Applicability of Two Newmark Models in the Assessment of Coseismic Landslide Hazard and Estimation of Slope-Failure Probability: An Example of the 2008 Wenchuan $M_w$ 7.9 Earthquake Affected Area

Siyuan Ma, Chong Xu

Key Laboratory of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Beijing 100029, China

© China University of Geosciences (Wuhan) and Springer-Verlag GmbH Germany, Part of Springer Nature 2019

ABSTRACT: This paper presents the landslide hazard assessment and slope-failure function using two Newmark displacement models regressed by regional and global station records. Taking the 2008 Wenchuan $M_w$ 7.9 earthquake area as an example, based on the topographic and geological data of the study area, we prepared a factor-of-safety ($F_s$) map and a critical acceleration ($a_c$) map, respectively. Then using these two simplified Newmark models, two displacement maps were compiled by combining the $a_c$ map and peak ground acceleration ($PGA$) map. By virtue of the actual landslide inventory of the Wenchuan earthquake, we constructed the slope-failure probability curves of the two Newmark models. The results show that the abilities to predict landslide occurrence of the two simplified Newmark models are largely identical, by which the assessment results can well delineate the macroscopic distribution of coseismic landslides, and most predicted landslide cells are distributed on the two sides of the Beichuan-Yingxiu fault, especially Pengguan complex rock mass in the hanging wall of this fault. The probability equations of two Newmark models are roughly the same, though the parameters vary slightly. The probability equation proposed in this paper can be applied to the Wenchuan region and other areas with similar tectonic environments.

KEY WORDS: Wenchuan earthquake, seismic landslides, Newmark displacement, peak ground acceleration ($PGA$).

0 INTRODUCTION

Coseismic landslides can cause significant economic losses and casualties, which have drawn great attention of geoscientists (Rao et al., 2017; Sharifi-Mood et al., 2017; Kargel et al., 2016; Tian et al., 2016; Xu et al., 2016; Tang et al., 2010; Keefer, 1984). Many studies on landslide inventories, landslides distribution, and landslide hazard assessment have been conducted, which offers important support to the mitigation of earthquake-induced landslide hazard (Xu et al., 2018, 2013a; Tian et al., 2016). Earthquake landslide hazard assessment is one of the most important research directions, which can provide references for the restoration and reconstruction of quake-hit areas. Currently, the commonly used methods of landslide hazard assessment include statistical analysis and the Newmark method. The statistical analysis uses coseismic landslide inventories to establish mathematical models between the observed landslides and landslide-related factors, which facilitates the landslide hazard assessment of the whole study area (Shao et al., 2019; Nowicki et al., 2018; Robinson et al., 2018; Xu et al., 2013a). The advantages of these statistical methods are that the models are constructed by actual landslide distributions, and the assessment results are relatively subjective. However, such methods need sufficient landslide samples to construct statistical models and that is why the assessment results lag behind the practical application.

In contrast, the Newmark method can be used for landslide hazard assessment without real landslide samples. This tool is commonly employed to deal with the seismic performance of dams and embankments, which was Newmark’s original intent (Newmark, 1965). Subsequently, several simplified approaches have been proposed using the Newmark’s method for quantitative landslide hazard assessments, such as the 1979 Coyote Lake earthquake (Wilson and Keefer, 1983), 1989 $M_w$ 6.9 Loma Prieta earthquake (McCrink, 2001), 1994 $M_w$ 6.7 Northridge earthquake (Jibson et al., 2000, 1998), 2013 $M_w$ 6.6 Lushan earthquake (Ma and Xu, 2019; Chen et al., 2014a), 2015 $M_w$ 7.9 Nepal earthquake (Gallien et al., 2017) and 2017 $M_w$ 7.0 Jiuzhaigou earthquake (Liu et al., 2017). Currently, it is widely used to assess the earthquake-induced slope failure.
used in seismic hazard assessment in the world (Jibson et al., 2013).

