

Newmark displacement model for landslides induced by the 2013 Ms 7.0 Lushan earthquake, China

Renmao YUAN (✉)¹, Qinghai DENG², Dickson CUNNINGHAM³, Zhujun HAN¹, Dongli ZHANG¹,
Bingliang ZHANG¹

¹ Key Laboratory of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Beijing 100029, China

² College of Earth Science and Engineering, Shandong University of Science and Technology, Qingdao 266590, China

³ Department of Environmental Earth Science, Eastern Connecticut State University, Connecticut 06226, USA

© Higher Education Press and Springer-Verlag Berlin Heidelberg 2015

Abstract Predicting approximate earthquake-induced landslide displacements is helpful for assessing earthquake hazards and designing slopes to withstand future earthquake shaking. In this work, the basic methodology outlined by Jibson (1993) is applied to derive the Newmark displacement of landslides based on strong ground-motion recordings during the 2013 Lushan Ms 7.0 earthquake. By analyzing the relationships between Arias intensity, Newmark displacement, and critical acceleration of the Lushan earthquake, formulas of the Jibson93 and its modified models are shown to be applicable to the Lushan earthquake dataset. Different empirical equations with new fitting coefficients for estimating Newmark displacement are then developed for comparative analysis. The results indicate that a modified model has a better goodness of fit and a smaller estimation error for the Jibson93 formula. It indicates that the modified model may be more reasonable for the dataset of the Lushan earthquake. The analysis of results also suggests that a global equation is not ideally suited to directly estimate the Newmark displacements of landslides induced by one specific earthquake. Rather it is empirically better to perform a new multivariate regression analysis to derive new coefficients for the global equation using the dataset of the specific earthquake. The results presented in this paper can be applied to a future co-seismic landslide hazard assessment to inform reconstruction efforts in the area affected by the 2013 Lushan Ms 7.0 earthquake, and for future disaster prevention and mitigation.

Keywords Newmark displacement of landslide, Arias intensity, critical acceleration, empirical relationship, the Lushan Ms 7.0 earthquake

1 Introduction

Landslides are one of Earth's most serious natural disasters and are often triggered by earthquakes, especially in mountainous regions where co-seismic landslides may occur over broad areas. For some recent large magnitude earthquakes, the majority of infrastructure damage and loss of life was due to landslides. Examples include the 2003 Tecoman (Colima) Mexico earthquake, the 2008 Wenchuan earthquake, and the 2013 Lushan earthquake (Keefer et al., 2006; Yin, 2009; Dai et al., 2010; Chen et al., 2013). It is therefore important to be able to accurately predict the quantity, locations, and severity of future co-seismic landslides for hazard assessment and for designing slopes to withstand earthquake shaking.

It is relatively easy to assess where landslides are likely to occur and what kind of seismic factors will cause landslide triggering. The basic method first presented by Newmark (1965), can be used to estimate the expected co-seismic displacements of a landslide based on a given recorded acceleration time history. This method was later modified and improved by different workers including Sarma (1981) and Wilson and Keefer (1983). Subsequently, the basic method of Newmark has been used widely in both specific slope analyses (e.g., Jibson and Keefer, 1993; Bray and Rathje, 1998; Pradel et al., 2005) and regional landslide hazard assessments (e.g., Jibson et al., 1998, 2000; Del Gaudio et al., 2003; Haneberg, 2006; Saygili and Rathje, 2008).

Generally, it is not easy to collect recordings of ground acceleration at a specific site for calculation of Newmark displacement. Therefore, regression equations were developed to describe the empirical relationships between seismic shaking parameters and estimated landslide displacements (e.g., Ambraseys and Menu, 1988; Jibson, 2007; Hsieh and Lee, 2011), which allow quick and easy

estimates of the Newmark displacements of earthquake-induced landslides.

Among those empirical relations, Jibson (1993) treated Newmark displacements as a function of the critical acceleration and the Arias intensity by analyzing selected strong-motion recordings. The relationship, referred to here as the Jibson93 model, is very simple and helpful for estimating landslide displacement. This method was further modified by making all terms logarithmic (Jibson et al., 1998, 2000); herein it is referred to as the Jibson98 model.

In this paper, the basic methodology outlined by Jibson (1993) and its modified forms are applied to the strong ground-motion records during the 2013 Ms 7.0 Lushan earthquake which occurred along the eastern margin of Tibet. Empirical equations for the estimation of Newmark displacement are developed based on the Arias intensity and critical acceleration. The goodness of fit and the estimation errors of these equations are then analyzed to create a suitable equation for the dataset of the Lushan earthquake. The results can be used for future earthquake-induced landslide hazard assessments in the area affected by the earthquake, and for future disaster prevention and mitigation.

2 Ground motion recordings during the Lushan earthquake

The Ms 7.0 Lushan earthquake on 20 April, 2013, was a destructive earthquake which struck Sichuan Province almost exactly five years after the 2008 Ms 8.0 Wenchuan earthquake. Its epicenter was located at 30.314°N, 102.934°E, in Lushan County, along the southern segment of the Longmenshan thrust belt, about 85 km from the epicenter of the Wenchuan earthquake (Fig. 1). By combining the spatial distribution of the relocated after-shocks and focal mechanism solutions, the Lushan earthquake was classified as a typical blind reverse-fault event (Xu et al., 2013). Due to strong shaking, the Lushan earthquake produced numerous landslides within a large area (Chen et al., 2013), which caused significant loss of life and property damage.

