

Evaluation model of landslide hazards induced by the 2008 Wenchuan earthquake using strong motion data*

Xiuying Wang^{1,†} Gaozhong Nie² and Mujun Ma³

¹ *Institute of Crustal Dynamics, China Earthquake Administration, Beijing 100085, China*

² *Institute of Geology, China Earthquake Administration, Beijing 100029, China*

³ *National Earthquake Response Support Service, Beijing 100049, China*

Abstract Landslides induced by the 2008 Wenchuan earthquake in the Longmenshan area were relatively well instrumented, which makes it possible to investigate the landslides using ground motion records. Firstly, this paper analyzes the data from Wenchuan earthquake on both regional and local site scale. The analyses show that the Newmark accumulative displacement calculated from the ground motion recorded in a particular geological hazard zone corresponds to the hazard intensity in that zone; the larger the displacement, the more serious the geologic hazard. The calculated result also shows that the displacement is related to the Arias intensity, which represents the total energy released during the earthquake at the observation site. Secondly, this paper constructs an evaluation model of Newmark displacement calculated with Arias intensities to estimate the subsequent slope failure resulting from the earthquake. The calculated results based on the model fit well with the distribution of actual landslides, suggesting that this method is useful for hazard evaluation. Therefore, this type of model can be used for estimating regional-scale distribution of earthquake-induced landslides and their associated hazards immediately after an earthquake.

Key words: Wenchuan earthquake; earthquake-induced landslide; evaluation model; Arias intensity; earthquake intensity

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1 Introduction

The M_S 8.0 Wenchuan earthquake of 12 May 2008 induced severe landslides and caused great economic and human losses. Much research has subsequently been carried out concerning, not only the earthquake, but also geological disasters triggered by the earthquake (e.g., Huang and Li, 2008; Liu, 2008; Yin, 2008).

The Wenchuan earthquake is not the only one that induced serious landslide hazards, in fact earthquake-induced landslide hazards are widely distributed in China. According to statistical data from earthquakes that have occurred since 1949, over 20 provinces and regions have records of such disasters,

especially in the western mountainous areas prone to earthquakes (Wang and Nie, 2009a).

Unfortunately, studies on earthquake-induced landslides have been rarely reported in China to date, especially those based on the measurement of ground motion parameters.

In the previous researches, earthquake intensity was taken as an earthquake triggering factor (Zhou and Zhang, 1994; Ding et al., 2000; Wang, 2003). But, it may be affected by the personal biases of the observers due to the qualitative criteria involved (Hu, 2006). Therefore, as far as the same earthquake is concerned, inconsistency and discrepancy may exist in its intensities from different observers. Moreover, landslide number and extent themselves are often part of the criteria used to assess the earthquake intensity (Hu, 2006). For these reasons, evaluations of earthquake-induced landslides from those studies using earthquake intensity are not

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† Corresponding author. e-mail: xiuyw@sohu.com

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highly reliable.

Up to now studies on ground motion data from the earthquakes such as the 1987 Loma Prieta earthquake, the 1994 Northridge earthquake, and the 1999 Chi-Chi earthquake, suggest that ground motion is one of the most important factors resulting in earthquake-induced landslides; ground motion parameters are closely related to the distribution of earthquake-induced landslides. Therefore, ground motion parameters have subsequently been introduced into more and more earthquake-induced landslide investigations (e.g., Harp and Wilson, 1995; Liao, 2000; Keefer, 2002; Khazai and Sitar, 2004; Pradel et al., 2005; Jibson, 2007; Saygili and Rathje, 2008).

However, due to lack of ground motion data that correspond to earthquake-induced landslides, previous research generally compared ground motion data from earthquakes with records with landslides induced by earthquakes without records. It is easy to understand that the results of such studies may be problematic, since the source, path of propagation, and local site conditions have great influence on ground motion records (Hu, 2006). Two earthquakes with similar magnitude and epicentral distance to the receiver may produce quite different site responses. Therefore, conclusions arrived at by comparing data from different earthquakes at different locations may be deficient.

The $M_S8.0$ Wenchuan earthquake triggered numerous landslides (Yin, 2008; Huang and Li, 2008; Liu, 2008), and a large quantity of strong motion data were recorded (Li et al., 2008; Yu et al., 2008). This provides an excellent opportunity to study the relationships between earthquake-induced landslides and ground motion parameters from a single strong earthquake, and also to study the landslides' distribution characteristics and their relation with ground motion parameters in southwestern China.

