Analysis of Landslide Hazards in the Beichuan County Town Induced by the Wenchuan Earthquake Using Strong Motion Data

Xiuying Wang
Institute of Crustal Dynamics,China Earthquake Administration, Beijing, China

Gaozhong Nie
Institute of Geology, China Earthquake Administration, Beijing, China

Song Wang
China Earthquake Network Center, Beijing, China

SUMMARY:
The county town of Beichuan County, China experienced very serious landslide hazards during the Wenchuan Earthquake. Three methods were employed to estimate the hazards using strong motion data. (1) Peak ground accelerations (PGAs), on the hanging wall, were used to evaluate the PGAs on the landslide sites in the town. The evaluated average PGAs were all greater than 1 g, indicating that the ground motion intensity was very strong during the earthquake. (2) Acceleration time histories, from another station with similar geological conditions to the town, were used to evaluate the critical acceleration changing range, and the estimated values showed the geological conditions were very susceptible to earthquakes. (3) Acceleration time histories, from two stations on the hanging and foot wall of the rupture, and near the town, were used to calculate the Newmark displacements, and all the evaluated displacements indicated that landslides were very likely.

Keywords: Wenchuan Earthquake landslide strong motion evaluation critical acceleration

1. INTRODUCTION

The Wenchuan Earthquake occurred on May 12, 2008, inducing very serious landslide hazards. According to the statistics, an area of over 2×10^5 km^2 was affected by the geological disasters triggered by this earthquake, of which over 1×10^5 km^2 was seriously stricken. Beichuan County was one of the most seriously affected regions. According to the survey after the earthquake, there were 564 landslides in Beichuan County, 21 of which were triggered in the county town. For example, the Wangjiayan landslide, triggered in the old county town, buried more than 1600 people, and the Tangjiashan landslide blocked the river and became the most dangerous landslide induced by this earthquake.

Many studies on the landslides induced in Beichuan County have been carried out since then. These studies include the distribution rule and the triggering mechanisms of earthquake-induced landslides (Wang et al. 2008; Huang et al. 2008; Xu, 2009). Most of these studies were qualitative, and lacked the support of quantitative calculation. Consequently, this paper presents a quantitative analysis using the strong motion data obtained from the Wenchuan Earthquake.

Because of serious surface damage, all the instruments deployed in the county town were destroyed. Fortunately, many sets of strong motion data were obtained from the earthquake rupture in the Longmenshan area, which provided the opportunity to analyze earthquake hazards using the ground motion data.

This paper calculated the strong motion intensity in the landslide sites and the probable displacements caused by the strong motion using the data obtained from the earthquake. The results showed that the county town experienced very strong ground motion during the earthquake, which was strong enough to trigger very large-scale landslides.

2. GEOLOGICAL BACKGROUND AND DATASET

The Wenchuan Earthquake occurred on the central Yinxiu-Beichuan Fault of the Longmenshan Fault Zone, which belongs to the transitional zone between the Qinghai-Tibet Plateau and Sichuan Basin, and features complex geological structures, topography and hydro-geological conditions (Xu et al. 2008), resulting in a considerable number of secondary geological disasters during the earthquake.

Beichuan County, located in the north-central part of the Wenchuan Earthquake rupture, belongs to the Mianyang City of Sichuan Province. The land surface is deeply riven in the Beichuan County, and the adjacent height differences are over 1000 m. The county town is located in the valley extending in a north-easterly direction and is covered by Cambrian sandstone and slate as well as Devonian dolomitic limestone, which are easily weathered.

There were two large-scale landslides induced in the Beichuan county town. The most destructive, the Wangjiayan Landslide, buried about 1600 people and covered most of the old county town. The most dangerous landslide, the Tangjiashan Landslide, blocked the Qianjiang River around the town and created a barrier lake, threatening 1.3 million inhabitants on the lower reaches. Table 1 summarizes some data on the two landslides.

Table 1 Summary information on the two landslides triggered in the county town

	Distance to rupture (km)	Landslide slippage (m)	Landslide volume (m^3)	Death toll
Wangjiayan Landslide	0.5	550	1.0×10^6	1600
Tangjiashan Landslide	2.3	900	2.0×10^7	100

Because of the serious damage, no strong motion data were obtained from the county town. However, there were a large number of ground motion observation instruments deployed along the Longmenshan Fault Zone before the Wenchuan Earthquake, so a large quantity of ground motion records were obtained from this earthquake (Li et al. 2008). Of these records, there were 23 groups from the hanging wall of the rupture in the Longmenshan area. The distribution of these stations and their relationship to the rupture and the county town are shown in Figure 1.

