The Application of GNSS to Monitoring Fault Deformation

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Key words: GNSS, fault deformation, baseline, crustal block, seismicity

SUMMARY

Strong earthquakes often occur along or near active faults. Thus, the monitoring and researches on fault deformation are quite important. Methods have been used to monitor fault activities for many years, such as short-leveling, short-baseline and integrated monitoring profile across fault belts. GNSS observations are mainly used to obtain horizontal velocity fields in large areas and to research on activities and deformation of major blocks. GNSS technology has been used in different ways to monitor and study deformation of faults. In this paper, some applications and new explorations of GNSS are discussed in the aspects as follows: 1. Researches on and monitoring strike-slip activities of faults. 2. Researches on and monitoring vertical activities of faults. 3. Setting up strain models of blocks on both sides of faults based on the deformation of each block, according to which activities and deformation of faults can be deduced. Then, a comparison can be made between the deduced results and the actual measurements. And it is concluded that the larger discrepancy between these two results indicates stronger impacts between the blocks, which could be important to the prediction of the locations of strong earthquakes, seismic risk analysis, as well as the trend of seismicity in a particular area.

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1. INTRODUCTION

Global Navigation Satellite System (GNSS) observations are usually used to study on horizontal deformation fields of large areas, block movements and inversion for deformation caused by earthquakes(Xu et al, 2009; Li et al, 2009; Jiang et al, 2003; Zhu et al, 2002; Huang et al, 2003; Liu et al, 2010; Zhang and Zhu, 2000; Jin and Zhu, 2002a; Jin and Zhu, 2002b; Jin and Zhu, 2002c; Cheng and Zhu, 2001; Ying et al, 1999; Zhu et al, 1999; Li et al, 2004; Li et al, 2001). GNSS is also being used more and more in study on fault deformation. The fault activities with compressional or extensional features can be shown from vectors of GNSS displacement or velocity on both sides of the fault by projecting them to the profile perpendicular to the fault, and the strike-slip or shear movement between both sides of a fault could be shown from fault-parallel components of GNSS vectors by marking them to the profile. Those meaningful efforts are important for researches on fault deformation and precursory deformation phenomena of strong earthquakes. It is difficult to use and study the vertical components of GNSS due to the relatively poor accuracy, but there is plenty of information in them, so it is more valuable to explore information in the vertical components. In recent years, comparison research between the vertical component of GNSS and precise leveling indicates that, although physical meanings of the vertical coordinates of them are different and their errors are different—there is a systematic error between them, the vertical velocities derived from both methods by certain data processing are well consistent and complementary to each other (Yang et al, 2011; Han et al, 2012; Gao et al, 2012). As a result, GNSS is being paid more attention to in researches on vertical deformation of faults (Bo et al, 2009).

2. MONITORING AND RESEARCH ON STRIKE-SLIP ACTIVITY OF FAULTS WITH GNSS

Two national scientific projects “Crustal Movement Observation Network of China” and “China Mainland Tectonic Environment Monitoring Network” have been carried out in China, in which over 2000 regional GNSS sites have been constructed. For seismic researches, GNSS sites are deployed densely along seismic belts. Repeated observations have been done, which have provided data for researches on fault activity. Previous researches on tectonic activity indicate that different sections of a fault can be distinguished according to different characteristics of fault activities. Therefore, the research results of strike-slip activity of faults can be estimated by GNSS measurements qualitatively and quantitatively in different sections (Zhang et al, 2003). Figure 1 shows the distribution of GNSS velocities along the profile across Xianshuihe fault, in which the horizontal axis indicates the distance in km from projection of GNSS station to the left end along the profile; the vertical line in the middle indicates Xianshuihe fault; and the vertical axis indicates the component of velocities of GNSS stations in the direction of the fault striking (N40˚W). Figure