Prior to the investigation presented in this paper, we studied the relationships between landslides induced by the Wenchuan earthquake and various ground motion parameters such as PGA, PGV, Arias intensity (I_a), and the lower and upper triggering limits of each of these parameters (Wang, 2009; Wang and Nie, 2009a, b; Wang et al., 2009, 2010a, b, c). We found that PGA, PGV and I_a are closely related to earthquake-induced landslides on both regional and local scales. Based on these studies, a quantitative evaluation model of landslides induced by the Wenchuan earthquake was built up to assess the regional-scale hazard. This will be useful for site selection and earthquake-induced landslide

hazard zoning for post-earthquake reconstruction work in the earthquake-hit area.

2 Data and methods

Since Arias intensity (I_a) is considered the most relevant ground motion parameter for studies of earthquake-induced landslides (Harp and Wilson, 1995; Jibson et al., 2000; Wang et al., 2009), this paper employs I_a as an estimation parameter in the model.

2.1 Definition of Arias intensity

Arias intensity (Arias, 1970) is defined as the sum of all the squared acceleration values from a strong motion record. It is a measure of the energy dissipated at a site by shaking.

$$I_a = \frac{\pi}{2g} \int_0^{T_d} [a(t)]^2 dt, \quad (1)$$

where $a(t)$ is the acceleration value from the record, T_d is the duration of the shaking, and g is the acceleration due to gravity. I_a is in m/s .

From equation (1) we can see this parameter incorporates both amplitude and duration information, making it more capable of representing the shaking intensity of ground motion than other parameters, such as PGA and PGV, in which only the instantaneous maximum values are selected to represent the shaking intensity. Therefore, this parameter is more suitable for evaluations of surface damage, including earthquake-induced landslides of course.

2.2 Newmark analysis

The Newmark analysis is often used in slope stability analyses in conjunction with seismic activity. For this method, the slope is taken as a rigid friction block. When the ground acceleration exceeds the slope's critical/yield acceleration (a_c), the threshold ground acceleration necessary to overcome the block sliding resistance, down-slope movement will be initiated and permanent movement of the block will begin to accumulate. If the critical acceleration of the slope is known, Newmark displacement can be calculated by double integrating all those values exceeding the slope's critical acceleration (a_c). The Newmark calculation process can be expressed as

$$D_N = \iint [a(t) - a_c] dt dt, \quad (2)$$

where D_N is the Newmark displacement, a_c is the critical acceleration, and $a(t)$ is the ground acceleration time history.

With this method, accumulated permanent displacement is calculated over the whole shaking process, and the calculated result is used to analyze the slope stability. Both lab and field investigations have proved that Newmark analysis is accurate when the slope geometry parameters, geotechnical controls, and ground acceleration time history are provided correctly. For example, the measured displacement of a landslide, triggered by the 1979 Coyote Lake earthquake in California, is in excellent agreement with the Newmark displacement calculated from the acceleration time history (Wilson and Keefer, 1983).

The critical acceleration, a_c , must be obtained in order to calculate the Newmark displacement. One way to determine a_c is to use the static safety parameter F_s , i.e., a different acceleration is applied to the slope, and then the acceleration value that makes F_s equal to 1.0 is the critical acceleration. Slope critical acceleration signifies that the slope may fail when the ground motion acceleration reaches or exceeds this value. It is the maximum ground motion acceleration that the slope can withstand when subjected to an earthquake, and it is related to the slope geotechnical parameters (shear strength, unit weight, pore water pressure, etc.), and the slope geometry. It can be calculated by the following equation (Wilson and Keefer, 1983):

$$a_c = (F_s - 1)g \sin \theta \tag{3}$$

where F_s is the static factor of safety, and θ is the slope angle.

The Newmark displacement is often used as an index of slope failure (Jibson, 2007); the larger is the Newmark accumulated displacement, the greater the probability of slope failure is. When the displacement exceeds the maximum displacement limit a slope can withstand, it is quite possible that a landslide will be triggered. Therefore, the failure of a slope after an earthquake can be deduced from the accumulated displacement, and the results evaluated by this method are much more reliable than those by PGA only. This is because it is not necessary to accumulate sufficient displacement if the PGA does exceed the critical acceleration, and the slope may resume its original status after undergoing a vibration episode.