During the 2013 Lushan earthquake, acceleration data were recorded at 92 stations of the China digital strong motion network (Fig. 1). Data collected from these stations have three-component acceleration records, including the peak acceleration values along N-S, E-W, and U-D trends. Part of the data from these stations was selected to evaluate landslide displacements during the earthquake.

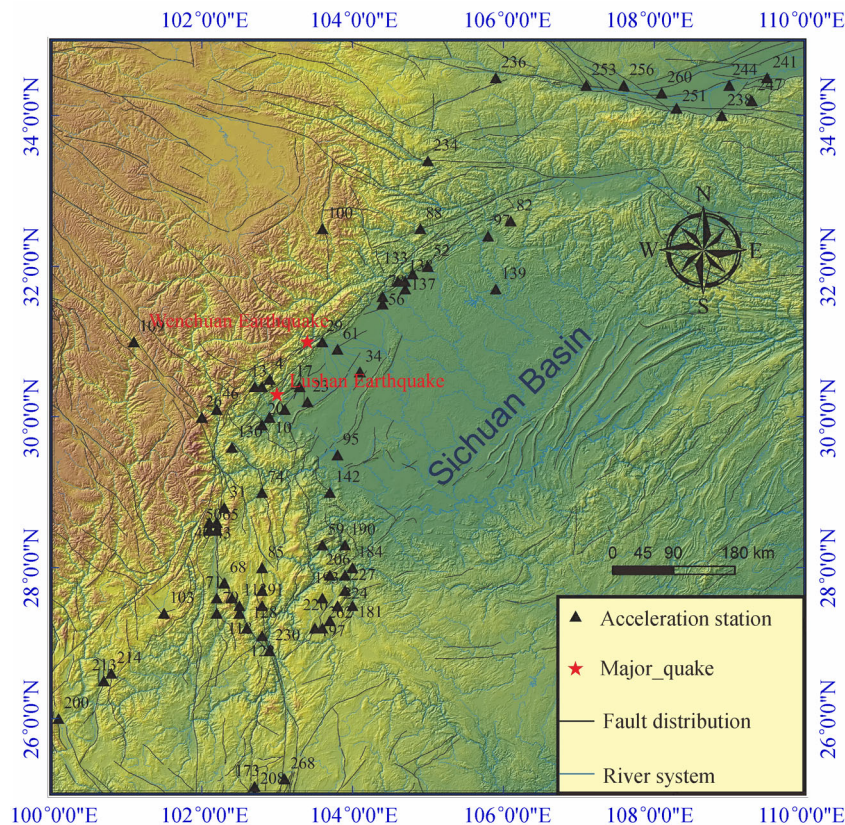


Fig. 1 Location of the Lushan earthquake and acceleration stations.

3 Basic models for estimating landslide displacement

Newmark (1965) introduced a method to calculate critical displacement for evaluating the stability of artificial embankments. It was then adapted to natural slope analysis (Wilson and Keefer, 1983). When accelerations exceed the critical value, the relative velocity between the sliding block and its base increases until the acceleration drops below the threshold acceleration. The cumulative displacement continues to increase owing to inertial forces, and stops when the velocity becomes zero.

The critical acceleration (A_c) for landslide triggering is defined as following:

$$A_c = (FS - 1)g \sin \delta, \quad (1)$$

where g is the acceleration of gravity, FS is the static factor of safety, and δ is the angle from horizontal of the slide surface or the thrust angle (Newmark, 1965).

The Newmark cumulative displacement for a sliding block is calculated by double integration of the acceleration time history data above the critical acceleration. The basic steps and method are presented in Fig. 2. During calculation of co-seismic displacement, any pore pressure increase is neglected, and residual un-drained/drained shear resistance remains unchanged during the deformation.

The Newmark method for computing displacement is

simple and straightforward, but sometimes it is difficult to get acceleration recordings at a specific site. Therefore, a modified approach for estimating Newmark landslide displacement needs to be developed. Some relationships can be derived by regression analysis between displacement values for landslide failure susceptibility and critical acceleration or strong ground-motion parameters.

Jibson (1993) developed the following regression equation based on 11 strong-motion recordings for different values of the critical acceleration, A_c :

$$\log D_n = 1.460 \log I_a - 6.642 A_c + 1.546 \pm 0.409 \quad (R^2 = 0.87), \quad (2)$$

where A_c is critical acceleration (g), I_a is the Arias intensity (m/s), D_n is landslide displacement in centimeters, and the last term is the estimation error of the model. Arias intensity, I_a , is defined by the following formula (Arias, 1970):

$$I_a = \frac{\pi}{2g} \int_0^T a(t)^2 dt, \quad (3)$$

where g is the acceleration due to gravity, $a(t)$ is the recorded acceleration time-history, and T is the duration of ground motion.