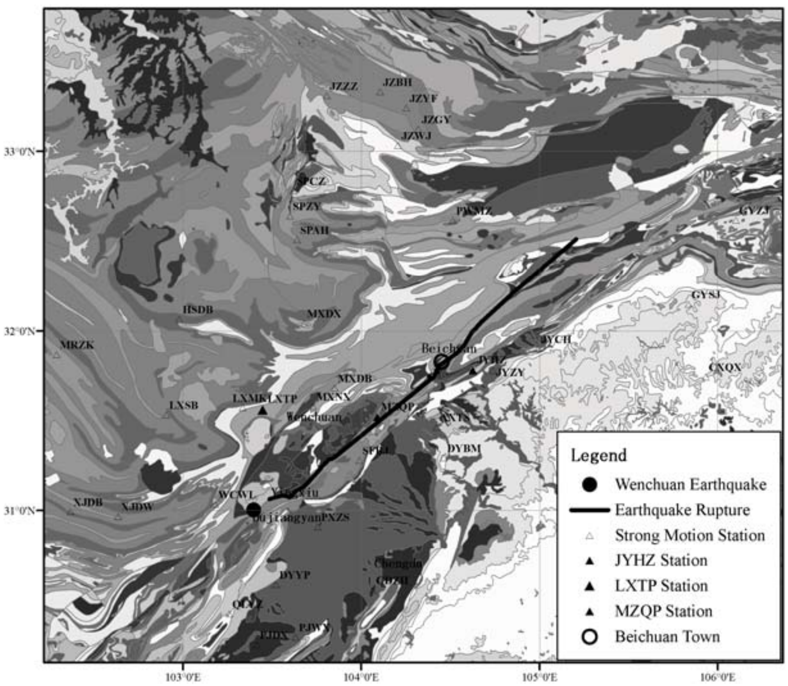

Figure 1. Distribution of the strong motion stations in the Longmenshan area

These groups of data provided us the opportunity to calculate the strong motion intensity in the Beichuan county town during the Wenchuan Earthquake, enabling us to quantitatively analyze the landslide hazards. We used this dataset to analyze the two landslides mentioned above.

3. LANDSLIDE HAZARD EVALUATIONS IN THE BEICHUAN COUNTY TOWN

3.1 Peak Ground Acceleration (PGA) Evaluation of the Landslide Sites

All the investigation carried out after the earthquake showed that disaster outcomes of this earthquake on the hanging wall were obviously more serious than on the foot wall (Xu et al. 2010). Studies also showed that the attenuation of the ground motion on the hanging wall was slower than it was on the foot wall (Yu et al. 2008). The landslides sites, located in the county town, were on the hanging wall of the earthquake rupture and very close to the rupture. To estimate the peak ground accelerations (PGAs) correctly, we used the data obtained from the hanging wall in the Longmenshan area to determine the attenuation fitting formula in three directions. The fitting results are as follows:

$$\lg(PGA_{EW}) = -1.39 \times \lg(D_f + 15.8) + 1.95, \quad \sigma = 0.22, \quad r = -0.84, \tag{1}$$

$$\lg(PGA_{NS} = -1.29 \times \lg(D_f + 16.2) + 1.76, \quad \sigma = 0.26, \quad r = -0.77, \tag{2}$$

$$\lg(PGA_{UD}) = -1.52 \times \lg(D_f + 13.7) + 2.05, \quad \sigma = 0.26, \quad r = -0.83. \tag{3}$$

Where D_f indicates the distance to earthquake rupture.

Using the rupture distances given in Table 1, we calculated the PGAs in the three directions for the two large-scale landslides, the Wangjiayan and Tangjiashan. The results are given in Table 2.

Table 2 PGA evaluation results for the two landslides

	PGA_EW and its estimation interval (g)	PGA_NS and its estimation interval (g)	PGA_UD and its estimation interval (g)
Wangjiayan Landslide	1.8 (1.1, 3.1)	1.5 (0.83, 2.8)	2.0 (1.1, 3.6)
Tangjiashan Landslide	1.6 (0.96, 2.6)	1.3 (0.73, 2.4)	1.7 (0.91, 3.0)

Analyzing the results given in Table 2, we determined that the estimated PGAs, in the three directions of the two landslide sites, were greater than 1 g. Considering the fitting error, the lower limits of the estimated values were also near to or greater than 1 g. These were in accordance with the speculated PGA data of 2-3 g, which were assumed from the observed damages. Moreover, the Wangjiayan and Tangjiashan landslides, as with many near-rupture large-scale landslides, had the characteristic of being propelled away from the top of the slope (Xu et al. 2009). For a large landslide mass to be propelled away so quickly, an acceleration greater than 1 g is required to overcome gravity. This demonstrates that over 1 g PGA evaluations are credible.

