Coseismic vertical deformation of the $M_s8.0$ Wenchuan earthquake from repeated levelings and its constraint on listric fault geometry*

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Abstract The devastating $M_s8.0$ Wenchuan earthquake ruptured two large parallel thrust faults along the middle segment of the Longmenshan thrust belt. Preseismic and postseismic leveling data indicated the hanging wall of the Yingxiu-Beichuan-Nanba thrust fault mainly presented coseismic uplift with respect to the reference point at Pingwu county town, and the observed maximum uplift of 4.7 m is located at Beichuan county (Qushan town) which is about 100 m west of the fault scarp. The foot wall of the Yingxiu-Beichuan-Nanba thrust fault mainly showed subsidence with maximum subsidence of 0.6 m near the rupture. By employing a listric dislocation model, we found that the fault geometry model of exponential dip angle $\delta=88^\circ \times [1-\exp(-9/h)]$ with depth of 18 km and uniform thrust-slip of 5.6 m could fit the observed coseismic vertical deformation very well, which verifies the listric thrust model of the Longmenshan orogenic zone.

Key words: Wenchuan earthquake; leveling; vertical deformation; listric faulting

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1 Introduction

The devastating $M_s8.0$ Wenchuan earthquake on 12 May 2008 struck densely populated Sichuan province, China, and killed more 80 000 people, injured over 370 000 people. After the event, China Earthquake Administration (CEA) organized a comprehensive investigation project, including field investigations of surface ruptures, regional geodetic measurements (GPS, leveling and gravity), geophysical exploration, and engineering damage investigations.

Field investigation results show that the $M_s8.0$ Wenchuan earthquake ruptured two large parallel northeast-striking thrust faults simultaneously along the middle segment of the Longmenshan thrust belt at the eastern margin of the Tibetan plateau (Figure 1, Xu et al, 2008, 2009a, b). The west rupture zone appeared along

the central Longmenshan active fault named Beichuan fault (or Yingxiu-Beichuan fault), with elongation over 200 km from southwest of Yingxiu town (the epicenter), Wenchuan county, to northeast of Nanba town, Pingwu county. The east rupture zone appeared along the front Longmenshan active fault called Pengguan fault (or Guanxian-Jiangyou fault), with elongation about 70 km from Tongji, Pengxian county, to Shangzao, Anxian county. A narrow northwest-striking rupture zone named Xiaoyudong rupture zone, links the two major rupture zones at the southern end of the Pengguan fault through a lateral ramp (Figure 1, Xu et al, 2009b).

Fault scarps of the Wenchuan earthquake on the surface mainly show high angle (60° – 90°) dipping northwest from field investigations, the dip angle at the depth of 15–20 km, however, is only 26° – 47° from focal mechanism solutions of different groups (Li et al, 2008b). Some researchers have attributed this dip angle change to listric-like geometry of the rupture fault from geological context and three dimensional distribution of

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aftershocks (Huang et al, 2008; Zhang et al, 2008; Chen et al, 2009; Wu et al, 2009; Xu et al, 2009a), but due to lack of high resolution seismic sounding data, the fault geometry is still not well constrained. Coseismic deformation data could provide some information on fault geometry inversion of the Wenchuan earthquake. For example, by jointly using GPS coseismic horizontal deformation data and InSAR line-of-sight deformation data, Shen et al (2009) inverted fault geometry and slip distribution of the event. They found that from southwest to northeast, the fault geometry changes from moderately northwest dipping to near vertical, and the rupture changes from predominantly thrust to dextral faulting. However, due to lack of near-field coseismic deformation either from GPS or InSAR, the detailed geometry of the fault is still unclear. In addition, although geologists have gradually reached agreement on rupture length and coseismic slip pattern of the Wenchuan earthquake, there have been some debates on the maximum vertical offset at Shaba village, north of Qushan town, Beichuan county (Li et al, 2008a; Liu et al, 2008; Xu et al, 2009a, b). In this paper, we use the near-field coseismic vertical deformation data obtained from precise repeat levelings to invert fault geometry of the Wenchuan earthquake and discuss its implication to the maximum dip slip and maximum vertical offset.