In recent years, in the application of the Newmark method, many studies have fitted various Newmark empirical formulas based on the different strong ground-motion records all over the world (Xu et al., 2012; Hsieh and Lee, 2011; Saygili and Rathje, 2008; Bray, 2007; Jibson, 2007). Among them, Xu et al. (2012) corrected the regression parameters of the simplified Newmark model and established a Newmark model suitable for the Wenchuan earthquake based on the 221 ground motion records of this earthquake. However, the existing studies about the Wenchuan earthquake do not quantitatively evaluate the applicability of this Newmark model (Wang et al., 2013; Godt et al., 2008). In addition, due to the lack of a detailed landslide inventory, the relationship between the Newmark displacement and the probability of failure has not been established yet. Jibson et al. (2000) indicated that although there is no direct correspondence between the Newmark displacement and actual slope movement, the Newmark displacement could be correlated with the probability of failure based on the actual landslide inventory. Jibson et al. (2000) established a regression equation between the probability of failure and displacement according to the inventory of landslides triggered by the Northridge earthquake. However, due to the differences in seismic, geological and topographic conditions, the applicability of this probability curve to the Wenchuan earthquake remains unclear. In addition, the study area selected by Jibson et al. (2000) is only the epicenter area of the Northridge earthquake where landslides are densely distributed, which does not include the whole affected area, thus likely causing discrepancy with the assessment of the whole affected area.

In this work, we made landslide hazard assessment of the Wenchuan earthquake based on two simplified Newmark models established by regional and the global station records, respectively. Then we conducted a detailed quantitative analysis of the two Newmark models. Meanwhile, based on a complete landslide inventory of the Wenchuan earthquake (Xu et al., 2014), the relationship between the Newmark displacements and the probability of slope-failure was analyzed, and the slope failure function of the Wenchuan earthquake was constructed. This study can provide an effective reference for regional coseismic landslide emergency assessment and prediction of potential earthquake-induced landslide hazard based on the Newmark method.

1 THE WENCHUAN EARTHQUAKE AND GEOLOGICAL SETTING

The collision of the Indian and Eurasian plates resulted in the uplift of the Tibetan Plateau and eastward motion of a series of blocks in this highland. Obstructed by the rigid Sichuan Basin, the Longmen Shan thrust zone formed along the boundary between the Tibetan Plateau and Sichuan Basin. It is composed of three thrust faults, which are the Maoxian-Wenchuan fault, the Yingxiu-Beichuan fault, and the Guanxian-Jiangyou fault from northwest to southeast. The 2008 Mw 7.9 Wenchuan earthquake was the result of the sudden rupture of the Yingxiu-Beichuan fault (Xu et al., 2009).

Due to the very strong shaking of the earthquake, plus the relatively fragile geological condition of the Longmen Shan area, the secondary geologic effect by this event was extremely serious (Yin et al., 2009). Investigations show that this earthquake triggered nearly 200 thousand landslides, which are the densest, largest in number and most widely distributed so far (Xu et al., 2014). Based on previous work (Xu et al., 2014), we took a nearly elliptical zone as the study area (Fig. 1). Its total coverage area is about 44 031 km², and the number of landslides is 196 007, with a total area of 1 150.43 km². Of them, the number of large-scale landslides (area >1 000 m²) is 158 225, accounting for 97.9% of the total landslides area. The landslides of the whole study area are mostly distributed along the Yingxiu-Beichuan fault. The strata of the study area include from Quaternary to pre-Sinian. The lithology is mainly composed of sandstones, limestones, slates, intrusive rocks and quaternary deposits. Among them, intrusive rocks are prone to sliding, where the landslide number density (LND) reached 18.6 landslides/km², which is highest in all lithological classifications (Xu et al., 2014).