The evaluated vertical PGAs of the two sites are both greater than their corresponding horizontal ones. Studies showed that the vertical motion was very strong near the earthquake rupture, but the rate of the attenuation was rapid with increasing distance from the rupture (Yu et al. 2008). Studies of examples of strong earthquakes also showed that landslide disasters near the earthquake-rupture were invariably very serious (Jibson et al. 2006; Liao et al. 2000; Huang et al. 2008). It was evident that there was a strong attenuation relationship between the near-rupture landslide hazards and the vertical strong motion, which demonstrated, to some extent, that although horizontal motion has a leading role in the landslide triggering process, as many researchers believed, the vertical motion must not be neglected, as it may aggravate the situation. This was also evident when we analyzed the problem in regional scale studies (Wang et al. 2009). Therefore, the vertical strong motion must be taken into consideration when near-rupture geological disasters are evaluated.

3.2 Slope Critical Acceleration Evaluation

The surface layer is very weak and deteriorates easily in county town, as stated in Section 2 of this paper. Therefore, its geological environment is susceptible to earthquake or other triggering factors. To analyze the landslide hazards quantitatively, we tried to evaluate the changing range of critical acceleration under such geological conditions using the strong motion data obtained from another station with similar geological conditions.

From the geological map in Figure 1, we established that the Taoping Station in Lixian County (LXTP) had the same emergency stratum as the Beichuan county town and the geological conditions in these two sites were similar. Therefore, we chose strong motion data from this station to carry out the evaluation process.

Two horizontal recordings were used to calculate the Newmark displacements by applying different critical accelerations. A group of Newmark displacements versus their corresponding critical accelerations was obtained, as shown in Figure 2.

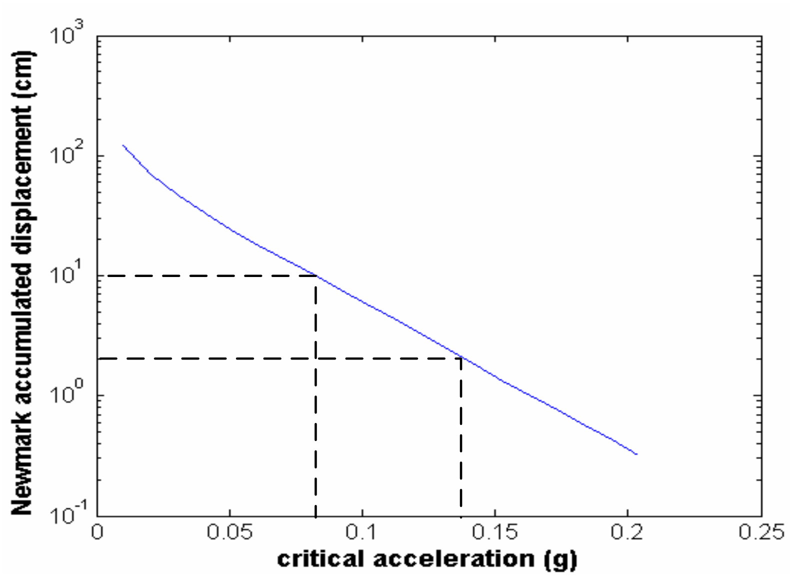

Figure 2. Newmark displacement vs. critical acceleration

According to the surveyed data, there were large- to small-scale landslides near the LXTP Station (Wang et al. 2009). This indicated that the strong motion near the LXTP Station was strong enough to trigger large-scale landslides. Wilson et al. (1985) stated that the critical displacement could be selected as 2 cm for brittle slopes and 10 cm for coherent large-scale landslides. Therefore, we used 2 cm and 10 cm as the critical displacements, and the corresponding critical accelerations were 0.14 g and 0.08 g. Furthermore, our analysis using the regional scale data showed that landslide disasters were very serious when PGAs exceeded 0.2 g (Wang et al. 2010), which showed that the critical acceleration on a regional scale could not be greater than 0.2 g (Wang et al. 2009). Therefore, we also used this value as a critical acceleration.