Jibson et al. (1998) modified the form of the Jibson93 model by making all terms logarithmic and then performed a rigorous analysis of 555 strong-motion records from 13

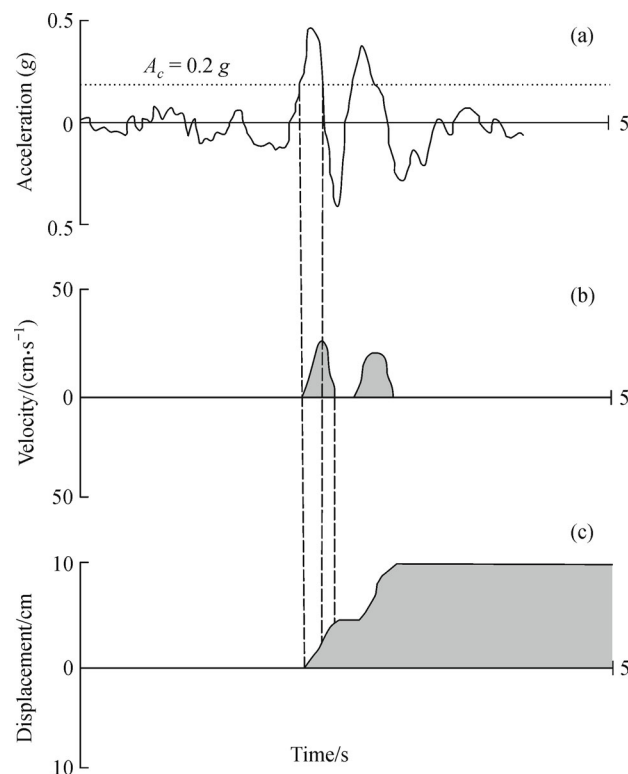


Fig. 2 Calculation of earthquake-induced landslide displacements (from Newmark, 1965).

earthquakes. A modified regression equation was then generated:

$$\log D_n = 1.521 \log I_a - 1.993 \log A_c - 1.546 \pm 0.375$$

$$(R^2 = 0.83). \quad (4)$$

The basic method and models mentioned above are used in the following analysis.

4 Regression models for displacement of landslides induced by the Lushan earthquake

In this study, a data subset of 20 continual horizontal acceleration recordings with $\text{PGA} > 0.2g$ from 10 stations was used for analysis. The distribution of the selected stations is shown in Fig. 1. Basic information concerning these stations and recordings is listed in Table 1. These original recordings are then baseline- and instrument-corrected with a filter in the frequency domain. The band-pass frequencies for the high-pass and low-pass filtering were selected to maximize the signal-to-noise ratio. PGA values are reduced by an average of about 5% during the filtering process.

At first, Arias intensities for each strong-motion dataset are calculated according to Eq. (3). The Newmark

displacement is then calculated based on the Jibson93 models and its modified forms for critical accelerations from $0.01g$ to $0.2g$.

4.1 Relationships between the I_a , D_n , and A_c of the Lushan earthquake

According to the Jibson93 and Jibson98 models, a linear relationship exists between $\log I_a$ and $\log D_n$ when A_c remains un-changed. In this study, the dataset of the Lushan earthquake is used to examine relationships between these parameters. I_a is calculated based on recordings from the selected stations, and A_c is fixed at $0.01g$ to calculate D_n . The goodness of linear fits for I_a-D_n , $I_a-\log D_n$, $\log I_a-D_n$, and $\log I_a-\log D_n$ are calculated respectively, and shown in Fig. 3. The values of R^2 for the I_a-D_n , $\log I_a-D_n$, and $I_a-\log D_n$ are 0.55, 0.61, and 0.28 respectively (Fig. 3(a)-(c)), indicating a poor linear fit. However, a good linear trend with $R^2=0.85$ exists in the $\log I_a-\log D_n$ plot (Fig. 3(d)).

Based on the method described above, a series of different A_c values from $0.01g$ to $0.2g$ were used to test the linear relationships between I_a-D_n . The fitted results are listed in Table 2.

According to the R^2 values in Table 2, good linear relationships exist between I_a-D_n and $\log I_a-\log D_n$ with average R^2 values of 0.77 and 0.89, respectively. However,

Table 1 Basic information on strong-motion data used in this study

Data file	Station code	Longitude	Latitude	Site condition	PGA(g)
1	51BXD	102.8	30.4	Soil	1.025
2	51BXD	102.8	30.4	Soil	0.39
3	51BXD	102.8	30.4	Soil	0.364
4	51BXY	102.9	30.5	Soil	0.394
7	51YAM	103.1	30.1	Soil	0.185
8	51YAM	103.1	30.1	Soil	0.149
10	51LSF	102.9	30.0	Soil	0.064
11	51LSF	102.9	30.0	Soil	0.032
13	51BXM	102.7	30.4	Soil	0.20
14	51BXM	102.7	30.4	Soil	0.269
16	51QLY	103.3	30.4	Soil	0.315
17	51QLY	103.3	30.4	Soil	0.165
19	51YAL	102.8	29.9	Soil	0.828
20	51YAL	102.8	29.9	Soil	0.254
22	51PJD	103.4	30.2	Soil	0.155
23	51PJD	103.4	30.2	Soil	0.188
130	51HYY	102.4	29.6	Soil	0.461
131	51HYY	102.4	29.6	Soil	0.372
133	51JYW	104.8	31.9	Soil	0.38
134	51JYW	104.8	31.9	Soil	0.357

