Asymmetrical Disaster Distribution and its Cause Analysis of the Mw7.9 Wenchuan Earthquake

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SUMMARY :
Seismic disasters displayed various asymmetrical distribution during the 2008 Mw7.9 Wenchuan Earthquake. The size and quantity of landslides and rock avalanches triggered by high-angle reverse faulting on the hanging wall are higher than that on the footwall. In the direction perpendicular to the fault strike, the zones with higher MM intensity on the hanging wall are wider than that on the footwall. These asymmetries reflect hanging wall effect on peak ground acceleration in reverse faulting event. In the direction of rupture propagation, Doppler effects induced intensity attenuating slowly northeastward and rapidly southwestward. In the region between mountain and basin, heavy casualties and serious destruction of buildings are probably caused by site magnification and basin effect. Possible reason for the buildings near surface rupture zone having withstand the strong earthquake is that the effective stress drop and low rupture velocity may exist in the shallow asperities, resulting in a relatively lower ground motion at the period about 1 sec. Steep dip-angle near surface for seismogenic fault is another reason for a narrower surface intense deformation zone.

Keywords：Mw7.9 Wenchuan Earthquake，seismic disaster， seismogenic fault，hanging wall effect， Doppler effect

1. INTRODUCTION

When the Mw7.9 Wenchuan earthquake occurred, the fault rupture and strong ground motion produced various kinds of geological disaster in the epicenter area. Landslides and rockfalls damaged or destroyed several mountain roads and railways and buried buildings in Beichuan-Wenchuan area. About 1600 people were killed by a landslide at Beichuan. Landslide also dammed several rivers, creating 34 barrier lakes. Soil liquefaction and ground subsidence took place primarily in the front-range basin with a relatively small scope of effects.

The spatial distribution of the geological disaster seems to be controlled by the causative fault. For a same distance to the fault, the geological disaster on the hanging wall is considerably more serious than that on the footwall. Site observations and the isoseismal map indicate that the intensity of structures destruction on the hanging wall is larger than that on the footwall. Along the fault, the isoseismal in epicentral region, elliptical in shape and oriented NE-SW, indicated that the intensity attenuates northeastward much slower than that southwestward. The MM intensity VII area in the plain region of the Sichuan Basin is much broader than that in the mountainous area in western Sichuan. Some masonry structures near the fault scarps sustained minor damage when subjected only to vibratory forces. In addition to the hanging wall effect, the asymmetric distribution of the geological disaster afore mentioned can be attributed to other factors superimposed.

2. ASYMMETRIC DISTRIBUTION OF GEOLOGICAL DISASTER INDUCED BY THE EARTHQUAKE

The powerful Wenchuan quake of 2008 has induced widespread geological disasters in the epicenter area and surroundings (Fig.2.1). Statistics shows that over 15000 localities were suffered from landslides, rock avalanches and mud flows, mostly distributed at Wenchuan, Shifang, Mianzu, Anxian, Beichuan and Qingchuan. Along the central Longmenshan fault zone (Beichuan fault), from Yingxiu of Wenchuan to Gaochuan of Anxian, and from Chenjiaba of Beichuan to Nanba of Pingwu, the density of landslides exceeded 50% with maximum 70% (Yin, 2009).