As a result, we determined the critical acceleration range was about 0.08 g to 0.14 g, and the maximum was less than 0.2 g, for the Beichuan county town's geological conditions. The critical acceleration changing range of 0.08 g to 0.14 g indicated that the geological conditions in the town were susceptible to earthquake and landslides were easily triggered.

3.3 Newmark Displacement Evaluation

Having determined the critical acceleration, the next step was to select an acceleration time history to calculate the probable Newmark displacement. To make a comparison, we chose two groups of records near the town, but located on the hanging and foot walls of the rupture respectively. They are the Qingping Station (MZQP) on the hanging wall, and the Hanzeng Station (JYHZ) on the foot wall, as shown in Figure 1. Although the MZQP Station is on the hanging wall as the town, its geological conditions are quite different from the town. While the JYHZ Station has similar geological conditions to the town, it is located on the foot wall with a greater distance to the rupture. Therefore, it is reasonable to use both sets of data.

The Newmark displacements, calculated from the critical accelerations given in Section 3.2 using the two selected stations' acceleration time histories, are shown in Table 3.

Table 3 Newmark displacement calculation results

	0.08 (g)	0.14 (g)	0.2 (g)
MZQP Station	60.3 cm	20.2 cm	7.7 cm
JYHZ Station	18.4 cm	6.3 cm	2.3 cm

From the results given in Table 3, we determined that if the strong motion intensity in the town was the same as for the MZQP station, landslides would be triggered under any of the critical accelerations given above. Even if the strong motion intensity was as obtained from the JYHZ station, landslides also would be triggered, but their scale might be smaller than under the conditions of the MZQP station. However, when the rupture distance and the foot wall location was taken into consideration, we determined that the strong motion in the town must be stronger than in the JYHZ station, and therefore landslide disasters would be more serious.

As a result, we can see that the Newmark displacements in the county town were large enough to trigger large-scale landslides under any of the critical accelerations mentioned above using the Wilson judging criterion. However, it must be noted that the calculated Newmark displacements were much smaller than those of the real landslide slippages, for example, the 550 m of the Wangjiayan landslide, given in Table 1. We think there are two reasons to explain this. First, the critical acceleration was kept at a constant value throughout the acceleration time history calculations, while in a real case when the slope is subjected to the earthquake, the mechanical properties of the soil might change and its anti-shearing ability be weakened, resulting in the critical acceleration becoming progressively smaller during the vibration. Second, the horizontal time history was adopted when the Newmark displacements were calculated, and the vertical neglected, which might play an important role in the near rupture landslide calculations mentioned above; therefore the vertical strong motion must be taken into consideration in future model studies.

As a result, the Newmark displacement, whether calculated from the time history, or evaluated in any other way, should not be taken as the real landslide slippage. However, when the regional characteristics are considered and a suitable judging criterion is adopted, the Newmark displacement, in a quantitative manner, is also a very good index to landslide risks on a regional scale or for certain landslide sites.

4. CONCLUSIONS

The Beichuan county town suffered the most devastating landslides of all the areas affected by the Wenchuan Earthquake, and no strong motion data were obtained from the town. Consequently, this study evaluated the probable PGAs of the town using the data from the hanging wall of the Wenchuan Earthquake in the Longmenshan area, and evaluated the critical acceleration range and corresponding Newmark displacements. Some conclusions are as follows:

(1) The average evaluated PGAs of the two landslides sites in the county town are all greater than

1 g. Even if the formula fitting error is considered, the minimum evaluated values are near to or greater than 1 g, which is in accordance with the results from other studies. The vertical strong motion is likely to play an important role in large-scale near-rupture landslides, which must be considered in future evaluation models.

(2) Acceleration time histories, from another station with the same geological conditions as the Beichuan county town, were used to evaluate the critical acceleration range, and the result was 0.08 g to 0.14 g, which showed that slopes in this condition were susceptible to earthquake, and landslides were easily triggered.

(3) Acceleration time histories, from two stations located on the hanging and foot wall and near the rupture, were selected to calculate the Newmark displacements. The results showed that landslides might be triggered even if the strong motion, located on the foot wall and a long distance from the rupture, was used. The Newmark displacement, combined with a suitable judgment criterion, is a good index for landslide risk evaluations, but it cannot be used for real landslide slippage.

We evaluated and analyzed the landslide hazards, where the damage was very serious, but without strong motion data, using data obtained from other stations recorded during the Wenchuan Earthquake. In this way, we made good use of the strong motion data. Furthermore, we can use the methods shown in this paper to evaluate parameters in other geological conditions in the Longmenshan area, which might be suitable for a decision rule or judging criterion in future project applications.

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