2 METHOD

2.1 Overview of the Newmark Method

The Newmark method was proposed for the stability analysis of dams under earthquakes (Newmark, 1965). It is believed the dam instability depends critically on the deformation of the dam rather than the minimum safety factor. It simulates a landslide as a rigid friction block that slides on an inclined plane at a known critical acceleration (a_c) which is simply the threshold base acceleration required to overcome shear resistance and initiate sliding (Jibson, 1993). The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to the effect of an earthquake acceleration-time history. Those portions of the record that exceed the critical acceleration are integrated twice to obtain the cumulative displacement of the block. In a real landslide hazard case, however, it is not easy to find the strong-motion record at a specific site for calculation of the Newmark displacement. To solve these problems, simplified Newmark models were developed (Wilson and Keefer, 1983).

The calculations of simplified Newmark displacements include the safety factor (F_s), critical acceleration (a_c) and the cumulative displacement (D_n), which are stated below.

(1) According to the geometric properties (slope thickness (t), the degree of slope saturation (m); slope angle (α)); and mechanical properties (effective cohesion (c'), internal friction angle (φ'), the weight of soil and rock (γ), and weight of underground water (γ_w)), the static factor of safety (F_s) for an infinite-slope model (Fig. 2) is computed as

\[ F_s = \frac{c'}{\gamma \sin \alpha} + \frac{\tan \phi'}{\tan \alpha} + \frac{\gamma_w \tan \phi'}{\gamma \tan \alpha} \]

(2) A map of critical acceleration (a_c) is generated assuming an infinite slope condition.

\[ a_c = (F_s - 1) \gamma \sin \alpha \]

(3) The distribution of the Newmark displacement in the study area is obtained by using a simplified Newmark model.
2.2 Generation of Factor-of-Safety and Preparation of Acceleration Maps

In this work, lithology was from a 1 : 200,000 geological map. The slope angles of the study area were derived from a DEM with resolution 20 m (Fig. 3a). Generally, the slopes less than 20° are very stable and rarely subjected to large-scale landslides, so these areas are not analyzed in this study (Fig. 3a).

At present, objective lithology assignment based on geological maps remains one of the difficult problems for regional assessment in the Newmark method. In this study, the strength parameters and details for each group are adopted from geological bibliography (Ministry of Water Resources of the People’s Republic of China, 2014; Ministry of Construction of the People’s Republic of China, 2009) and previous studies (Dreyfus et al., 2013; Wang et al., 2013; Godt et al., 2008). The rocks of the study area can be classified into four groups: Group 1 (loose rock), Group 2 (soft rock), Group 3 (relatively hard rock) and Group 4 (hard rock) (Fig. 3b). The distribution area of loose rock (Group 1) mass is the smallest, mainly in the alluvial and flood plain areas of the frontal Longmen Shan fault zone, which comprises Quaternary gravels and clay deposits. The relatively hard rock and soft rock are the most widely distributed. The soft rock (Group 2) mainly includes Silurian phyllite, slate, Devonian carbonate rock with mudstone, Carboniferous limestone with mudstone, Jurassic siltstone, Cretaceous siltstone, mudstone. The relatively hard rock (Group 3) is dominated by Sinian dolomite, Ordovician limestone, Devonian bioclastic limestone, Permian limestone-dolomite, and Cretaceous quartz sandstone. The distribution of the hard rock (Group 4) contains the Pengguan complex rock mass between the Yingxiu–Beichuan fault and the Wenchuan–Maoxian fault. Figure 3b shows the rock grouping and mechanical parameters of each group.

It needs to be noted that although the Pengguan complex rocks are dominated by granites, diorites, and intrusive dikes, they contain numerous joints and fractures, leading to a lower strength. Besides, the actual landslide indicates that a large number of slope failures occurred in the Pengguan complex rock mass, which covers nearly 70% of the all landslides with the highest LND of 18.6 landslides/km². Considering the particularity of the Pengguan complex rock mass, we referred to the classification of rock masses engineering (Ministry of Water Resources of the People’s Republic of China, 2014; Ministry of Construction of the People’s Republic of China, 2009) and the
previous studies (Wang et al., 2013), so appropriate reduction was made to mechanical values of hard rock (Group 3) in Pengguan complex mass (the reduction coefficient was set as 0.7).