2 Levelings

2.1 Preseismic levelings

Precise leveling is important for maintenance of the national elevation datum as well as crustal deformation monitoring. Before the Wenchuan earthquake, there were several first-order and second-order leveling routes deployed across the Longmenshan thrust belt (Figure 1), which were jointly surveyed by State Bureau of Surveying and Mapping (SBSM) and CEA. The Wenchuan-Yingxiu-Chengdu primary leveling route, which goes across the south end of the Yingxiu-Nanba rupture zone, was leveled twice before the event by SBSM respectively in 1975 and 1997. The Maoxian-Beichuan-Mianzhu first-order leveling route across the middle portion of the rupture zone was leveled three times before the earthquake by CEA respectively in 1983, 1987 and 1997. Around the north portion of the rupture and the aftershock zone, four second-order leveling routes namely the routes of Beichuan-Guixi, Mianyang-Guixi, Guixi-Pingwu and Pingwu-Qingchuan were deployed, which were leveled only once before the earthquake by

Figure 1 Pre-seismic leveling routes around Longmenshan fault belt. Black solid line stands for the first-order leveling route, black dotted line for the second-order leveling route, and gray thick line for ruptures of Wenchuan earthquake.

SBSM respectively in 1983, 1983, 1983 and 1986.

2.2 Postseismic leveling

In September and October 2008 shortly after the Wenchuan earthquake, the First Monitoring Center and the Second Monitoring Center, CEA, jointly conducted first-order repeated levelings of the Mianzhu-Beichuan, Beichuan-Guixi, Jiangyou-Guixi and Guixi-Pingwu routes (Figure 2). In May 2009, the Second Monitoring Center, CEA, conducted another first-order releveing along the Maoxian-Beichuan route west of the rupture zone, but unfortunately failed to connect the tie-point of the former 2008 leveling routes at Qushan town, Beichuan county, because of blocking of the Tangjiashan barrier lake induced by the great event. The Wenchuan-Yingxiu-Chengdu leveling route and the Pingwu-Qingchuan leveling route across the south and north ends of the rupture zone, were not resurveyed because most of the original leveling benchmarks were lost before the event.

3 Coseismic vertical deformation and error estimation

3.1 Coseismic vertical deformation

Coseismic vertical deformations of the Wenchuan earthquake are deduced from height difference changes before and after the event. In order to decrease the contamination of interseismic vertical deformation, we use the last preseismic leveling data of each route. For the releveing routes in 2008, we set the benchmark Pingbai 2 (104.525°E, 32.410°N) at the west end of the route

Figure 2 Post-seismic repeated leveling routes across the rupture zone of the Wenchuan earthquake. Black dotted line represents repeated leveling route conducted in September 2008; black solid line represents repeated leveling route conducted in May 2009; gray thick line represents rupture of the Wenchuan earthquake; and black circle represents relocated aftershocks of Wu et al (2009).

near Pingwu county town as one reference point, and for the isolated Maoxian-Beichuan releveing route in 2009, we set the benchmark Maobei 1 (103.878°E, 31.698°N) at the west end of the route near Maoxian county town as another reference point. According to regional interseismic vertical deformation result (Lu et al, 1996), the differential uplift rate between the two reference points is less than 1.0 mm/a. If we consider the long span of 1983 to 2008, the vertical deformation bias with respect to the two individual reference points would be less than 25 mm.

Table 1 lists the coseismic vertical deformation results, and Figure 3 shows the corresponding vertical deformation vector. In order to show more vertical deformation of the Wenchuan earthquake, coseismic vertical displacements derived from GPS measurements and gravity measurements are also included and plotted in Table 1 and Figure 3, where vertical deformations of GPS are obtained from two campaigns in summer of 2007 and in May to June of 2008 shortly after the Wenchuan earthquake (CMONOC Group, 2008). Vertical displacements of gravity surveys are derived from coseismic gravity changes between May 2007 and October 2008 measurements, and only Bouguer gradient of surface elevation change was taken into consideration, where Bouguer gradient is taken $0.1964 \times 10^{-8} \text{ m} \cdot \text{s}^{-2}/\text{mm}$.