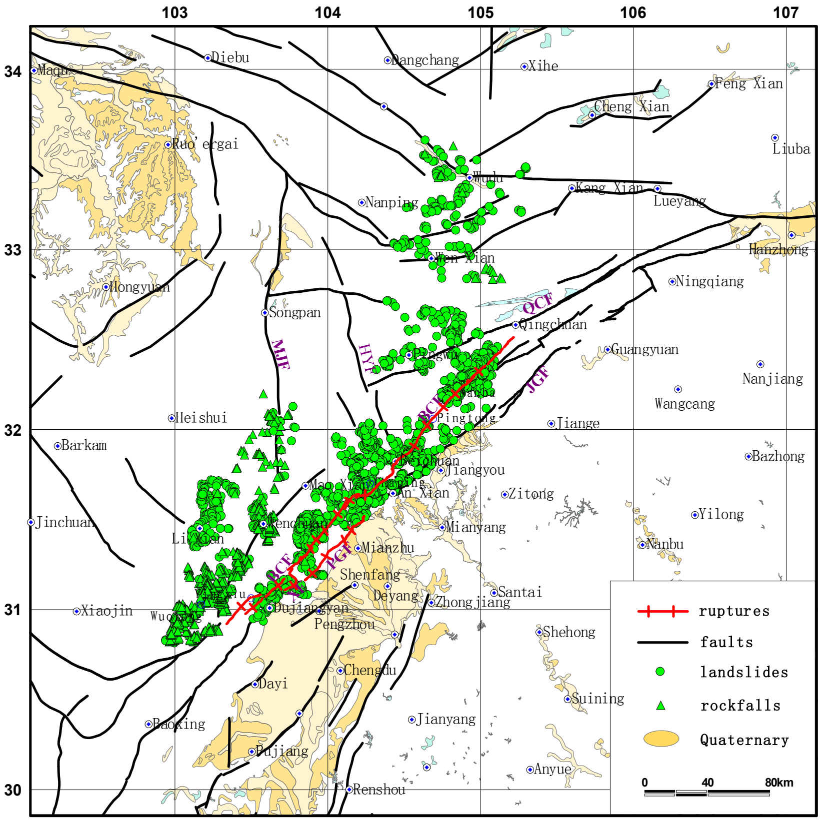

Figure 2.1 Map showing surface ruptures, rock avalanches and landslides induced by the Wenchuan earthquake BCF-Beichuan fault; HYF-Huya fault; JGF-Jiangyou-Guangyuan fault; MJF-Mingjiang fault; PGF-Pengguan fault; QCF-Qingchuan fault; WMF-Wenchuan-Maowen fault; XF-Xiaoyudong fault

The majority of the geological disaster occurred in the northwest bounded by the front-range fault (Pengguan fault), which can be viewed as the hanging wall of the Longmenshan fault zone in a generalized sense. Among the three faults of the Longmenshan fault zone, the front-range and central fault hosted the surface rupture belts produced by the temblor with lengths 72km and 240km, respectively, while no such rupture was seen on the hinter-range fault (Maoxian-Wenchuan fault).

From Fig.2.1, geological disaster bear an obvious positive correlation with the three faults mentioned above, and mostly lie on their hanging walls.

Except very few small-scale landslides appeared within 6km to the surface rupture on the footwall of the front-range fault, other rock avalanches and landslides were present on its hanging wall. Excluding the devastating sites in Wenxian and Wudu, a 270km-long and 90km-wide avalanche and landslide belt can be delineated from Wuolong to Qingchuan along the Longmenshan fault zone. Widespread landslides and rockfalls blocked Dujiangyan-Wenchuan highway and Wenchuan-Beichuan highway. Beichuan, Wuolong and Yinxiu were almost completely destroyed.

Huang et al. (2009) has made statistics for the relationship between 85 big landslides (each has area exceeding 50 000m^2) and the distribution of faults. 72 landslides lie on the hanging wall of the Beihcuan-Yingxiu fault, that account for 85% of the total, and the rest 13 ones are situated on the hanging wall of the Pengguan fault, though on the footwall of the Beichuan fault at the same time. It seems that the 13 big landslides were spawned by both the Beichuan fault and Pengguan fault. The all 85 big landslides actually took place on the hanging wall of the causative faults.

Chen et al. (2011) noted that there was conspicuous difference in amounts and sizes of earthquake-induced rock avalanches and landslides between the hanging wall and footwall of the Beichuan fault. The total area of landslides on the hanging wall is of more than eight times that of the footwall. In a same slope condition, the proportion of landslide occurrence on the hanging wall is greater than three times that on the footwall.