2.3 Distribution of strong motion data

Before the Wenchuan earthquake, a large number of ground motion instruments were deployed in the Longmenshan area. Therefore, a large quantity of acceleration records were obtained from both the main shock and its aftershocks (Li et al., 2008; Yu et al., 2008). Nearly 40 groups of records from the main shock were selected for this study. Their stations are distributed along the earthquake rupture trace both on the hanging wall and footwall, corresponding well with the most serious earthquake-induced geological disaster areas. Figure 1 shows the distribution of these strong motion stations

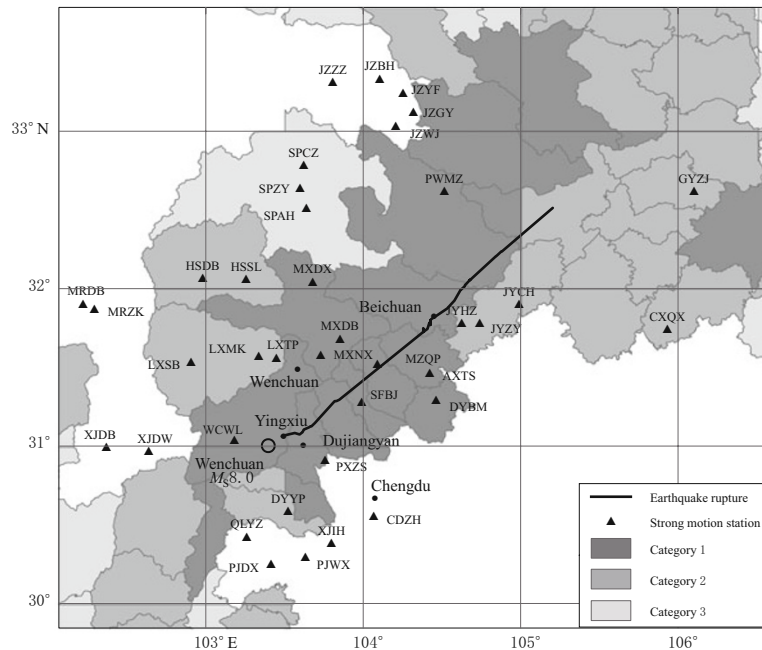


Figure 1 Distribution of geological disaster zones and ground motion observation stations in the Longmenshan area.

and their positions relative to the earthquake rupture and the Longmenshan fault zone.

After the Wenchuan earthquake, the China Institute for Geo-Environmental Monitoring, Ministry of Land and Resources, divided the disaster-stricken areas into three categories based on geological data obtained from field investigation immediately after the earthquake. The three categories, divided according to the average disaster levels calculated for each administrative unit, are category 1, category 2 and category 3, respectively, as shown in Figure 1. We divided the strong motion stations into different groups according to their positions within the three categories. The stations that do not fall into anyone of the three categories were grouped into category 4, where we think the average disaster level is slight. In this way, we can compare the ground motion intensity with the disaster level on a regional scale.

3 Newmark displacement evaluation model

3.1 Relationship between Newmark displacement and geological hazard

From the geological hazard zoning map shown in Figure 1, we can deduce that in the places where the geological hazard is serious, e.g., where the average number of landslides is high, the landslide displacement calculated by the Newmark method [equation (2)] will be large. This is because many of the landslides that took place in this region covered large areas and had longer runout distances. We can also deduce that the ground motion intensity will be strong in these locations, and therefore the corresponding Arias intensity will be high.

Since no critical acceleration data is available and the analysis is not on a concrete slope, we calculate the Newmark displacement for a range of a_c and plot D_N versus a_c for given acceleration time histories. We can then chart these D_N versus a_c curves according to their geological categories, as shown in Figure 2. The figure legends show the corresponding average I_a of the horizontal components.

Comparison of the four charts shown in Figure 2 leads to some observations as below.

