot wall of the fault is in the tension state, the extrusion state is negative. Considering the absorption of the medium around the fault, the hypothesis of this paper is that the fault produces a large disclination at the epicentre depth, and its disclination will decay continuously during the propagation process, and the disclination will be attenuated to the minimum when it reaches the surface.

Concerning the absorption of the medium around the fault, the hypothesis of this paper is that the fault produces a large disclination at the epicentre depth, and its disclination will decay continuously during the propagation process, and the disclination will be attenuated to the minimum when it reaches the surface.

The complexity of the Wenchuan coseismic fault model is featured by the follows: starting form the southern tip of the fault, the focal mechanism type changed from the thrust at the beginning into the final dextral strike slip through the transition zone of various types of alternating appearance of the focal mechanism. There is a certain tectonic setting for this subsection (Zhang et al. Zhao et al., 2009; Wang et al., 2009; Yi et al., 2012). Based on the Yi et al. (2012) focal mechanism type, the Longmenshan Fault Zone, which is ~315 km in length, is divided into 3 parts: the south, the middle and the north. The white line represents the boundary line (see Fig.2). In the middle section of the fault, the horizontal displacements of the ZHJI and 2037 H037 points calculated by the USGS dislocation model fit well with the GPS observations. Therefore, the disclination at the middle section is set as 0. The surface positions at both the southern end and the northern end are chosen as the rotating base point of the disclination. The orientation of the fault strike is acted as the rotation axis. According to formula (3), (4), (5), and (6), the horizontal displacement caused by the disclination is calculated by using PSGRN/PSCMP program Wang et al. (2006).

3.3. Determination of the disclination of the fault

In order to verify the existence of the disclination W2 component of the Longmenshan fault, GPS points which can represent the characteristics of the fault movement were selected. The disclination W2 goes through a grid search in the scope of [0.0", 10"] with the interval of 0.5" to calculate the residual of each point as shown in Fig.3. In Fig.3, the horizontal axis represents the magnitudes of the disclination and the vertical axis represents the residual of the surface displacement. The black, green, red and blue lines represent, respectively, the residuals at the points of H046, H040, H031, and H025. In addition, it can also be seen from Fig.3(a) and (b) that the residuals of N component and E
component exhibit approximately linear change with the increase of the disclination. In Fig.3(c), the point residual of each point exhibits a parabolic distribution along with the increase of disclination $W_2$. When the disclination $W_2=0.0^\circ$, the fault model is a simple dislocation model and the residual of each point is large.

The influence of disclination on the point position residual of each point can't be negligible. When the disclination $W_2=1.0^\circ$, the residual of the E component at H025 point and the residual of the point position become smaller instantly. When the disclination is $5.0^\circ$, the residuals of all points basically reach the minimum, indicating the existence of the $W_2$ component with the value of $5.0^\circ$. In order to demonstrate that the disclination-dislocation is better than the dislocation alone model in explaining the surface seismic displacement, more GPS observations are needed for statistical verification.

![Image](image_url)

**Fig.3** The relationship between the residual of GPS points and $W_2$ disclination of the fault: (a) The residuals of N-direction; (b) The residuals of E-direction; (c) The residuals of point

4. Results and discussion

4.1. Analysis of the results

In Fig.4, the blue and the dark blue arrows represent, respectively, the GPS observations of different scales. The green and the dark green arrows stand for the horizontal displacement of different scales calculated by the dislocation model. The purple and the red arrows refer to the horizontal displacement of different scales calculated by the disclination-dislocation.

By comparing the calculated results by the dislocation model and by the disclination-dislocation with the GPS observations. It is found that the horizontal displacement of the three are similar in magnitudes and in direction except for a few points. At the points of H025, H031, H032 and Z158 in the northern section of the fault, the horizontal displacement calculated by the disclination-dislocation is closer to the GPS observations than that calculated by the dislocation model. At the points of H040, H052, JYAN and ZHJI in the southern section of the fault, it is also found that the horizontal displacement calculated by the disclination-dislocation is closer to the GPS observation value than that calculated by the dislocation model. At the points of JB34, H046, and H047 in the neighborhood of the middle section of the fault, the horizontal displacement calculated by the dislocation model is consistent in direction with that calculated by the disclination-dislocation, but in magnitudes the result calculated by the disclination-dislocation is much closer to the GPS observations than that calculated by the dislocation model.
4.2. The dislocation model VS the combined model