Field investigations and aerial photographs indicate that the surface ruptures along the causative fault decided the scope and scale of rock avalanches and landslides on either side. One of the most devastating areas by the quake lies between the Beichuan and Chenjiaba, where landslides increased abruptly approaching to the NE trending Beichuan fault. A series of rock avalanches and landslides were distributed on both banks of the NE striking Qianjiang river and Guanhe river. East-facing slop produced far more landslides than west-facing slop. Because of different lithology, the landslides in the west were dominated by weathered and broken rock or soil, while those in the east were mostly big gravels and rolling stones. At the Chaba village of Chenjiaba, where the largest fault scarp was found, heavy vegetation on high hills was preserved after the quake in the east, and no geological destruction was seen on the west-facing slop except the place where the fault runs through. In contrast, landslides were present everywhere on the east-facing slop (west bank).

Same phenomena were noted in the valley of Qingchuan county, where rock avalanches and landslides were more on the west slope than that on the east slope in amounts and sizes, as exemplified by the landslides at Shiba, Donghekou-Shibangou and Banqiao.

In sum, the distribution of geological disaster by the Wenchuan earthquake exhibits a prominent "hanging wall effect", which means a higher density and bigger size of individual on the hanging wall of the fault than that on the foot wall.

3. ASYMMETRY ON THE ISOSEISMAL MAP

The isoseismal based on field investigations describes destruction of buildings and geological bodies by the Wenchuan earthquake (Fig. 3.1). Overall, this map is characterized by multiple ellipses, of which each shows asymmetry in directions both along the long axis and short axis.

3.1 Asymmetry in the Direction Perpendicular to the Causative Fault

To illustrate the asymmetry in the direction perpendicular to the causative fault, we take the central fault as the central line and Qingchuan, Beichuan and Yingxiu as centers to make statistical analysis of radii of the isoseismic lines which reflect intensity attenuation (Table 3.1).

Table 3.1 Statistics of radii of isoseismic lines (taking the central fault as the center line) (unit: km)

Center	Survey line	Hanging wall (h) and footwall(f)	Radius corresponding to MM intensity (km)				
			XI	X	IX	VIII	VII
Qingchuan	A-A′	h			26.5	41.6	55.6
		f			15.6	21.5	122.2
Beichuan	B-B′	h	9.9	8.0	10.6	43.3	56.0
		f	4.1	4.2	4.1	29.7	80.7
Yingxiu	C-C′	h	21	4.2	10	33.9	51.8
		f		4.8	5.9	8.9	57.5