The pore water pressure ($m=0$ in Eq. 1) was neglected because of the dry condition during the temblor in the study area. As it is difficult to obtain the accurate values of landslide depth, this parameter in the Newmark method was typically set as 3 or 5 m. Combining the landslide type and its scale, based on field observations and previous research (Chen et al., 2014b; Dreyfus et al., 2013; Jibson et al., 2000), this work assumed the depth of the failure surface was 5.0 m (Bojadzieva et al., 2018; Wang et al., 2013). Using the input data, the factor-of-safety (Fig. 4a) and the critical acceleration (Fig. 4b) in the study area were calculated using Eq. 1 and Eq. 2.

In the calculation of the static factor of safety ($F_s$), the calculated $F_s$ value may be less than 1 (we assumed that all regions before the earthquake were stable, that is, $F_s>1$). In order to solve this problem, Jibson et al. (1998) enhanced successively the mechanical parameters of rocks by an iterative method until the static factor $F_s$ with slope angle less than $60^\circ$ is greater than 1. However, Dreyfus et al. (2013) thought that this would cause higher mechanical parameters of rocks in steep slopes. So, we made a statistical analysis of the distribution of $F_s$ from the assumed parameters, showing that the values of $F_s$ in the most study area are greater than 1, while the regions with the $F_s$ less than 1 only account for less than 5% of the entire study area, which corresponds to the places with slope gradients exceeding $50^\circ$. This also shows the reliability of the lithological parameters set in this work. In the end, we referred to a previous study (Dreyfus et al., 2013) and assigned the region of the static coefficient $F_s<1$ to 1.01, which can avoid the exorbitant value of rock mechanical parameters by the iterative method.

![Figure 3. Maps showing distribution of slope angles (a) and rock groups of rock strengths (b).](image1)

![Figure 4. Maps showing the distribution of static factors of safety ($F_s$) (a) and critical acceleration ($a_c$) (b).](image2)
2.3 Calculation of Newmark Displacement

In this study, we used the PGA map for the 2008 Wenchuan earthquake published by USGS. Because it is based on a finite fault model (USGS, 2008), the PGA values in the hanging wall of the seismogenic fault are obviously larger than that in the footwall, which can better reflect the effect of the hanging wall (Li et al., 2010; Wen et al., 2010). From Fig. 4, the maximum value of PGA in the whole study area is 1.74 g, and the minimum is 0.08 g.

Simplified Newmark models were regressed by analysis of strong ground-motion records, which are influenced by the seismic wave propagation path, the spread medium and the site effect, resulting in the regression model having regional features based on the different regional strong ground records (Chousianitis et al., 2014; Hsieh and Lee, 2011; Romeo, 2000). At present, many studies have fitted different Newmark models based on the global strong-motion records (Hsieh and Lee, 2011; Saygili and Rathje, 2008; Bray, 2007; Jibson, 2007; Jibson et al., 1998). According to 2,270 strong-motion records of 30 worldwide earthquakes, Jibson (2007) obtained different simplified Newmark models of different ground motion parameters. In this study, we selected one of the Newmark models using the PGA parameter. Xu et al. (2012) corrected the regression parameters of this model and established the Newmark model for the Wenchuan earthquake based on the 221 ground motion records of the Wenchuan earthquake. In this study, we used these two empirical models to perform the landslide hazard assessment and calculate the slope-failure probability of the Wenchuan earthquake. The two Newmark models are shown in Table 1.

The two curves in Fig. 6 show the changes between Newmark displacement and $a_c/PGA$ of the two models. It is clear that the $D_n$ value calculated by Xu2012 is slightly higher than that of the $J_{2007}$ model.

Based on these two models, the distributions of Newmark cumulative displacements were obtained (Fig. 7).