From Table 1 and Figure 3 we can see that, the Yingxiu-Beichuan fault is the major rupture fault during the Wenchuan earthquake, where the hanging wall (NW side) of the rupture zone mainly showed uplift with large magnitude after the event, and the uplift decayed rapidly northwestward. The benchmark Beiyun 1, which is only about 100 m west of the fault scarp at Qushan town, Beichuan county, showed the maximum uplift of 4.7 m. The foot wall (SE side) of the Yingxiu-Beichuan rupture zone mainly showed subsidence after the event, the maximum subsidence along the fault valley being around 0.6 m near Beichuan county town. The vertical offset between two walls of the Yingxiu-Beichuan fault is about 5.3 m near Qushan town, Beichuan county.

3.2 Contamination of non-coseismic deformations

It is necessary to point out that, the vertical deformations listed in Table 1 are not purely coseismic vertical displacements of the Wenchuan earthquake, and they actually contain contaminations of leveling errors, pre-seismic deformation and postseismic deformation.

According to leveling code of China, the total mean error limit M_W of the first-order leveling is 1.0 mm/km, and that of the second-order leveling is 2.0 mm/km. The deformation error M_V between pre-seismic leveling and postseismic leveling can be estimated by following equation:

Table 1 Coseismic vertical deformation of the Wenchuan earthquake

Point name	Long./°	Lat./°	Vertical displacement/m	Pre- and post-seismic survey time	Remarks
Pingbai 2	104.526	32.410	0	1983–2008-09	Leveling benchmark (ref. 1)
Pingbai 3	104.554	32.388	−0.025 7	1983–2008-09	Leveling benchmark
Pingbai 5	104.620	32.386	−0.043 8	1983–2008-09	Leveling benchmark
Pingbai 6	104.650	32.375	−0.108	1983–2008-09	Leveling benchmark
Pingbai 7	104.670	32.344	−0.068 3	1983–2008-09	Leveling benchmark
Baiyun 1	104.686	32.344	−0.045	1983–2008-09	Leveling benchmark
Baiyun 3	104.722	32.324	−0.053 5	1983–2008-09	Leveling benchmark
Baiyun 5	104.764	32.296	0.069 6	1983–2008-09	Leveling benchmark
Baiyun 11	104.833	32.202	1.003	1983–2008-09	Leveling benchmark
Baiyun 14	104.780	32.105	−0.377 7	1983–2008-09	Leveling benchmark
Baiyun 15	104.762	32.079	−0.278 8	1983–2008-09	Leveling benchmark
Baiyun 16	104.746	32.065	−0.302 5	1983–2008-09	Leveling benchmark
Baiyun 17	104.719	32.055	−0.392 8	1983–2008-09	Leveling benchmark
Baiyun 20	104.660	32.020	−0.581 5	1983–2008-09	Leveling benchmark
Beiyun 7	104.594	31.951	−0.619 6	1986–2008-09	Leveling benchmark
Beiyun 3	104.528	31.870	−0.504	1986–2008-09	Leveling benchmark
Beiyun 1	104.458	31.829	4.711 4	1986–2008-09	Leveling benchmark
Beiguan 6	104.443	31.663	−0.202 1	1997–2008-09	Leveling benchmark
Beiguan 8	104.395	31.630	−0.161 6	1997–2008-09	Leveling benchmark
Beiguan 11	104.332	31.560	−0.160 5	1997–2008-09	Leveling benchmark
Beiguan 15	104.337	31.445	−0.087 8	1997–2008-09	Leveling benchmark
Beiguan 17	104.228	31.383	−0.093 3	1997–2008-09	Leveling benchmark
Beiguan 18	104.263	31.357	−0.102 8	1997–2008-09	Leveling benchmark