2 shows NS velocity components of GNSS stations in the profile across Xiaojiang fault which is in the direction of NS. From figure 1 and figure 2 we can see as follows: ① the velocity difference between both sides of Xianshuihe fault is comparable to that of Xiaojiang fault, which is about 10mm/a; ② the spatial jump of twisting displacement distribution along Xianshuihe fault indicates the existence of a significant main slip plane in the fault, which means this part of the fault slips easily and won't accumulate more energy because the plates are relatively hard to get locked in a short time. There seems to be a twisting deformation belt along Xiaojiang fault, which indicates the presence of twisting deformation to some extent or accumulation of multiple strike-slip faults; ③ these two faults show obviously left-lateral activities, which is consistent with the tectonic moving trend of the area. It can be concluded that tracing such fault deformation will be very important and valuable for researches on crust stress variation and seismicity.

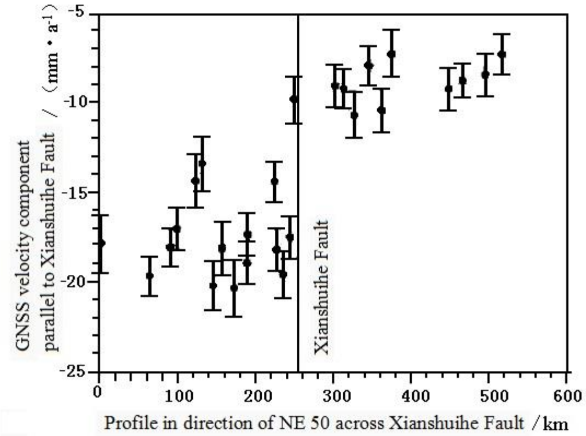


Fig. 1 the GNSS velocity profile across Xianshuihe fault

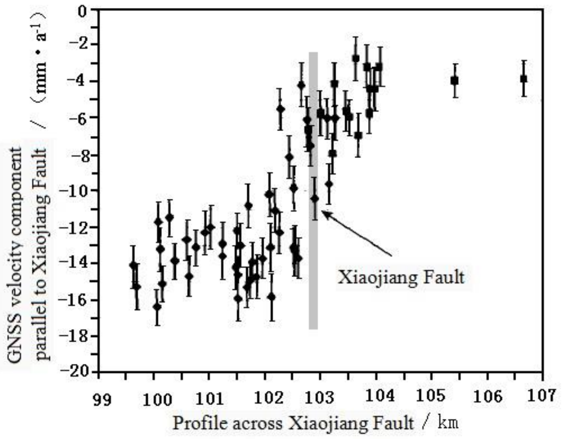


Fig. 2 the GNSS velocity profile across Xiaojiang fault

The characteristics and magnitude of fault activity can be estimated by using displacement field of GNSS vectors. But it would be difficult to assess the quality and magnitude of fault activity when a large common parallel component is contained in the movements of GNSS stations located on both sides of the fault, and thus the reference frame for movement should be changed. And then GNSS displacement should be decomposed into vectors of parallel to and perpendicular to the fault. The results are useful to assess the active pattern of fault, normal or reverse, as well as it is locked or not.

3. MONITORING AND RESEARCHES ON VERTICAL ACTIVITY OF FAULTS WITH GNSS

The vertical component of GNSS displacement is relatively sensitive to the interference caused by ionosphere, troposphere, vertical satellite orbital perturbation, etc. Effects of these factors are difficult to eliminate completely, which results in positioning error relatively larger in the vertical component than that in the horizontal ones. To some extent, the variation of these factors has limited application of GNSS for monitoring and research on vertical activity of faults. But the special advantages of GNSS are shown in vertical co-seismic displacement measurement and it has been confirmed by researches on deformation of the hypocentral region of Wenchuan Earthquake