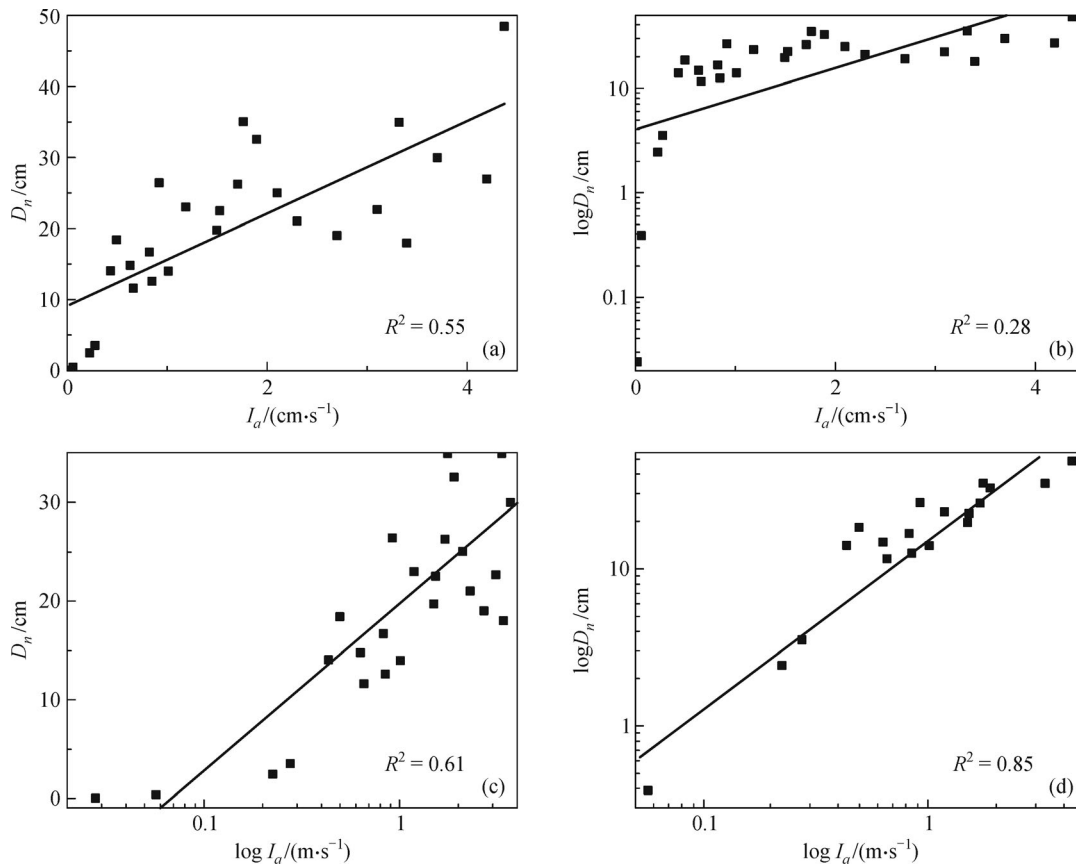


Fig. 3 I_a - D_n relationships with fixed $A_c=0.01g$: (a) I_a - D_n ; (b) I_a - $\log D_n$; (c) $\log I_a$ - D_n ; (d) $\log I_a$ - $\log D_n$.

Table 2 R^2 values for linear relationships between I_a and D_n for different critical acceleration A_c values

A_c	$R^2(I_a-D_n)$	$R^2(\log I_a-D_n)$	$R^2(I_a-\log D_n)$	$R^2(\log I_a-\log D_n)$
0.01	0.55	0.28	0.61	0.85
0.05	0.89	0.41	0.59	0.90
0.1	0.91	0.66	0.42	0.92
0.15	0.87	0.56	0.33	0.83
0.2	0.73	0.78	0.25	0.86
Average	0.77	0.54	0.44	0.89

the relationship between I_a - D_n is not consistent with large variation of R^2 values for different critical accelerations. Therefore, the goodness of fit for the $\log I_a$ - $\log D_n$ is better due to more consistent and larger R^2 values. It further confirms that $\log I_a$ is proportional to $\log D_n$, which was proposed first by the Jibson93 models.