Beiguan 20	104.190	31.338	−0.118 7	1997–2008-09	Leveling benchmark
Yunmian 3	104.636	31.983	−0.504 5	1983–2008-09	Leveling benchmark
Yunmian 8	104.727	31.883	−0.158 7	1983–2008-09	Leveling benchmark
Yunmian 9	104.746	31.845	−0.145 8	1983–2008-09	Leveling benchmark
Yunmian 11	104.736	31.772	−0.044 5	1983–2008-09	Leveling benchmark
Yunmian 12	104.733	31.769	−0.044 8	1983–2008-09	Leveling benchmark
Maobei 1	103.878	31.698	0	1997–2009-05	Leveling benchmark (ref. 2)
Maobei 5	103.905	31.722	−0.002 71	1997–2009-05	Leveling benchmark
Maobei 6	103.922	31.718	0.004 63	1997–2009-05	Leveling benchmark
Maobei 7	103.947	31.728	0.000 84	1997–2009-05	Leveling benchmark
Maobei 11	104.013	31.757	0.031 61	1997–2009-05	Leveling benchmark
Maobei 12	104.048	31.763	0.079 29	1997–2009-05	Leveling benchmark
Maobei 13	104.078	31.768	0.101 68	1997–2009-05	Leveling benchmark
Maobei 16	104.135	31.793	−0.004 82	1997–2009-05	Leveling benchmark
Maobei 17	104.167	31.803	0.009 03	1997–2009-05	Leveling benchmark
Maobei 21	104.267	31.838	0.619 25	1997–2009-05	Leveling benchmark
Maobei 22	104.297	31.860	0.769 57	1997–2009-05	Leveling benchmark
Maobei 23	104.313	31.855	1.249 88	1997–2009-05	Leveling benchmark
Maobei 24	104.338	31.860	1.466 29	1997–2009-05	Leveling benchmark
H035	104.444	31.802	−0.675	2007-06–2008-06	GPS site
H033	104.831	32.182	−0.663	2007-06–2008-06	GPS site
H010	105.226	32.571	0.300	2007-06–2008-06	GPS site
H050	103.145	31.008	−0.228	2007-06–2008-06	GPS site
H049	103.692	31.060	−0.216	2007-06–2008-06	GPS site
Z126	104.250	31.511	−0.204	2007-06–2008-06	GPS site
Z122	104.446	31.689	−0.466	2007-06–2008-06	GPS site
Yingxiu	103.486	31.063	1.616 1	2007-05–2008-10	Gravity point
Yinxing	103.482	31.141	1.872 2	2007-05–2008-10	Gravity point
Mianhu	103.495	31.358	0.431 3	2007-05–2008-10	Gravity point
Zhicheng	104.320	31.859	1.303 5	2007-05–2008-10	Gravity point

Figure 3 Coseismic vertical displacement vector of Wenchuan earthquake. Red vector stands for vertical deformation derived from repeated levelings, blue vector for maximum coseismic uplift at Qushan town from repeated levelings, magenta vector for vertical deformation derived from GPS measurements, green vector for vertical deformation derived from gravity measurements, and black line for the surface rupture of the Wenchuan earthquake.

$$M_V = \sqrt{M_{W1} + M_{W2}} \sqrt{L}, \quad (1)$$

where L is the leveling distance in km, M_{W1} and M_{W2} are respectively the total mean error of pre-seismic and postseismic levelings. For the 2008 repeated leveling routes, the maximum leveling length from Pingwu at the northwest end to Mianzhu at the southeast end was about 200 km, by taking $M_{W1}=2.0$ mm/km and $M_{W2}=1.0$ mm/km, the estimated maximum error along the Pingwu-Beichuan-Mianzhu route is about 32 mm. For the 2009 repeated leveling along the Maoxian-Beichuan route (85 km long), the estimated maximum error is about 13 mm by taking $M_{W1}=1.0$ mm/km and $M_{W2}=1.0$ mm/km.