3 RESULTS

3.1 Comparison of Different Displacement Models

The study area covers roughly all the coseismic landslides of the Wenchuan event. Considering the DEM with resolution 20 m, we only selected landslides larger than 1,000 m² in individual size. Based on the detailed Wenchuan landslides inventory available, 158,225 landslides (area >1,000 m²) were selected with a total area of 1.12645 km². Using median elevation of each landslide to define the source zone and deposit zone, landslide source areas were defined to include those grid cells that have elevations above the median elevation for each landslide, so that the upper half of each landslide was considered a source area (Dreyfus et al., 2013; Jibson et al., 2000).

Finally, the source area of these landslides is 541.44 km². The Newmark displacement distributions obtained by the two simplified models (Fig. 5) are compared with the actual landslide inventory. Referring to previous studies (Dreyfus

![Figure 5](image-url) Distribution of PGA across the study area during the Wenchuan earthquake (USGS, 2008).

![Figure 6](image-url) Newmark displacements plotted logarithmically as a function of critical acceleration ratio for two models.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Two simplified Newmark models based on global seismic motion records and Wenchuan earthquake’s records</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Equation</td>
</tr>
</tbody>
</table>
| $J_{2007}$ | \[
\log D_n = 0.215 + \log \left( 1 - \frac{a_c}{PGA} \right)^{2.541} \times \left( \frac{a_c}{PGA} \right)^{-1.438}
\] | Jibson (2007) |
| $Xu_{2012}$ | \[
\log D_n = 0.194 + \log \left( 1 - \frac{a_c}{PGA} \right)^{2.626} \times \left( \frac{a_c}{PGA} \right)^{-1.754}
\] | Xu et al. (2012) |

Note: $D_n$ is Newmark displacement (cm), $a_c$ is the critical acceleration (g), and PGA is the peak ground acceleration (g).
et al., 2013; Dreyfus, 2011), we used three parameters for evaluation analysis, i.e. the percentage of ground failures captured (%GFC) (Eq. 3), the percentage of the quadrangle covered with predicted landslides %Ls_Pred (Eq. 4) (i.e., cells with computed displacements above a threshold value) and the ratio of predicted landslide area to actual landslide area (Ls_Pred/Ls_Obs) (Eq. 5). These parameters are computed as follows.

\[
%\text{GFC} = \frac{\text{Number of landslide source cells with } D_n > x \text{ cm}}{\text{Total number of landslide source cells}} 
\]

(3)

\[
%\text{Ls}_\text{Pred} = \frac{\text{Number of cells with } D_n > x \text{ cm}}{\text{Total number of cells in the study zone}} 
\]

(4)

\[
\frac{\text{Ls}_\text{Pred}}{\text{Ls}_\text{Obs}} = \frac{\text{Number of cells with } D_n > x \text{ cm}}{\text{Total number of landslide source cells}} 
\]

(5)

where \(D_n\) is the predicted Newmark displacement in cm; and \(x\) is the specified displacement threshold in cm.

At present, there are still disputes about the value of critical displacement (Jibson, 2011; Jibson and Michael, 2009; Jibson et al., 2000; Miles and Ho, 1999). In this paper, we set up the displacement threshold as 15 cm, and any cells with a predicted displacement exceeding this threshold were considered predicted landslide cells.

Compared with the actual landslides distribution, the quantitative evaluation results (Fig. 8) show that the GFC value obtained by the model Xu2012 is 42.2%, which indicates that the 42.2% of the observed landslide cells are captured. The GFC value based on the J2007 model is 35.5%. The Ls_Pred value is a measure of the over-prediction (or under-prediction) of the overall landslide area from the two models, without consideration of whether the landslide locations are accurately identified. The Ls_Pred value based on the Xu2012 model is 5.74%, implying that the predicted landslide cells account for 5.74% of the whole study area, and the Ls_Pred value based on the J2007 model is 4.5%. However, the total source area of all landslides accounts for 1.2% of the study area, which indicates that the predicted landslide cells are greater than the observed. According to the evaluation parameters, the evaluation results of two Newmark models based on different strong ground motion records have little difference. On the whole, the predicted landslide cells based on the Xu2012 model are slightly larger than those of the J2007 model.