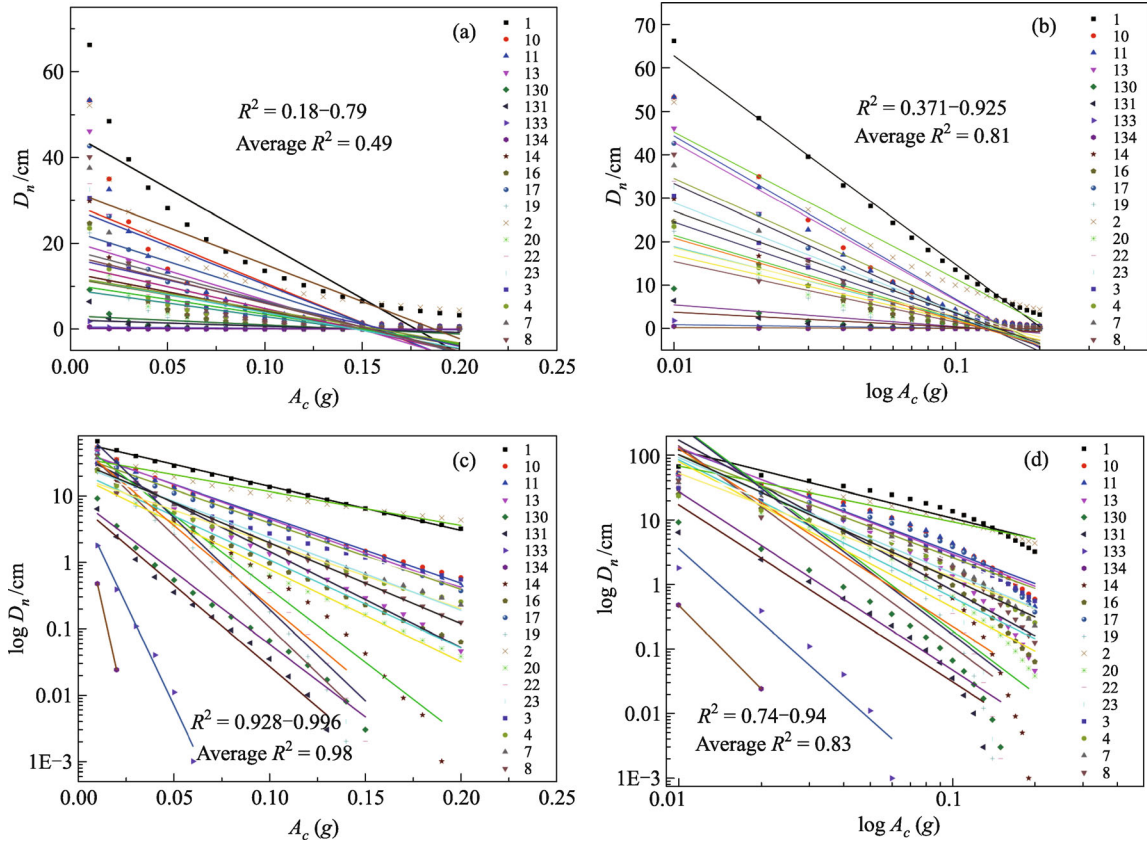
The linear relationship between the A_c and $\log D_n$ was first described in the Jibson93 model (Jibson, 1993). It was modified into the relationship between $\log A_c$ and $\log D_n$ in the Jibson98 model (Jibson et al., 1998). In our study, recorded data with $PGA > 0.2g$ during the Lushan earthquake are used to test the relationships between A_c and D_n . In the calculation for each record, the value of I_a was fixed and then the goodness of fit was determined. All relation-

ships of A_c - D_n , $\log A_c$ - D_n , A_c - $\log D_n$, and $\log A_c$ - $\log D_n$ are plotted in Fig. 4, and the summarized results are listed in Table 3.

Table 3 and Figure 4 clearly reveal the variable goodness of fit to a line for different relationships between D_n and A_c . The average R^2 in the A_c - D_n plot is only 0.49, indicating a poor regression relationship (Fig. 4(a)). A poor relationship is also suggested in the $\log A_c$ - D_n with R^2 ranging from 0.371 to 0.925, although the average R^2 is better (0.81; Fig. 4(b)). However, A_c - $\log D_n$ and $\log A_c$ - $\log D_n$ plots show better linear trends with $R^2=0.98$ and $R^2=0.83$, with a small range of all R^2 values from 0.928 to 0.996 and from 0.74 to 0.94, respectively (Figs. 4(c) and 4(d)). It suggests that the linear relationships in A_c - $\log D_n$ and

Table 3 R^2 values for different linear relationships between A_c and D_n for A_c values between 0.01g–0.2g

	A_c - D_n	$\log A_c$ - D_n	A_c - $\log D_n$	$\log A_c$ - $\log D_n$
R^2	0.18–0.79	0.371–0.925	0.928–0.996	0.74–0.94
Average	0.49	0.81	0.98	0.83

**Fig. 4** Relationships between A_c and D_n for recorded data of the Lushan earthquake: (a) A_c - D_n ; (b) $\log A_c$ - D_n ; (c) A_c - $\log D_n$; (d) $\log A_c$ - $\log D_n$.

$\log A_c$ - $\log D_n$ are very good. The same results were obtained for the data set of the 1999 Taiwan Chi-Chi earthquake (Hsieh and Lee, 2011).

The analysis presented above on the different relationships between the I_a , D_n , and A_c variables of the Lushan earthquake suggests that the forms of the Jibson93 and Jibson98 models can be used for the earthquake's dataset with new coefficients.

4.2 Regression models for landslide displacement induced by the Lushan earthquake

In order to develop a suitable empirical relationship between Newmark displacement, critical acceleration, and Arias intensity for the 2013 Lushan earthquake dataset, Newmark displacements are calculated for different critical accelerations from 0.02g to 0.1g. All calculated results are plotted in log-log space. Data points for

different critical accelerations show fairly linear relationships with regression coefficients $R^2=0.86$ – 0.97 in log-log plots of Arias intensity versus Newmark displacement (Fig. 5(a)). New multivariate regressions are then fit to the dataset of the Lushan earthquake based on the forms of the Jibson93 and Jibson98 models, as shown in Fig. 5(b).