(Bo et al, 2009). Some recent studies show the existence of common mode error in vertical component of GNSS (Yang et al, 2011). The factors mentioned above are almost the same for two close GNSS stations, and it can be concluded that vertical common mode error of closely distributed stations should be larger. Therefore, common mode error of GNSS stations can be eliminated by the difference of vertical coordinates between two stations if they are close enough. In other words, vertical difference between two close stations measured by GNSS should be good enough despite the poor vertical positioning accuracy of GNSS. To calculate the vertical displacement of two sides of a fault, we only need to know the accurate vertical differences of concerned stations on two sides and their variation. So it is practicable to measure vertical deformation of faults using GNSS, through which the relation between mechanism of fault deformation and generation of earthquakes can be studied. Normally, vertical deformation of faults can't be easily observed in vertical velocity field of GNSS. These are three reasons: ① the spatial dense of GNSS stations near the fault is too low or these stations are not properly distributed; ②vertical movements on both sides of faults always contain synchronous deformation (moving up or down simultaneously); ③ errors induced by vertical satellite orbital perturbation, ionosphere, troposphere etc. can not be eliminated completely, resulting in larger common mode errors. Those three reasons cause difficulty in analyzing vertical deformation of faults, but through further researches on the three factors above, it is possible to distinguish vertical movement and deformation of faults by appropriate vertical reference datum.

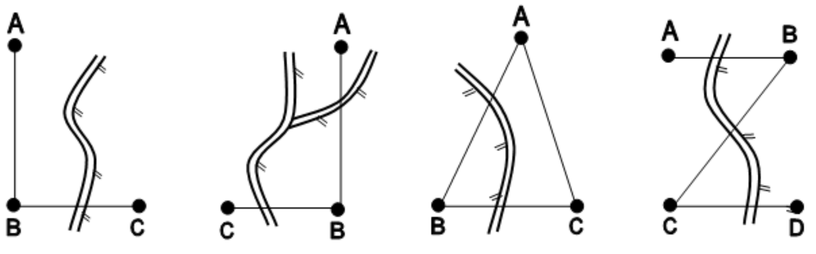
Effects of vertical satellite orbital perturbation would be different between two distant stations. Ionosphere and moisture in troposphere at faraway stations would vary a lot, and their common mode errors might be reduced, leading to larger error in vertical difference between them. However, vertical deformation of two distant points is rarely analyzed. For example, difference of velocities of vertical deformation between North China and Qinghai-Xizang Plateau is remarkable, and seismic activities in these two regions are also greatly different. Such a conclusion about different vertical velocities of North China and Qinghai-Xizang Plateau is supported by different methods. But it is difficult to precisely determine the difference. To know the accurate amount of deformation in Qinghai-Xizang Plateau is usually not necessary for research on earthquake prediction for North China, and vice versa. Actually there is a big limitation in precise leveling for measuring vertical deformation between two distant points. Firstly, time spent in leveling makes it hard to deal with deformation during the measuring; secondly, error propagation and accumulation are proportional to the square root of distance in leveling. When the distance between two points is large enough, the error can't be neglected. On the contrary, using velocity results from continuous GNSS observations as constraint references in large leveling network can effectively reduce the influence of cumulated observation error on the estimation of velocity of vertical crustal deformation (Gao et al, 2012).

4. BLOCK ACTIVITY AND FAULT DEFORMATION

The horizontal deformation field of mainland China derived from GNSS shows the regional consistency of displacement vectors in magnitude and direction, which indicates the existence of integrated movement and deformation in a block cut by major deep-reaching faults. The characteristics of movements and deformation are usually different in different blocks. The bigger difference between two adjacent blocks means stronger activities and deformation of the fault between them, as well as higher seismicity. The distribution of crustal deformation within a block would be relatively regular, which could be described by mathematical models. The parameters of these models could be determined by using data of displacement field according to least squares theory (Li et al, 2001). Then deformation of places without GNSS stations could be estimated using these models. Thus, suppose there was no fault between these two blocks, deformation on the boundary could be estimated respectively by extrapolating deformation from both blocks. In the process of movement and deformation of two adjacent blocks, the two blocks strongly restricts each other by interaction on the boundary fault, and it will cause extension, compression, lock, and strike slip etc. on the boundary. Deformation measured at the boundary of blocks usually differs greatly from results derived from models, and the reason lies in the strong constraint on the boundary. Unlike relatively consistent deformation inside blocks, deformation near the boundary deviates from the consistency could be taken as distortion caused by interaction between blocks. The distortion distorted or hindered what the deformation should be on the boundary according to the deformation model of the block. The larger deviation, the stronger distortion, as well as the more strain energy accumulated. On the contrary, if the measured movement and deformation of faults are consistent with the results deduced from models, it indicates the fault activity conform to the whole block movement, which means no stronger energy accumulated around. So to understand the difference, that is to know the intensity of distortion, has great significance for study the features and intensity of fault activity and for estimation of risk and intensity of coming earthquakes.