In Figure 2, the Newmark displacement is the largest in category 1, the most serious geological disaster area, followed by category 2, then category 4. Category 3, with relatively fewer observation stations, lacks adequate strong motion data. The general trend in Figure 2 shows that a decrease in geological hazard lev-

el (or disaster level) corresponds to a decrease in the Newmark displacement. This indicates that the Newmark displacement is proportional to the seriousness of the geological hazard, including landslides, on a regional scale and can be taken as an indicator of the severity of potential geological disaster. Therefore, based simply on strong motion records, the Newmark displacement can be used to estimate the seriousness of the geological disasters resulting from an earthquake and can provide information for earthquake emergency rescue services and reconstruction works after the earthquake. In this way, earthquake hazard evaluations can be obtained much more quickly than by assessing earthquake intensity, which often takes a long time to be accurately determined after an earthquake.

Strong motion records also relate to the local geological hazard in the same category. Considering locations with the same a_c , those locations with larger Newmark displacements are also those with the most serious geological disasters. For example, the Bajiao station (SFBJ in Figure 1) in Shifang city, the Wolong station (WCWL in Figure 1) in Wenchuan county, and the Qingping station (MZQP in Figure 1) in Mianzhu city obtained the top three Newmark displacements during the Wenchuan earthquake; all three are in category 1, the region of most serious geological disaster according to the average disaster levels. Numerous landslides, many of which were large, were triggered at these three sites. For this reason, we can see that the Newmark displacement can also be a good indicator of the landslide hazard on a local scale. Given a slope and its a_c , the larger is the calculated Newmark displacement, the larger the failure probability of the slope is. The Newmark displacement can therefore be used to judge the failure possibility of a slope or disaster seriousness in small region after an earthquake.

From Figure 2, we can see that, at observation points with large Newmark displacement, the corresponding Arias intensity values are large, too. This indicates that the Newmark displacement is proportional to I_a , the ground motion parameter that can represent the ground intensity released by the earthquake at a local site. There are some other parameters used more often than I_a , but the analysis in our study (Wang et al., 2010c) shows that I_a is more related to ground motion intensity and earthquake damage. Therefore, larger I_a implies more energy released. As a result, more serious landslide disaster will be triggered by the earthquake.

The above analyses support the conclusion that the Newmark displacement can well indicate the disaster