The formula based on the Jibson93 model is:

$$\log D_n = 1.846 \log I_a - 13.86 A_c + 1.42 \pm 0.409. \quad (5)$$

The formula based on the Jibson98 model is:

$$\log D_n = 1.83 \log I_a - 1.997 \log A_c - 1.96 \pm 0.375 \quad (6)$$

It appears that the goodness of fit in Eqs. (5) and (6) with

the new coefficients is better than that in the original Jibson93 and Jibson98 models, with the same estimation errors. However, the fit lines for different critical accelerations from 0.02g to 0.1g present a fan-shape in Fig. 5(a), with lines disproportionately spaced and unparallel unlike that presented in the original Jibson93 and Jibson98 models (Jibson, 1993; Jibson et al., 1998). Similar results were presented by Hsieh and Lee (2011), indicating that these models could be modified to get more reasonable results.

In 2011, Hsieh and Lee suggested that the Jibson 93 and Jibson98 models needed to be modified for the 1999 Chi-Chi earthquake data set (Hsieh and Lee, 2011). Two new forms of empirical formula thus were developed by modifying the $\log I_a$ to $A_c \log I_a$ based on the Jibson93 model:

New form I:

$$\log D_n = C1A_c \log I_a + C2A_c + C3 \pm \varepsilon. \quad (7)$$

And new form II:

$$\log D_n = C1 \log I_a + C2A_c + C3A_c \log I_a + C4 \pm \varepsilon. \quad (8)$$

where, C1, C2, C3, and C4 are coefficients.

Because there is a linear relationship between $\log D_n$ and A_c or $\log I_a$, it can be concluded that a linear relationship also exists between $A_c \log I_a$ and $\log D_n$. Therefore, the modified formulas are reasonable. These modified formulas are used to test the Lushan earthquake dataset. The fitting results which are shown in Figs. 6(a) and 6(b), are fan-shaped and similar to the fitting results of the Chi-Chi dataset (Figs. 6(c) and 6(d); Hsieh and Lee, 2011).

The best fitting formulas for Eqs. (7) and (8) are the following:

$$\log D_n = 23.372A_c \log I_a - 13.278A_c + 1.355 \pm 0.1831, \quad (9)$$

$$\log D_n = 1.147 \log I_a - 13.664A_c + 9.673A_c \log I_a + 1.396 \pm 0.1716. \quad (10)$$

The goodness of fit for the new Eqs. (9) and (10) are $R^2=0.866$ and $R^2=0.901$, respectively.

5 Discussion

In order to further analyze the estimated D_n based on different empirical equations, a checking point at $I_a=1\text{m/s}$ and $A_c=0.1\text{g}$ is selected to validate the Jibson93 model and its modified forms. The checking results are listed in Table 4.

The estimation errors based on the Jibson93 and Jibson98 models are always larger than those based on Eq. (7) (new form I) and Eq. (8) (new form II), as shown in Table 4. The modified new forms should be more accurate in describing the characteristics of Newmark displacement of earthquake-induced landslides. D_n values estimated from the Lushan equations and the Chi-Chi equations are much lower than those estimated from equations based on global models or models derived from the dataset of several earthquakes. The compared results of D_n in Table 4 indicate that global equations should not be directly used to estimate Newmark displacement of landslides induced by one specific earthquake. Rather, it is better to perform a new multivariate regression to derive new coefficients based on the global equation for the dataset of the specific earthquake.

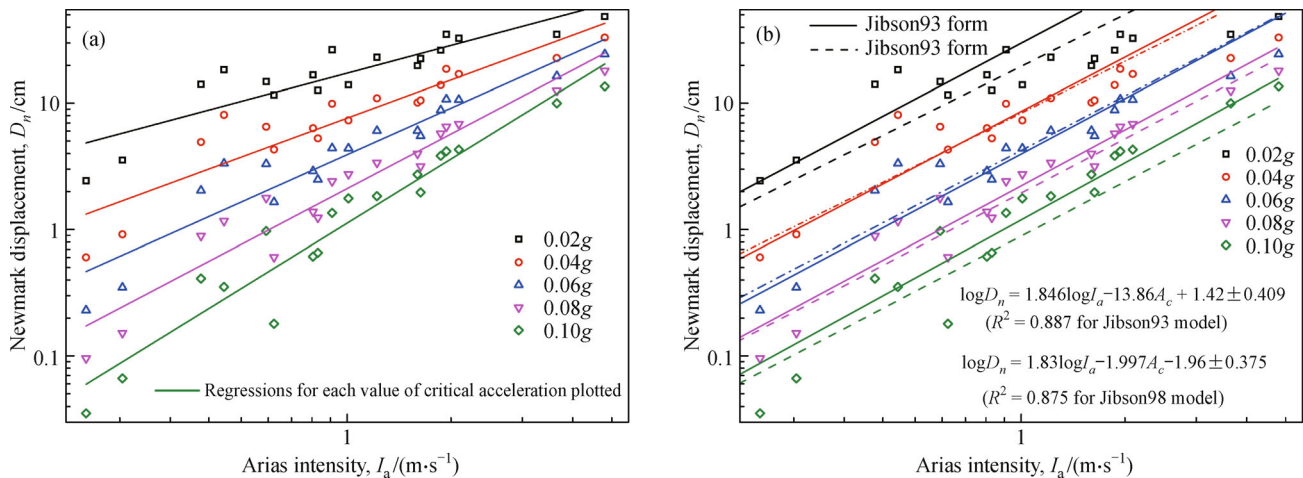


Fig. 5 Fit lines for each value of critical acceleration plotted (a) and multivariate regression models of the Lushan earthquake with the Jibson93 form and Jibson98 form (b).