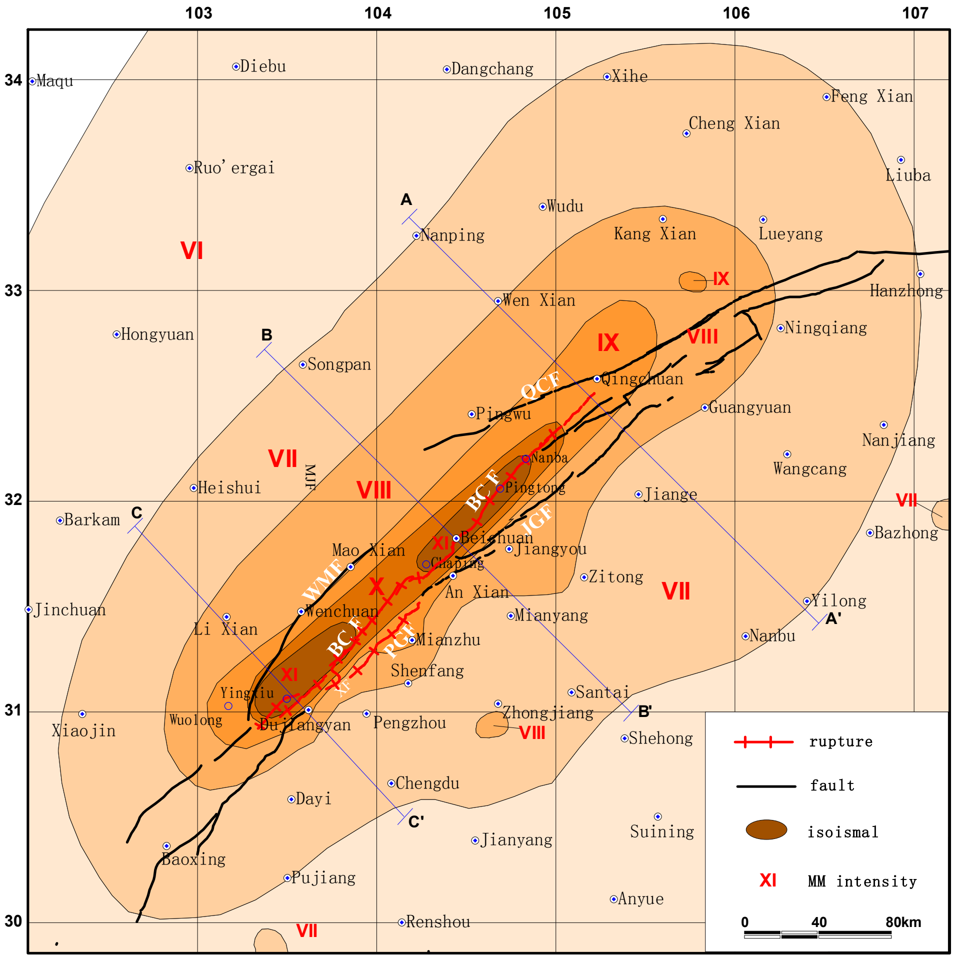

Figure 3.1. Surface ruptures and isoseismal in the Wenchuan earthquake

BCF-Beichuan fault; JGF-Jiangyou-Guangyuan fault; PGF-Pengguan fault; QCF-Qingchuan fault; WMF-Wenchuan-Maowen fault; XF-Xiaoyudong fault

In the high-intensity area (MM intensity≥VIII), intensity on the hanging wall of the fault attenuate relatively slow. Except for Yingxiu (C-C′) where the MM intensity X range has almost same width on the hanging wall and footwall, for a same intensity the width on the hanging wall is 1.5 times that of the footwall or more. Especially southwest nearby Yingxiu, for the intensity VIII area, the width on the hang wall is 3.8 times that on the footwall.

The asymmetry of the MM intensity VII area is just opposite to that of the area for MM intensity≥VIII. The width of VII is 50-70km in the northwest (hanging wall) and 50-120km in the southeast (footwall), respectively with largest discrepancy times or more. This contrary can be attributed two reasons. The first is that the footwall lies in the plain of the Sichuan Basin where thick sediments make seismic acceleration attenuate slower. While on the hanging wall in the mountainous northwest, with increasing distance to the fault, the hanging wall effect weakens. The second reason is associated with the quality of investigations after the event. With respect to the mountainous northwest, dense population and convenient transportation led to much more detailed and thorough investigations in the southeast region.

3.2 Asymmetry along the Causative Fault

Along the NE trending central fault, there are two MM intensity XI epicentral areas in Yingxiu and Beichuan. The intervals between lines of X, IX and VIII in the northeast are obviously larger than that in the southwest (Table 3.2). It means that intensity decays slower northeastward than southwestward.

Table 3.2 Statistics of intervals between isoseismic lines (taking the central fault as the center line) (unit: km)

Direction	MM Intensity				
	X	IX	VIII	VII	VI
northeast	24	76	64	90	210
southwest	4	22	26	69	140

4. CAUSES OF ASYMMETRY IN DISTRIBUTION OF SEISMIC DISASTERS BY THE EARTHQUAKE

4.1 Hanging Wall Effect of the Fault

Abrahamson and Somerville (1996) have studied the ground motions recorded during the Northridge earthquake of 1994 and other reverse-faulting events. They found that the peak accelerations on the hanging wall of the fault are systematically greater than on the footwall. From the analysis to the Chi-chi, Taiwan event of 1999, Yu and Gao (2001) prove the existence of the hanging wall/footwall effects of reverse-faulting quakes, evidenced by relatively slower attenuation of peak accelerations on the hanging wall than the footwall.

The records of the China strong ground motion observation network (Li et al., 2008) shows that the bigger peak accelerations by the Wenchuan shock were distributed on either side of the causative fault, with generally larger values in EW direction than that in NS, and bigger ones on the hanging wall than on the footwall.