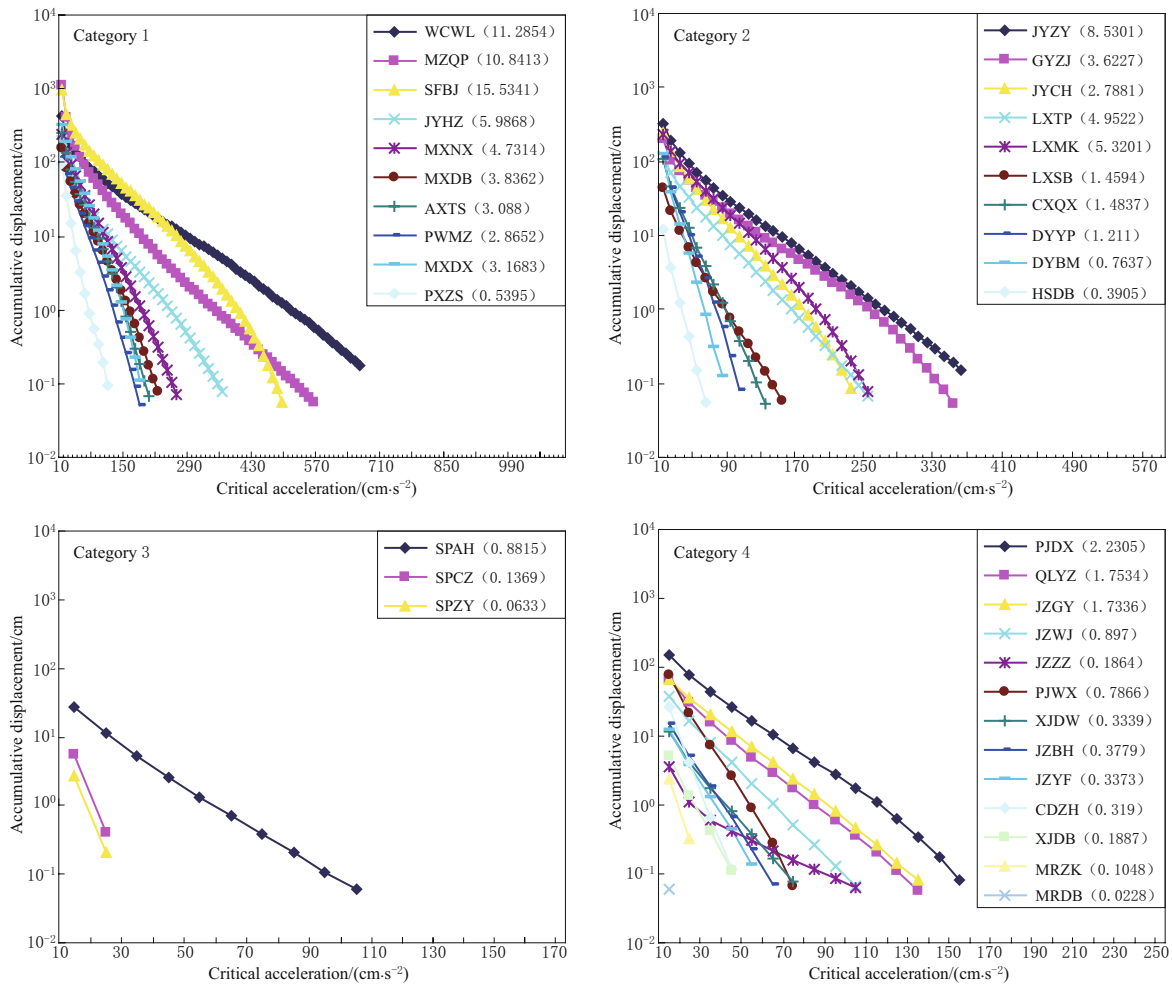


Figure 2 Newmark displacement plotted against critical acceleration for the four geological hazard categories. The legends show the average I_a of the horizontal components from the seismic stations shown in Figure 1.

level, at the same time, it is proportional to the ground intensity. Therefore, the Newmark displacement can be estimated by the ground intensity parameter and be used to evaluate the seriousness of landslide disasters.

3.2 Newmark displacement and Arias intensity

Here, we quantitatively analyze the relationship between the Newmark displacement and Arias intensity. For a given a_c value, we calculate the Newmark displacement for each acceleration time history and get the D_N versus I_a as shown in Figure 3. We calculated four groups of D_N versus I_a values by taking a_c values as 50, 100, 150, and 200 cm/s^2 , respectively .

As shown in Figure 3, the Newmark displacement is obvious proportional to I_a , i.e., it decreases with Arias intensity decreasing. As for the a_c , the Newmark displacement is negatively correlated with it, i.e., it decreases with an increase in a_c . It is understandable that a larger a_c , a parameter reflecting the maximum ground

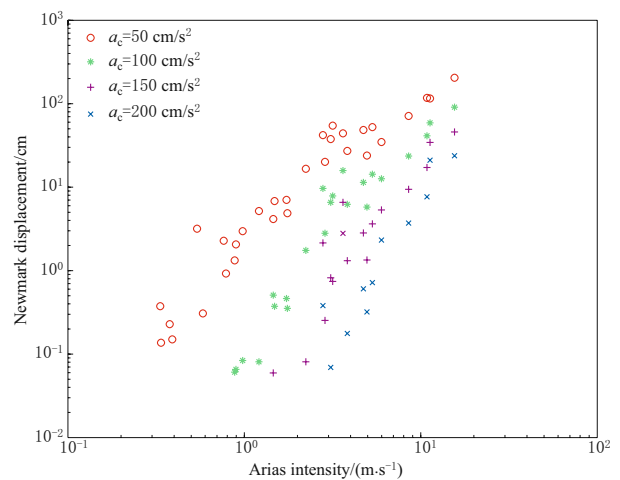


Figure 3 Newmark displacement versus Arias intensity I_a for a range of a_c .

motion intensity a slope can withstand, means that the slope has a higher ability to withstand strong ground motion intensities without failure.