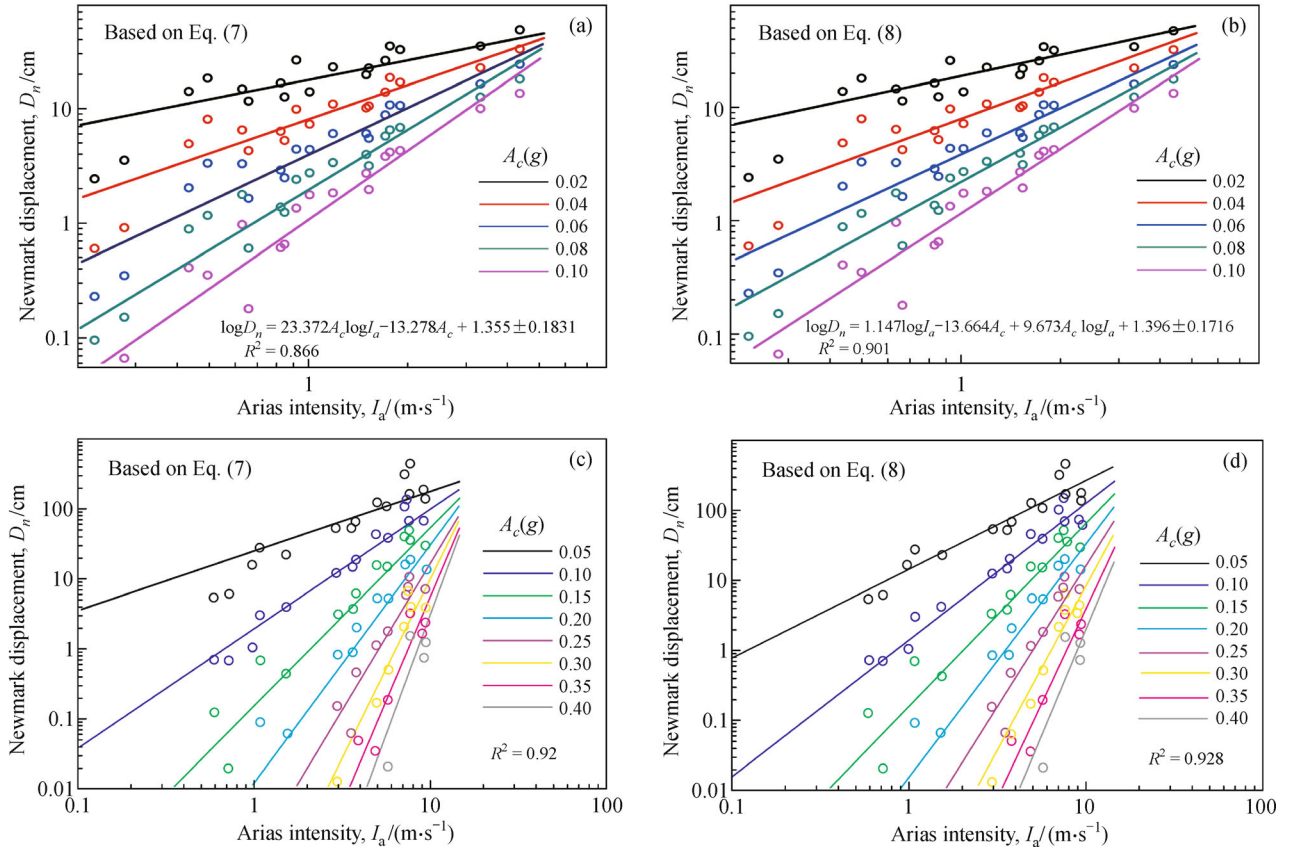


Fig. 6 Fitting results based on the modified formulas for the Lushan earthquake data (a, b) and for the Chi-Chi earthquake data set (c, d; revised from Hsieh and Lee, 2011).

Table 4 Different empirical equations and estimated D_n based on checking point at $I_a=1$ m/s and $A_c=0.1g$