3.2 Estimation of Slope-Failure Probability

Predicted Newmark displacements do not directly relate to the slope instability, but the value of Newmark displacement can provide an index to correlate with slope movement (Jibson et al., 2000). The larger the predicted Newmark displacement is, the higher the probability of the slope failure is. Jibson et al. (2000) compared predicted Newmark displacements with the actual inventory of landslides triggered by the Northridge earthquake to confirm the relationship between Newmark displacement and the probability of slope failure. Firstly, the displacement grid cells are grouped into bins. For each bin, the proportion of the cells that are in landslide source areas is calculated. The proportion of cells in each bin occupied by landslide source is taken as the probability of the slope failure, then the regression curve between the probability of slope fail-
ure and the $D_a$ value is established based on the Weibull curve, which was initially developed to model the failure of rock samples (Jasper and Cook, 1969). Jibson et al. (2000) showed that the probability of slope failure increases rapidly with the growth of Newmark displacement in the first few centimeters; and when $D_a$ reaches a certain value, the probability of slope failure remains basically unchanged.

The functional form of the Weibull curve is

$$P(f) = me^{-aDh^b}$$

where $P(f)$ is the proportion of landslide cells, $m$ is the maximum proportion of landslide cells, $D_a$ is the Newmark displacement in centimeters, and $a$ and $b$ are the regression constants to be determined. Prediction of the proportion of landslide cells $P(f)$ can be used to directly estimate the probability of slope failure as a function of Newmark displacement.

Based on the actual landslide inventory and the distributions of Newmark cumulative displacements based on two Newmark models, two regression curves of the Wenchuan earthquake are

$$P(f) = 0.1005\left\{1 - \exp(-0.2217D_a^{0.6511})\right\}$$

$$P(f) = 0.1169\left\{1 - \exp(-0.1803D_a^{0.5165})\right\}$$

Two curves fit the data extremely well, the $R^2$ is 99.0% and 99.2% respectively.

From Fig. 9, the regression curves based on two Newmark models are roughly the same, but the regression coefficients are slightly different. When the Newmark displacement reaches about 150 cm, the probability of failure reaches its maximum. The maximum probability of failure based on the $J_{2007}$ model and Xu$_{2012}$ model is 10.05% and 11.69%, respectively. It can be seen that the failure curve based on the Xu$_{2012}$ model is relatively gentler, while the failure curve obtained by $J_{2007}$ is relatively steeper. This may be due to the differences of the absolute displacement values calculated by the two Newmark models. In the case of the same probability of failure, the corresponding $D_a$ value of the Xu$_{2012}$ model is large, the $D_a$ value calculated by the $J_{2007}$ model is small (Fig. 9).

### 3.3 Preparation of Seismic Landslide Hazard Maps

Based on the Newmark displacement map, the landslide hazard maps of the Wenchuan earthquake were prepared using the slope-failure curves (Fig. 10). Compared with the real landslides distribution, these maps characterize well the macroscopic distribution of the coseismic slides, most predicted landslide cells are distributed in the two sides of Beichuan-Yingxiu fault, especially Pengguan complex rock mass in its hanging wall.

Here we compare the seismic landslide hazard maps obtained from two slope-failure curves. Figure 11a shows the differences in corresponding pixel values between the two maps. Fig. 11b is the statistical result of the cell number at different intervals. From Fig. 11b, it is notable that most grids are distributed from -0.1% to 0.2%. The areas with large differences

![Figure 10](image10.png)

Figure 10. Map showing probability of seismic landslide hazard maps in Wenchuan earthquake. (a) $J_{2007}$ model; (b) Xu$_{2012}$ model.