GPS measurements reveal that the eastward motion of the eastern margin of the Tibetan plateau is bigger than the westward shift of the Sichuan basin in amplitude, and the co-seismic displacements decay slower toward west than toward east at a same distance to the Beichuan -Yingxiu fault (Zhang et al., 2009).

Previous work suggests a hanging wall effect existing in peak acceleration values for reverse-faulting earthquakes. Such an effect is also present in the observations of the Wenchuan event of 2008.

4.2 Directional Effect of Causative Faults

Huang et al. (2009) has made a statistical analysis of slide directions of 85 big landslides at localities within a scope surrounding the causative fault. Although these directions seem divergent, they are dominated by NW-SE and EW orientations which are nearly perpendicular to or high-angle oblique to the fault. It implies that under strong ground motion, the topographic conditions did not exert a major controlling role in slide direction, instead the propagation of seismic waves perpendicular to the fault had a more powerful effect. Just because of this reason, many projectile-like avalanches occurred in landslides along the direction orthogonal to the fault. It indicates a prominent directional effect of seismic waves and ground motion.

4.3 Doppler Effects along the Fault Rupturing Direction

Somerville et al. (1997) has considered the directional effect of fault rupturing in their study of attenuation of seismic ground motion. They noted that the average horizontal component of ground motion increases along the direction of fault rupture spreading, and decreases in the opposite direction. The propagation of seismic waves along the causative fault is analogous to the acoustic wave Doppler effects in daily life. For example, when a train is approaching and moving away, the observer will listen to the voice intonation become from high to low. In other words, the wave frequency rises when the source moves toward the listener and declines when the source away from him. The huge Wenchuan quake was the result of superimposition of several rupturing events along the fault. The rupture started from Yingxiu in the southwest, extending toward northeast to Beichuan, and Qingchuan. Doppler effects along the fault rupturing can explain why the intensity attenuates northeastward much slower than that southwestward.

4.4 Site Effects

Due to the combined effect of rupturing on the Beichuan and Pengguan faults, strong ground vibration occurred nearby the Pengguan fault. Because the rupture was shallow, this vibration and the local site amplification effects from soft soils resulted in widespread severe disasters.

Previous studies indicate that site conditions can pose major influence on peak accelerations in addition to the magnitude, duration and propagating medium of earthquake. In general peak accelerations on bedrock are greater than that on soft sites in the near field, while it is on the contrary in the far field (Idriss, 1978).

For the Wenchuan event of 2008, seismic destruction was widespread along the fault (10-15km to the fault). Particularly in the range-front areas, a number of buildings were damaged southeast of the Beichuan fault, such as the downtown of Dujiangyan city; Xiangé, Dujiangyan; Hongbai, Shifang; and Hanwang, Mianzu - which lie in between mountains and the basin. At these places, due to the local geological condition, ground motion was amplified or focused， causing intensive devastation to buildings there.

Another interpretation is that when the dominant frequency of seismic vibration was close to the self-frequency of buildings, the resonance together with 90s duration of ground motion led to severe destruction even if the seismic acceleration was not very large.

In Wenxian and Wudu of Gansu Province, which were in the MM VII intensity region more than

60km away from the epicentral area of the Wenchuan event, the earthquake created widespread avalanches and landslides. They can be attributed to four reasons as follows: (1) high altitude and steep slopes, which have spawned frequent landslides before the Wenchuan event; (2) amplification effect of peak accelerations at high terrain; (3) propagation of seismic waves from southwest to northeast which made energy increase; and (4) long duration of ground motion.

4.5 Stress Drop of Surface Rupture

A big trench was excavated at the Bailu School in Bailu Town，Pengzhou. Observation on the wall of this trench reveal folding deformation of the hanging wall and little disturbance in strata of the footwall (Fig.4.1a)(Ran et al.,2010).

Field investigations noted relatively gentle fault scarps at cement roads or other hard surfaces, like that seen at the Bailu School. It means that the deformation of the strata under a hard surface on the hanging wall made the affected range of the footwall expanded, and when the surface was merely farming soil or superficial soil, the scarps became steeper, like that seen at the outcropped folding scarp at Wangjiakan in the Bailu town (Fig.4.1b). In the former case, the intense deformation zone on the surface was broader than that reflected by the folding several meters beneath the ground.