4.1 *Deformation measured directly on both sides of faults*

A lot of short-leveling and short-baseline across faults are deployed up in China as illustrated by figures 3 and 4. And observation sections (about 50 km long) with multiple methods across fault zones are set up for monitoring wider fault belt (A lot of such profiles have been set up across some major seismic belt since the 10th 5 year period for earthquake monitoring). PS-InSar can be adopted for the most inaccessible places or concerned areas (Luo et al, 2012). These methods can all provide the real movement of both sides of faults. Using observations shown as in figures 1 and 2 or other similar methods, difference of movement and deformation between both sides of faults can be easily obtained if there are enough GNSS stations near the fault. It should be the evidence for us to find the segment with accumulated strain (stress) if the deformation varied a lot and distributed irregularly along the fault.



（a）　　（b）　　（c）　　（d）

Fig.3 Sketch maps of leveling site across fault
（a）L type site 1; （b）L type site 2; （c）Triangular type site; （d）Z type site; ● Bench mark; ‖ Fault

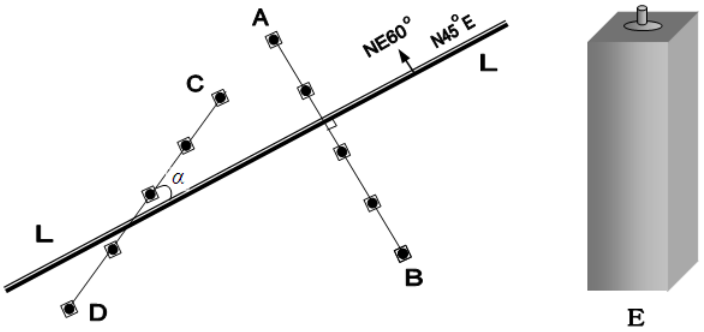


Fig.4 Sketch map of base-line site across fault

Legends: LL: Fault; AB: Vertical base-line; CD: Base-line across fault with a sharp angle; E: Base-line post with a mark

4.2 *Difference of movement on both sides of fault deduced from models*

There are four mathematical models to describe movements and deformation of blocks, namely rigid motion model, elastic-plastic strain model, rigid elastic-plastic motion-strain model, and integral-rotation linear strain mode (Li et al, 2001; Li et al, 2006). The first model assumes the block is only in rigid motion; the second merely takes elastic-plastic strain of blocks into consideration; both rigid motion and elastic-plastic motion are considered in the third model; and the forth model also considers the spatial linear variation of strain on the basis of the former models. The more complex the model is, the more parameters need to be determined. To deal with more parameters, more intensely and more regularly distributed GNSS stations are needed. In addition, it is expected that the model fits the regular deformation of the block, which is to know the deformation regulation of the whole block. Thus the location of significant difference between actual and calculated deformation can be found. Such a location would be the place with strong interaction of blocks and intensive distortion, and could be the possible location of coming earthquakes since the strain energy would accumulate easily here. According to these reasons, the third model is recommended, which is rigid elastic-plastic motion strain model of blocks. The model can be described as follows (Li et al, 2001):