Preseismic contribution can be estimated by long-term preseismic repeated levelings. According to repeated levelings of the Maoxian-Beichuan-Mianzhu leveling route in 1983 and 1997, the pre-seismic differential uplift rate between the Longmenshan thrust zone and the Sichuan basin was about 1.5 mm/a. At this long-term differential uplift rate, the estimated maximum preseismic deformation would be less than 38 mm during the time span of 1983 to 2008.

Postseismic deformations, induced by the afterslip of the fault as well as relaxation of underlying viscous layers, decay exponentially along with time and can last several to decades of years after the event. Based on postseismic levelings of the Tangshan $M7.8$ earthquake

and Gonghe $M7.0$ earthquake, the maximum postseismic vertical deformation of the Wenchuan earthquake, with uplift on the west side and subsidence on the east side, might reach 50 mm in the following first year along the Maoxian-Beichuan route, and the maximum postseismic vertical deformation along the Pingwu-Beichuan-Mianzhu leveling route in the following five months might reach 20 mm.

From above comprehensive analysis, the maximum non-coseismic deformation contamination in the extreme case would be less than 100 mm, which is 1–2 order smaller than the meter-level vertical displacements detected by preseismic and postseismic repeated levelings, so in the following analysis, we roughly take the measured deformation of Table 1 as the coseismic vertical deformation of the Wenchuan earthquake and neglect the bias between the two reference points.

4 Fault geometry inversion of the Wenchuan earthquake

Fault geometry is a primary control on deformation of hanging wall. Listric-type normal faults have been found extensively in extensional regimes. In collisional orogens and subduction zones, there are also some listric thrust faults reported (Amos et al, 2007). In this section, we mainly perform inversion of fault geometry of the Wenchuan earthquake by modeling the measured co-

seismic vertical deformations with elastic dislocation model of Okada (1985). The fault is constructed as listric geometry from some priori knowledge.

4.1 Construction of listric fault

Listric fault is defined as curvilinear fault in which the fault surface concaves upwards, its dip decreases with depth. There are different ways to construct a listric fault. In this paper, we construct a listric fault by following exponential expression:

$$\delta = \delta_0 \times \left[1 - \exp\left(-\frac{C}{h}\right) \right], \tag{2}$$

where δ is dip angle of fault which is the function of depth h , δ_0 is the dip angle near the surface, C is the constant which controls curvature of a fault. One important goal of this section is to invert the constant C of the fault geometry for the Wenchuan earthquake.

4.2 Fault geometry inversion

Based on dislocation model, coseismic vertical deformation is primarily sensitive to dip-slip component of the fault, so in this paper, we mainly focus on the inversion of fault geometry with dip-slip dislocation model. Right lateral slip distribution of the Wenchuan earthquake had been inverted by Shen et al (2009) using GPS horizontal displacement data.

For the middle segment of the central Longmenshan rupture zone with leveling data, vertical deformation contribution of the front Longmenshan fault (namely Pengguan fault) was small, so for simplification, we employ a single listric fault to model the observed vertical deformation within the middle segment of the central Longmenshan rupture zone. From the priori information such as rupture elongation, dip angle near the surface and at focal depth, fault length is set 200 km roughly from Yingxiu to Nanba with fault center at Qushan town, Beichuan county; dip angle is set between 60°–90° near the surface, U_2 of the thrust slip component is set between 4–10 m from investigated vertical offset, and constant C which controls fault curvature is set between 6–15. The constructed listric fault is divided into N strips

in depth with each strip being 1.0 km, and dip angle of the middle depth is set as the mean dip angle of the strip. Vertical deformation data north of benchmark Baiyun 20 (near Guixi town) and around Yingxiu are discarded in order to eliminate the end effects of thrusting.

By employing trial-and-error method, we find that the listric dislocation model listed in Table 2 fits the observed vertical deformation very well. Figure 4 shows the comparison of the observed vertical deformation and modeled vertical deformation along the cross-section of the Beichuan fault. Figure 5 shows inverted listric fault and distribution of aftershocks along the cross-section of the Beichuan fault.