I_a represents the ground motion intensity of an earthquake, while a_c (in the unit of m/s^2) represents the ability of a slope to remain stable when the slopes are subjected to an earthquake. Therefore, a higher a_c will result in less Newmark displacement under the same ground motion intensity. On the other hand, the same slope will result in a larger Newmark displacement when subjected to stronger ground motion intensity. Hence, we can construct a model by the following equation:

$$\lg D_N = a \lg I_a - b \lg a_c + c. \quad (4)$$

Equation (4) is the improved equation of Jibson et al. (2000). Here, we will prove that this is correct by assessing the regional hazard distribution and quantitatively analyzing the data obtained from the Wenchuan earthquake. The resulting regression equation based on data shown in Figure 3 is

$$\begin{aligned} \lg D_N &= -4.0687 + 2.0551 \lg I_a - 2.9325 \lg a_c, \\ \sigma &= 0.11, \end{aligned} \quad (5)$$

where D_N is the Newmark displacement in cm, I_a is the sum of the Arias intensity in the horizontal direction in m/s , and a_c is the critical acceleration in g .

Equation (5) can be used to estimate the possible Newmark displacement in different parts of the earthquake-affected regions once a_c and I_a are known in advance. Since it is difficult to get the correct a_c value for each slope, the possible a_c values have been evaluated based on the acceleration time history records and landslides triggered by the Wenchuan earthquake, which can be found in another study of our series research (Wang et al., 2009).

Next we will consider the I_a . Here, we follow the normal way to get the ground motion parameters, e.g., to establish the attenuation relationship of I_a [equation (6)] based on the same data set mentioned above. The detailed deduction can be found in Wang et al. (2010c).

$$\begin{aligned} \lg I_a &= -2.96 \lg(D_f + 42.0) + 6.39, \\ r &= -0.79, \quad \sigma = 0.40, \end{aligned} \quad (6)$$

where I_a is the sum of the Arias intensity of the horizontal components in m/s and D_f is the observation distance to the earthquake rupture in km.

The Newmark displacement estimated in this way is not the actual displacement caused by the earthquake.

Instead, it can be used as an indicator of the failure status (hazard level) of the slopes analyzed above. If a larger D_N is obtained by equation (5), we are sure of a greater possibility of triggered landslides; otherwise, the possibility of landslides will be lower.

4 Application of the model

To assess the landslide hazard distribution model, $0.1g$ is taken as a representative critical acceleration value for the Longmenshan area. This a_c value was obtained from previous work (Wang, 2009; Wang et al., 2010a). Combining equations (5) and (6), we calculated the various Newmark displacements as shown in Figure 4. The different critical displacements are selected based on the results usually adopted by many researchers.

In Figure 4, the 29 km innermost closed curve corresponds to a critical displacement of 10 cm, a value taken by most researchers as the maximum movement that most slopes can undergo when the Newmark displacement model is used (e.g., Wilson and Keefer, 1985; Jibson, 2007). Displacements inside this closed curve are larger than 10 cm, which means that slope failure is almost certain. Huang and Li (2008) reported most landslides and all the large landslides triggered by the Wenchuan earthquake were located within 30 km of the earthquake rupture. The 29 km distance contoured in Figure 4 fits well with the actual landslide distributions, although it looks smaller than that for category 1, the most serious landslide hazard area, which may incorporate some locations with less significant hazard during the averaging process.

The middle closed curve, at a distance of 48 km from the rupture, corresponds to a critical displacement of 2 cm, a value adopted by Wilson and Keefer (1985) for slopes with brittle material that is common in the Longmenshan area (Huang and Li, 2008; Feng et al., 2007). This curve generally corresponds to category 1. Within this range, the Newmark displacement is larger than 2 cm, but less than 10 cm, which corresponds to a very high probability of landsliding, especially for those slopes consisting of brittle material.

The outermost closed curve, at a distance of about 100 km from the earthquake rupture, corresponds to the positions where no accumulated displacement is estimated. Within the 48–100 km band, the displacement is greater than zero but less than the critical displacement of 2 cm; therefore landslides might still be triggered, but the possibility is decreased.