As revealed by the trench, the small disturbance of the footwall and the shape of folding scarps depend on physical properties of the surface. When a fault reaches the surface, it exhibits effects of its hanging wall and footwall in a small range, and the effect of the footwall is relatively weak. If the surface is superficial soil or farming soil, because of its strong plasticity and weak elasticity, the folding scarps reflect real deformation in the shallow subsurface.

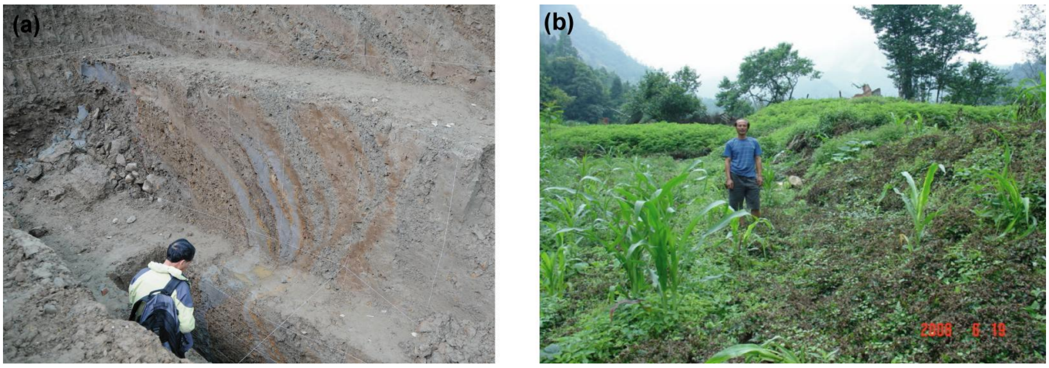

Figure 4.1 Earthquake induced deformation fold and fault scarp

(a) Strata deformed in Bailu Middle School(view to N);(b)Fault scarp in maize field near Wangjiakan village, Bailu town (view to SW)

Investigations in some areas which were heavily struck by the Wenchuan quake, such as the Leigu, Chenjiaba, Hanwang, Hongbai, Hongkou and Xiaoyudong, demonstrate the following common features in seismic destruction: (1) almost all the buildings on rupture zones collapsed; (2) many buildings very close to the rupture zones were severely damaged but not fell down; (3) structures were demolished in a large area distant to the fault.

Based on the work of Somerville (1997, 1999), Kagawa (2004a, 2004b) has collected many results of seismic source inversion and comparison of buried and surface rupture models. He concluded that the lowered effective stress drop and slip velocity in surface-rupture earthquakes can produce relatively smaller ground motion at the period about 1 sec. Dynamic simulation also supported this inference

(Dalguer et al., 2003).
For the phenomenon that some buildings near the surface rupture zone did not collapse during the Wenchuan shock, Zhao et al. (2008) suggested the following explanations: (1) other than their performance of seismic resistance, most of them located at hard sites or on bedrock in the surface rupture zone; (2) the effective stress drop and low rupture velocity may exist in the shallow asperities, resulting in a relatively lower ground motion at the period about 1 sec. The first explanation remains controversial, and the second one seems reasonable. The field investigations in many places confirmed that the buildings nearby the fault indeed did not collapse, implying lowered seismic acceleration or velocity there.

4.6 Difference of Earthquake-Proof Capability

In addition to the causes aforementioned, relatively better earthquake-proof capability of buildings may be another factor that can account for why the buildings near the causative fault did not collapse. For example, at Shenxigou of Hongkou， some new buildings of brick-concrete structure on either side of the fault remain to stand after the great quake. The surface rupture zone that ran through the Beichuan county town, together with avalanches and landslides, destroyed most of buildings in this region. Nevertheless some damaged storied houses did not topple during the temblor. Similar situations are also seen in other towns.
Many buildings for their poor quality were completely destroyed by the quake, though they are far away from the causative fault. In particular, the collapse of some school buildings attracted much concern nationwide. For instance, a four-story building broken down in the Jianxin Primary School in Dujiangyan city, while the nearby structures including a new hotel and an old building which built 30 years ago remained standing after the quake. At the Juyuan Middle School, 16-17km away from the causative fault, due to the collapse of a three-story building, nearly 1000 people were crushed to death in the seismic shaking.
Investigation in many places demonstrates that the quake-protection capability of buildings is the critical factor that decides their fate in a coming major or great temblor. Although it is necessary to introduce the safety distance away from active faults, municipalities in earthquake-prone regions will have to update building codes and strengthen enforcement.