Figure 4 Observed and modeled coseismic vertical deformation profile across the Beichuan fault.

Figure 5 Cross-section of the inverted listric fault and aftershock distribution.

Table 2 Inverted listric dislocation model by trial-and-error method

Dip angle near surface $\delta_0/^\circ$	Constant C	Dip-slip/m	Upper depth/m	Lower depth/m	Inverted faulting geometry
88.0	9.0	5.6	0	18.0	$\delta=88^\circ\times[1-\exp(-9/h)]$

5 Discussion and conclusions

It has exceeded our initial expectation that a simple uniform-slip listric thrusting model can fit the observed

vertical deformation very well, it, on the other hand, implies that the Yingxiu-Beichuan fault is a true listric thrust fault. In addition, from the well-fitted vertical deformation in Figure 4, we can see that the Pengguan

thrust rupture affects little the observed vertical deformation even along the Beichuan-Mianzhu leveling route east of the Pengguan fault (Figure 2). A possible explanation is that the Pengguan rupture is also a listric thrust fault dipping northwest, with this listric fault geometry and geologically investigated 3.5 m maximum coseismic vertical offset (Xu et al, 2009a), the maximum subsidence of the foot wall would be less than 0.1 m, which did affect little the observed vertical deformation. As for whether the Pengguan thrust gradually merged into the Yingxiu-Beichuan listric thrust as inferred by Zhang et al (2008) and Xu et al (2009a), our vertical deformation could not give any definite conclusion due to lack of leveling data across the fault.

Wang et al (2008) once obtained a maximum slip of 12 m at depth of 10.3 km near Beichuan county town by joint inversion of teleseismic wave and GPS measurements; our 5.6 m uniform dip-slip inversion result seems against so big coseismic slip even considering a 5–6 m dextral slip. As for the 9–11 m maximum vertical offset at Shaba village in debate, north of Qushan town, Beichuan county (Li et al, 2008a; Liu et al, 2008; Xu et al, 2009b), the leveling-observed maximum offset between the hanging wall and foot wall at Beichuan county town is only 5.4 m, so we infer that the 9–11 m maximum vertical offset at Shaba village should contain other contributions such as localized coseismic flexural scarp. As a matter of fact, there did occur a coseismic flexural scarp with height of about 3 m at Qushan town and Shaba village during the earthquake (Fu et al, 2009).

From Figure 5 we can also see, the relocated aftershocks of Huang et al (2008) and Wu et al (2009) with double difference relocation algorithm mainly distributed within the hanging wall of the Beichuan thrust fault, and the inverted 18 km lower depth of the thrust fault is well consistent with lower boundary of the aftershocks. This consistence, on one hand, verifies the reasonability of the inverted lower depth of the fault, on the other hand, it also reveals that the brittle-to-ductile transition depth of the crust along central Longmenshan is around 18 km. As for why most of the aftershocks concentrate in the hanging wall of Beichuan fault (Figure 5), one important attribution is that the coseismic shear strain of the hanging wall is much larger than that of the foot wall, which is favorable to trigger aftershocks. From this point of view and the aftershock distribution map of Figure 2, we infer that the whole Yingxiu-Beichuan-Nanba rupture zone should be of listric geometry, although the listric parameters such as dip angle δ_0 near

surface and C may change from one segment to another. The northeastern Nanba-Qingchuan aftershock zone presents very different pattern of aftershock distribution and fault. The inverted results of Shen et al (2009) demonstrated that this is a dextral slip segment with near vertical fault plane.

In order to get more details of the fault geometry of the ruptures of the Wenchuan earthquake, joint inversion and comprehensive analysis on data of leveling, GPS, gravity, InSAR, aftershock distribution as well as geology and high resolution geophysical prospecting are needed. Moreover, how the listric Yingxiu-Beichuan fault in brittle upper crust extends to the middle and lower crust is still an unsolved problem, it directly concerns the mechanism of the $M_s8.0$ Wenchuan earthquake.

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