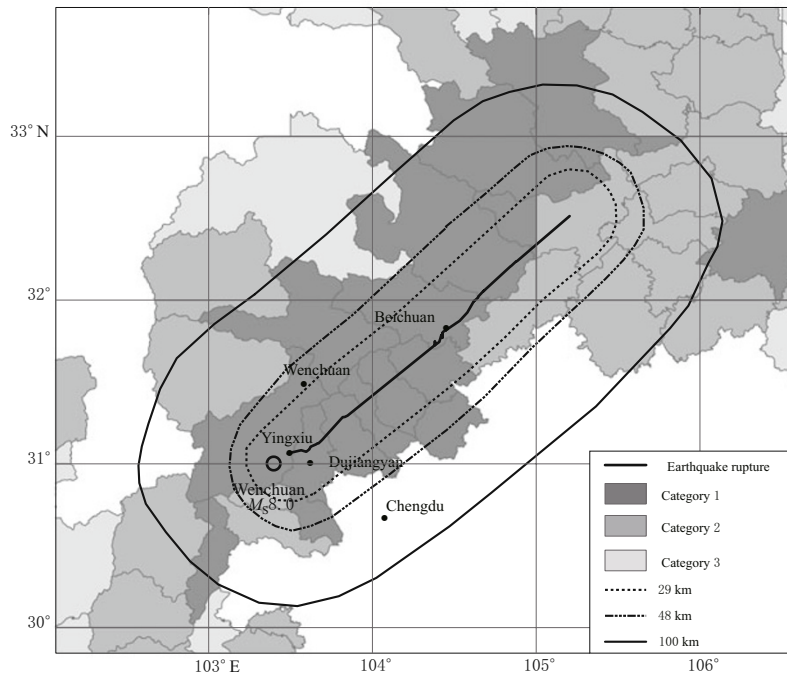


Figure 4 Comparison of the modeled and actual landslide distributions.

This model can provide a general distribution map of regional landslides (Figure 4). However, earthquake-induced landslides are affected by many factors. Ground motion intensity is not the only important factor; geological and topographical conditions can also exert great influence on landslide occurrences. Therefore, as can be seen from Figure 4, differences may exist between the modeled and actual cases. For example, notice that to the southeast of the earthquake rupture, on the foot-wall of the fault, landslides hazard is less than modeled, whereas on the northeast side of the rupture, the hazard is more severe. This is due to the thrust faulting mechanism and the propagating effect of the earthquake. Moreover, on the northeast side of the rupture, the geological distribution of loess deposits is quite different from those in the Longmenshan area. Hence, if a more accurate result is needed, many additional factors, including local geology, must be taken into account in the evaluation model.

In spite of the generalized model results, the Newmark displacement method can provide a better result than those obtained by earthquake intensity. The latter produces isoseismal maps with much larger areas where the earthquake intensity is greater than IV (Department of Earthquake Emergency Rescue, China Earthquake Administration, 2008), an earthquake intensity

value adopted by many researchers as a threshold for triggering landslides. If this evaluation model could be produced immediately after an earthquake, it would be helpful for decision-making during emergency rescue. For example, it could be used to focus rescue work in regions with greater hazard. If more accurate parameters are provided, the evaluation model can produce better result. This may even be useful for engineering applications during reconstruction work following a large earthquake like Wenchuan.

5 Conclusions

Studies of earthquake-induced landslides in China using ground motion parameters have been rare. This paper made an attempt to improve this situation using valuable ground-motion data from the 2008 Wenchuan earthquake. Based on landslide zonation of regional scale and their corresponding Newmark displacements, this paper shows that the Newmark displacement can well describe the spatial distribution of geological disasters. Moreover, the Newmark displacements from different sites in the same category can also reflect the damage situation of the local sites. The calculated result from the selected records demonstrated that the Newmark displacement is proportional to ground motion intensity and is inversely proportional

to slopes' critical acceleration. Therefore, the Newmark displacement evaluation model was built up for the Wenchuan earthquake in the Longmenshan area. The modeled landslide distribution fits well with the actual case, especially with the most serious geological disaster area.

The study also shows that a model constructed through ground motion parameters can produce better results than the one constructed using earthquake intensity that has been previously used for routine assessments in China. Earthquake intensity measurements have already been replaced by ground motion parameters in earthquake engineering applications (Hu, 2006). Therefore, the study on earthquake-induced landslides with ground motion parameters is in agreement with this type of work. By using ground motion parameters, researchers can link the study of landslides with the achievements of the ground motion parameters zoning work developed through earthquake engineering. The research in this paper is only preliminary. Further studies are needed to incorporate more data and design new methods.

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