![Figure 9](image9.png)

Figure 9. Proportion of landslide cells as a function of Newmark displacement. Black and red lines are the best fits of the Weibull function of two Newmark models, respectively.
Applicability of Two Newmark Models in the Assessment of Coseismic Landslide Hazard

Figure 11. (a) Map showing differences in pixel values between the Xu2012 model and J2007 model; (b) Statistics of differences of pixel values between two maps.

Figure 12. Success rates for landslide hazard assessment based on two Newmark models. (a) J2007 model; (b) Xu2012 model.

 (>1%) are concentrated in the Pengguan complex rock mass in the hanging wall (Fig. 10a). The statistical results show that the differences between the two maps are small on the whole, and the areas of differences from -0.1% to 0.2% account for 90.6% of the entire area. The areas of differences larger than 1% account for 6.7% of the whole area.

The actual landslide distribution was used to evaluate the validity of the landslide hazard assessment results. The areas below the curves explain how well the model work and can thus be used to validate the model qualitatively. A total area equaling to one denotes perfect prediction accuracy whereas an area of less than 0.5 shows that the model is invalid. In this study, the areas under the curves (AUCs) are 83.02% and 83.03%, respectively, which indicate that the hazard assessment results based on two Newmark simplified models are identical (Fig. 12).

4 DISCUSSION

Some attempts have been made to assess the landslide hazard of the Wenchuan earthquake area using the Newmark model (Di et al., 2017; Wang et al., 2013; Godt et al., 2008). Their purpose is rapid assessment even though it lacks a detailed quantitative analysis of evaluation results. In this study, based on the detailed landslide inventory available, we carried out the landslide hazard assessment of the Wenchuan earthquake area using two simplified Newmark models based on regional station records and global station records, respectively, and evaluated the assessment results. Meanwhile, the relationship between the Newmark displacement value and the probability of slope failure was analyzed, and the slope-failure curves were obtained.

In a previous study (Romeo, 2000), the simplified regression models to estimate Newmark displacement were based on analysis of strong-motion records. As shown in Fig. 8, the assessment results of simplified Newmark models based on different ground station records are overall identical, and the two Newmark models can identify the relative hazard level of seismic landslides. However, the absolute $D_n$ values of these two Newmark models are different, which leads to the difference in the slope failure curves. It means that probability functions established by different Newmark models are different.

Statistics show that the maximum probabilities of slope failure are 10.05% and 11.69%, respectively based on the two Newmark models. Jibson et al. (2000) concluded that the highest failure probability is in the epicenter area of the Northridge earthquake where landslide densely developed is 33.5%. Ge et al. (2013) indicated that the max-probability of failure reached 55.73% based on landslides data of the epicentral area for the 2008 Wenchuan event. This indicates that the probability function is greatly influenced by actual landslide data in the study area.
area. Although the scale, number, and density of landslides triggered by the Wenchuan earthquake are much greater than the Northridge earthquake, the study area of this study almost covers all the coseismic landslides, which causes the overall development degree of the landslides in Wenchuan earthquake lower than that in epicenter area of the Northridge earthquake. So the maximum probability of slope failure is lower than the values of previous studies. In addition, it should be noted that the slope failure curve of Jibson et al. (2000) showed that when the $D_n$ value is greater than 15 cm, the slope failure curve tends to be gentle. While the results of this work show that when the $D_n$ value reaches 50 cm, the slope failure curve tends to be gentle. This may be because that the landslides triggered by the Northridge earthquake are mostly small shallow landslides (Harp and Jibson, 1996); Compared with the Northridge earthquake, the landslide scale triggered by Wenchuan earthquake is bigger. Only when the Newmark displacement reaches a greater value, the landslide occurs.

Xu et al. (2013b) used the weight index model to map earthquake-triggered landslide susceptibility based on topographic and geological data and other information. The validation result indicated that the areas under the curves (AUCs) based on different factors ranged from 86% to 91%. However, the assessment results in this study based on the Newmark model show that the AUCs of two models are 83.02% and 83.03%, respectively, which means that the success rate based on the statistical analysis method is slightly higher than the Newmark method. In contrast, the assessment results based on the Newmark method are not much different from those based on statistical method, which is in the same order of magnitude. As we know, the coseismic landslide hazard assessment based on statistical analysis requires the landslide samples to obtain more accurate assessment results, which is often difficult to achieve in a short time after the earthquake. The simplified Newmark model can carry out a landslide hazard assessment without landslide samples. That is to say that the hazard assessment based on the Newmark model can be finished quickly after the earthquake, which can not be achieved by the statistical analysis model.