When the magnitude of the horizontal displacement is close to each other, it is important to study its direction. For the convenience of comparison, the magnitudes of the variable is not considered. The GPS observations is reduced to the unit vector that is vertical to the fault strike, on the basis of which the results calculated by the dislocation model and by the disclination-dislocation are treated as shown in Fig.5. In Fig.5, the blue arrow is the unit vector of the GPS observations, the green arrow means the unit vector of the dislocation model, and the purple arrow is the unit vector of the disclination-dislocation. Fig.5 shows that most of the green arrows are covered with purple arrows, indicating that the predictions by the disclination-dislocation are better than the dislocation model. In this paper, 102 points are totally chosen for calculation, of which 16 points are with the direction difference more than 20° and 86 points are with the direction difference less than 20°, accounting for 84.3% of the total.

The GPS observation is acted as the true value. The dislocation model and the disclination-dislocation are respectively applied for calculating the direction residual of each observation point. The direction residuals less than 20° are classified according to the interval of 5° and the percentage of the points in each interval is calculated as shown in Fig.6. As a whole, the percentage exhibits a normal distribution. In the interval where the direction residuals is smaller, which have a concentrated features. Except for the interval of [10°, 15°], the percentage of the disclination-dislocation is larger than that of the dislocation model in other intervals. At the interval of [-10°, 10°], the dislocation model is 54.9% while the disclination-dislocation is 62.75%, which proves that the latter is superior to the former.
Fig. 5 The horizontal deformation profiles across the Longmenshan mountain fault

![Horizontal deformation profiles](image)

Fig. 6 The percentage of the number of GPS points varies with the residual

![Percentage of GPS points](image)

4.3 Discussion

4.3.1. The points residual. In section 3.3, the reason why the points of H046, H040, H031, H025 and other GPS sites are chosen as the feature points of the fault are explained when the disclination is determined. First of all, the points above are respectively located in the southern, middle and northern sections of the fault. Then, the surface displacement is at the same magnitude. The displacement of point H032 is relatively large. The relationship between the residual of the point position and the disclination $W_2$ of the fault is shown in Fig. 7, in which the red line refers to the residual of the
N-direction, the black line is the residual of the E-direction, and the blue line stands for the residual of the point. When the disclination is close to 5°, the point position residual at this point reaches the minimum value, which also shows the existence of the component and the size of the disclination $W_2$.

![Graph showing the relationship between the residual of the H032 points and $W_2$ disclination of fault](image)

**Fig. 7** The relationship between the residual of the H032 points and $W_2$ disclination of fault

### 4.3.2. Other factors

In the western part of the Longmenshan fault, compared to the predictions by the dislocation model, the predictions by the disclination-dislocation are more consistent with the GPS observations in Fig.4. However, in the Sichuan basin region, the results calculated by the disclination-dislocation are not superior than those calculated by the dislocation model.

The difference between the simulation results and the actual observation values can be explained in a reasonable way from the following aspects: on the one hand, the GPS observations are related to the relative position of the fault. Generally, the displacement is greater near the fault and the residual is also larger. As shown in Fig.4, at the points of H028, H031, and H036, which are far away from the fault, the fitting effect is better, whereas at the points of H044, H049, and PIXI, which are closer to the fault, a great difference exists between the simulation results and the GPS observations. This may be related with the existence of the low speed skating delamination in the region or may be associated with the observation time. If the GPS observations is not obtained in the first time, it will be difficult to distinguish the post earthquake slip and the coseismic displacement. On the other hand, the elevation difference between the two sides of the Longmenshan fault is nearly 5km and the lateral difference between the two sides is large. The influences of the terrain factors and the medium difference on the GPS observations are still under further investigation.

### 5. Conclusion

In this paper, the disclination-dislocation of the Longmenshan fault is built on the basis of the USGS dislocation model. The dislocation model and the disclination-dislocation model are, respectively, used to calculate the surface displacement. The calculated results are compared with the coseismic GPS observations. It is found that the horizontal displacement calculated by the disclination-dislocation model is much closer to the GPS observations than the dislocation model. The results prove that the disclination-dislocation is the further supplement and perfection of the dislocation theory. By the disclination-dislocation, the surface GPS observations can be explained from the three-dimensional space translation and rotation of the fault. This model not only helps us understand more clearly about the earthquake and the crust deformation mechanism, but also provides us a reference for the research of the lithosphere tectonic movement and the earthquake dynamics.

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