$$\begin{bmatrix} V_e \\ V_n \end{bmatrix} = \begin{bmatrix} -r\sin\varphi\cos\lambda & -r\sin\varphi\sin\lambda & r\cos\varphi \\ r\sin\lambda & -r\cos\lambda & 0 \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \begin{bmatrix} \varepsilon_e & \varepsilon_{en} \\ \varepsilon_{ne} & \varepsilon_n \end{bmatrix} \begin{bmatrix} (\lambda-\lambda_0)r\cos\varphi \\ (\varphi-\varphi_0)r \end{bmatrix} \qquad (1)$$

where V_e is the eastern component of displacement of the point; V_n is the north component; r is the radius of the Earth; λ and φ denotes the longitude and latitude of the point; ω_x, ω_y, and ω_z are called Eular vectors and denote the block rigid motion vectors; ε_e, ε_{en}, ε_{ne}, and ε_n denote horizontal strain parameters of the block; λ_0 and φ_0 denotes the longitude and latitude of the center of the block. It is clear that Eular vectors and horizontal strain parameters of a block can be determined according to least squares theory by substitution of GNSS results into formula (1). Thus the horizontal movement and deformation model of ground points are determined in xyz earth-centered coordinate system, and horizontal movement vectors of any point $V=(V_e\ V_n)^T$ can be calculated by substituting its longitude λ and latitude φ into Formula (1). If there are enough GNSS stations on both blocks beside a fault, displacements of both sides can be calculated by each model established according to Formula (1) into which the longitudes and latitudes of points along the fault are substituted. Then the fault's activity, including twisting and extension or compression, could be determined according to the models.

As early as in 2004, the above method has been used to obtain the calculated difference of activity of both sides of Longmenshan fault (Figure 5). In Figure 5, the moving parallel component of the fault belt has been deducted. Seen from Figure 5, the south-west segment of Longmenshan fault is strongly pressed in a near east-west direction, while the north-east segment is in a tension pattern with right-lateral strike slip. From horizontal velocity field of GNSS in the same period in Figure 6 (Bo et al, 2006), it can be seen that the difference of displacement on both sides of Longmenshan fault is not significant before 2008 Wenchuan Ms 8.0 Earthquake. And there is no remarkable anomaly in short-leveling observations across the fault (Although short leveling in Gengda showed a great variation which is later verified to be disturbance, there remains arguments. Bo et al, 2009; Zhu et al, 2010). Therefore, results shown in Figure 5 seem to be doubtable. With further analysis, it is just the difference between those results that possibly indicats the risk of the coming earthquake. The seismic risk has been proposed as early as in 2004 in a report (Researches on the relation between evolution of fault deformation and strong earthquake, in the archives of First Crust Deformation Monitoring and Application Center, China Earthquake Administration). Figure 5 shows the calculated in situ changes extraploated from block moving models which is determined on the basis of observations, while Figure 6 shows actual measurements that illustrate no such obvious changes along the fault. No obvious deformation here is exactly the result from strong interaction of the two blocks. In other words, movement of the block is stucked near the fault, but the whole block continuously moves until accumulated energy is large enough to rupture the fault or to generate new fault, through which the deficiency of deformation is compensated by coseismic deformation. Rupture of 2008 Wenchuan Ms 8.0

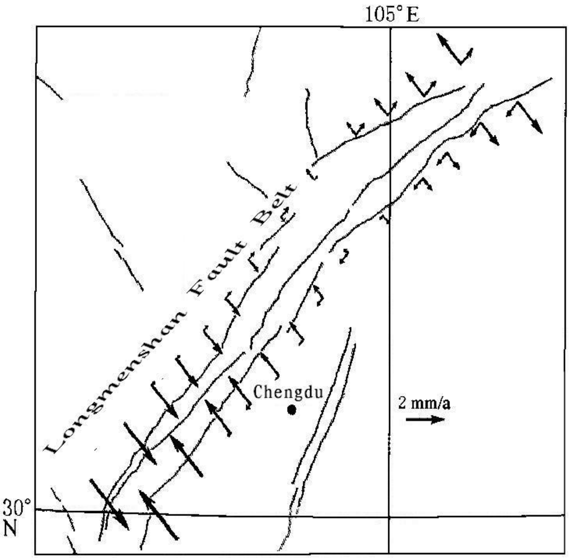


Fig.5 Differences of relative activity between two sides of Longmenshan fault given by block strain model