4.7 Dip Variation of Faults

Most buildings and structures collapsed within the surface rupture zones, whereas building damage in the adjacent areas of the rupture zones was surprisingly minor. Among a total of twenty co-seismic surface ruptures surveyed in the field, seventeen are less than 40 m wide, about a half of them are 10-30 m, and only three are over 40-59 m (Zhou et al., 2010; Xu et al., 2008).
Previous studies show that the width of the affected area by a reverse fault depends on the fault dip (Han et al., 2002). The Longmenshan thrust belt is composed of many imbricate reverse faults, including the Wenchuan-Maowen, Beichuan, and Pengguan faults as well as the blind faults beneath the Sichuan basin to the east. Among them, the Beichuan fault, served as the causative fault for the main shock, dips $\geq 70^{\circ}$ northwest at the surface, and dips $\geq 47^{\circ}$ in average in upper crust derived from envelope lines of dense aftershocks (Xu et al., 2008). It means that the dip of this fault turns gentle downward in the subsurface, and flattens into the basal detachment at depth 15-20km. The Pengguan

fault, as one of low-angle reverse faults on the footwall of the Beichuan fault, extends downward to depth 10km and merges with the Beichuan fault (Xu et al., 2008). Field observations indicate that the measured dips of faults at the surface are generally rather steep. For instance, the dip of the fault outcropped at Bajiaomiao, Shengxigou of Hongkou is 76º (He et al., 2008). The Beichuan fault runs through the Beichuan town and continues to extend to northeast, reaching the surface at the east bank of the Qianjiang River where it dips 70º-80º southwest, a verging direction opposite to that at depth. As the fault becomes steep near the surface, horizontal ground motion normal to the fault decreases, resulting in reduced affected range on the footwall of the surface rupture zone.

5. CONCLUSIONS

Because the West Sichuan block is moving southeastward and poses compression onto the Sichuan basin, the Longmenshan fault zone behaves as a thrust with strike-slip component, of which the hanging wall is active and footwall is passive in movement. The peak accelerations by the Wenchuan event on the hanging wall were generally larger than that on the footwall. Consequently, the geological disaster, including rock avalanches and landslides, on the hanging wall (northwest wall) caused by the quake is much more severe than that on the footwall (southeast wall). The same asymmetry is also seen on the isoseismal map in the meizoseismal area.

During the fault rupturing for 90 seconds, northeastward propagation of seismic waves produced the Doppler effects. Thus the energy density on the northeastern section of the fault increased, and attenuation of ground motion acceleration became slower in the northeast direction while faster in the southwest direction. Its manifestation is that intervals between intensity contours of X, IX, and VIII intensity in the northeast are apparently bigger than that in the southwest on the isoseismal map.

The geological disasters map and the isoseismal map based to building damage reveal the hanging wall effect from a macro-scope view. While such an effect seem not obvious when a rupture zone is observed at a small distance. Because the fault turns steep when it reaches nearby the surface, both the effective stress drop and rupturing velocity are relatively low, resulting in reduced ground motion around period of 1 sec. Combined with different quake-protection capability of buildings, these factors may account for why some buildings nearby the fault were damaged but did not break down and the affected area of the surface rupture zone was relatively narrow.

In sum, the rupturing manner of the causative fault, its geometry, spreading direction, and varied ground motions in different site conditions are the primary factors that produced the asymmetry of disaster by the Wenchuan quake of 2008. The decisive role of the seismogenic faults in this event should receive sufficient attention in reconstruction and planning of the victim regions.

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