The probability equation proposed in this paper can be applied to the Wenchuan region and other areas with similar tectonic environments. But when concerning other areas, greater uncertainty in the output must be assumed (Jibson et al., 1998). Values of $a$, $b$, and $m$ (Eqs. 6, 7 and 8) could vary if the strengths of geologic materials, topography, ground motion or soil moisture conditions were significantly different from those in the Wenchuan earthquake area (Jibson et al., 2000). In other words, the equation must be corrected by actual landslides data.

The landslides triggered by the Wenchuan earthquake are mainly shallow landslides and high-speed debris flows (Dai et al., 2011; Huang and Li, 2009). However, the Newmark method is suitable for shallow landslides (assuming the slide as a rigid block) and ignores the influence of dynamic pore pressure (Jibson, 1993). This method is ideal for the case where the shear strength of rock and soil mass does not decrease or slightly decrease within the earthquake, but for the case where the excessive pore pressure or the destruction of soil structure may cause the shear strength to decrease significantly, the predicted displacement will be significantly smaller than measured values (Jibson et al., 2013; Meehan and Vahefard, 2013). Many studies (Wang et al., 2014; Cui et al., 2010; Xu et al., 2010) have shown that with the vibration liquefaction, the shear strength could be decreased and a large displacement could be generated, which provides a necessary condition for the generation of rapid and long run-out landslides (Sun et al., 2010). However, due to the limitations of current data and technology, we did not consider the effect of pore pressure on Newmark displacements (the degree of slope saturation ($m$) as 0), which caused that the predicted displacement of some large high-velocity landslides may be far less than the actual value. Therefore, using residual strength instead of peak strength to calculate sliding displacements (Liu and Ling, 2012), and the prediction of sliding displacement considering pore pressure should be issued to be further addressed in future work.

Dreyfus et al. (2013) demonstrated that comparing different Newmark simplified models, accurate input parameters may have a greater influence on the assessment results. In this study, we compared the assessment results of two Newmark models obtained by regional station records and global station records respectively, and the result shows that the ability to predict landslide occurrence of these two Newmark models is identical, which indicates that improving the Newmark model may have little effect on the accuracy of landslide hazard.

At present, the problems of the Newmark model mainly arise from the accuracy of input parameters and specified parameters. On one hand, for input parameters, it is difficult to reasonably estimate input parameters such as rock mechanical parameters and ground motion parameters, which limit the output of the Newmark model. On the other hand, different landslide types and landslide scales usually correspond to the different sliding thicknesses and threshold Newmark displacements. Therefore, the validity of predicted displacement results will be further reduced by using uniform sliding thickness and threshold Newmark displacement ($D_n$). In future research, for the Newmark model, the improvement of input parameters is an important step to improve the assessment results of the Newmark model.

5 CONCLUSION

In this study, founded in the landslide inventory available, we carried out the landslide hazard assessment of the Wenchuan earthquake area using two simplified Newmark models based on regional station records and global station records respectively and quantitatively evaluated the assessment results. Meanwhile, two probability equations were obtained. The results show that the distributions of $D_n$ based on two Newmark models have little difference. On the whole, the predicted landslide area based on Xu2012 model is slightly larger than that of J2007 model. The probability equations of two Newmark models are roughly the same, though the parameters vary slightly. The validation results show that the success rates of the two Newmark models are 83.02% and 83.03%, respectively, which indicates that the hazard assessment results based on the two Newmark models are identical. It is found that the improving Newmark model may have little effect on the accuracy of landslide hazard assessment.