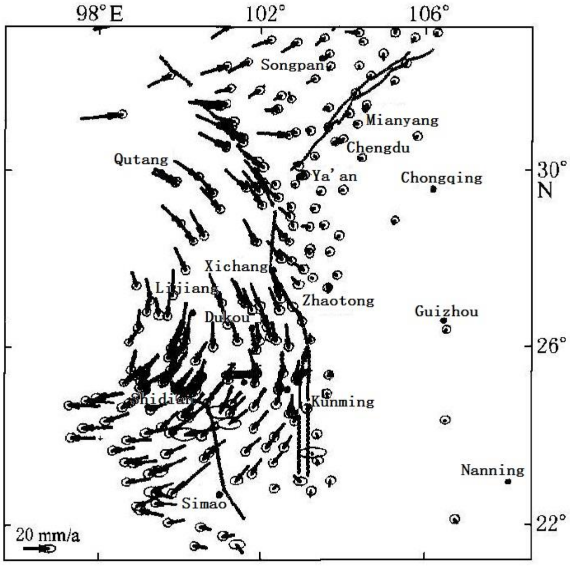


Fig.6 Crust horizontal movement in Sichuan-Yunnan area (Under the None-rotation reference of China Continent)

Earthquake shows the main thrust-up pattern in the middle-south segment of Longmenshan fault, and the main right lateral strike-slip pattern shown by several aftershocks in the middle-north segment (Xu et al, 2010), which qualitatively compensates the deficiency of deformation shown in Figure 6 with respect to Figure 5. Therefore, difference between Figure 6 and Figure 5 could be an evidence or clue for prediction of the coming earthquake. It should be noticed that movement and deformation derived from models should represent what the in situ normal movements and deformation of the boundary would be. To ensure that, the rank of faults should match with the rank of blocks. In other words, to study a first-level boundary, blocks on both sides described by models must be of the first level. This method needs more test and improvement although evidence shows that it's possibly supported by 2008 Wenchuan Ms 8.0 Earthquake.

5. DISCUSSION AND CONCLUSION

Deformation of faults is usually monitored with short-leveling and short-baseline across faults, and decades of observations are accumulated with lots of research results. Since the China's 10th five year, a lot of observation sections with multiple measurement methods are deployed across major faults in China. The length of an observation section is about 50 km. Several creepmeters and leveling pipes are also deployed. There are over 2000 campaign and continuous GNSS stations for crustal deformation and earthquake study in China, and a series of research results on large scale crustal movement and deformation of blocks have been achieved. Because the distribution of GNSS stations are not dense enough, deformation near faults is always extrapolated in the analysis of fault activity using regular movements and deformation of large area and integral blocks. These calculated results are usually quite different from the measured results, and it is easily regarded as error of models, which limits the application of GNSS data to researches on deformation of faults.

It is concluded that magnitude and feature of the difference between calculated deformation from models and measurements could be important to estimate the risk of coming earthquakes, if the model is appropriate and there are enough properly distributed GNSS stations. If the deformation deduced from the models differs greatly from measurements, it indicates that aberrant deformation of the fault occurs with the interaction and mutual impact between the adjacent blocks. The larger aberrant deformation means the larger energy accumulated and the more possibility of strong earthquakes' preparation. Activity of Longmenshan fault before Wenchuan Earthquake has proved the conclusion to some extent. Thus, it is concluded that GNSS measurements together with other methods is very important to researches on fault deformation and estimating seismic risk.

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BIOGRAPHICAL NOTES

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Associated achievements: Li Yanxing, Zhang Jinghua, Feng Shengtao. 2011. A rotating elastic plate/block model for Eurasia. Geodesy and Geodynamics 05/2011; 2(2):71-78. DOI: 10.3724/SP.J.1246.2011.00071.1

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