Models	Formula	R^2	Fitting data set	Estimated D_n/cm
Jibson93 model	$\log D_n = 1.460 \log I_a - 6.642 A_c + 1.546 \pm 0.409$	0.87	Data Set from 7 earthquakes	7.62
Jibson98 model	$\log D_n = 1.521 \log I_a - 1.993 \log A_c - 1.546 \pm 0.37$	0.83	Data Set from 13 earthquakes	2.08
Eq. (7) (New form I) (Hsieh and Lee, 2011)	$\log D_n = 11.287 A_c \log I_a - 11.485 A_c + 1.948 \pm 0.357$	0.84	Data Set from worldwide earthquake	6.3
Eq. (8) (New form II) (Hsieh and Lee, 2011)	$\log D_n = 0.847 \log I_a - 10.62 A_c + 6.587 A_c \log I_a + 1.84 \pm 0.295$	0.89	Data Set from worldwide earthquake	6.02
Eq. (7) (New form I) (Hsieh and Lee, 2011)	$\log D_n = 11.287 A_c \log I_a - 11.485 A_c + 1.948 \pm 0.357$	0.84	Data Set from the Chi-Chi earthquake	1.55
Eq. (8) (New form II) (Hsieh and Lee, 2011)	$\log D_n = 0.847 \log I_a - 10.62 A_c + 6.587 A_c \log I_a + 1.84 \pm 0.295$	0.89	Data Set from the Chi-Chi earthquake	1.59
Eq. (9) based on New form I	$\log D_n = 23.372 A_c \log I_a - 13.278 A_c + 1.355 \pm 0.1831$	0.866	Data Set from the Lushan earthquake	1.06
Eq. (10) based on New form II	$\log D_n = 1.147 \log I_a - 13.664 A_c + 9.673 A_c \log I_a + 1.396 \pm 0.1716$	0.901	Data Set from the Lushan earthquake	1.07
Eq. (5) based on Jibson93 model	$\log D_n = 1.846 \log I_a - 13.86 A_c + 1.42 \pm 0.409$	0.887	Data Set from the Lushan earthquake	1.08
Eq. (6) based on Jibson98 model	$\log D_n = 1.83 \log I_a - 1.997 \log A_c - 1.96 \pm 0.375$	0.875	Data Set from the Lushan earthquake	1.09

Comparative analysis of goodness of fit and estimation errors for results calculated from Eqs. (5) or (6) and Eqs. (9) or (10) reveals good model fits for all four formulas. However, the goodness of fit for the Lushan dataset

applying Eq. (10) is 0.901, which is better than 0.887 for the Jibson93 formula and 0.875 for the Jibson 98 formula. Moreover, the pattern of fan-shaped lines in Figs. 6(a) and 6(b) is similar to that based on Eqs. (7) and (8) in Figs. 6(c)

and 6(d). Eq.(10), with smaller estimation errors, appears most suitable for estimating the Newmark displacement of the Lushan earthquake-induced landslides. This result further verifies the conclusions presented by Hsieh and Lee (2011), but more case studies are needed to broaden this conclusion.

According to the analysis of results presented in this study, it seems that for the Lushan earthquake dataset, the Jibson93 and Jibson98 approach with simple formulas is still applicable, but not optimal. Instead, for describing displacement of landslides induced by the Lushan earthquake, the modified Eq. (10) is more suitable because of the improved goodness of fit and smaller estimation errors.

6 Conclusions

In this work, strong ground-motion records from the 2013 Lushan Ms 7.0 earthquake are used to analyze the Newmark displacement of landslides based on methodology outlined by Jibson (1993). Comparative analysis of results suggests that a global equation should not be used directly to estimate the Newmark displacement of landslides induced by one specific earthquake. Instead, a multivariate regression to derive new coefficients should be performed based on the global equation.

Appropriate empirical equations for estimation of Newmark displacement induced by the 2013 Lushan earthquake can be developed based on the Jibson93 model and its modified formulas by fitting new formula coefficients. However, the modified Eq. (10) with better goodness of fit and smaller estimation errors appears most suitable and effective for the Lushan earthquake dataset. Eq. (10) is thus recommended for the Lushan dataset to estimate landslide displacement in the Lushan earthquake-affected area. This can then be used for an earthquake-induced landslide hazard analysis to aid future construction and redevelopment in the area.

Acknowledgements The authors would like to express sincere appreciation to the reviewers for their valuable comments and suggestions, which were helpful for improving the MS. This work was financially supported by the Basic Science Fund of the Institute of Geology, China Earthquake Administration (IGCEA-1401), and the National Natural Science Foundation of China Projects (Grant Nos. 41372219, 41272298, and 41172193), for which grateful appreciation is expressed. We also would like to state our deep appreciation to the China Strong Motion Networks Center for supplying recordings of strong motion.

References

Ambraseys N N, Menu J M (1988). Earthquake-induced ground displacements. *Earthquake Eng Struct Dynam*, 16(7): 985–1006

Arias A (1970). A measure of earthquake intensity. In: Hansen R J, ed. *Seismic Design for Nuclear Power Plants*. Cambridge: Massachusetts Institute of Technology Press, 438–483

Bray J D, Rathje E M (1998). Earthquake-induced displacements of solid-waste landfills. *Journal of Geotechnical and Geoenvironmental Engineering*, 124(3): 242–253

Chen X L, Yu L, Wang M M, Li J Y (2013). Brief communication: landslides triggered by the Ms=7.0 Lushan earthquake, China. *Nat Hazards Earth Syst Sci*, 1(4): 3891–3918

Dai F C, Xu C, Yao X, Xu L, Tu X B, Gong Q M (2010). Spatial distribution of landslides triggered by the 2008 Ms 8.0 Wenchuan earthquake, China. *J Asian Earth Sci*, doi: 10.1016/j.jseae.2010.04.010

Del Gaudio V, Pierrri P, Wasowski J (2003). An approach to time-probabilistic evaluation of seismically induced landslide hazard. *Bull Seismol Soc Am*, 93(2): 557–569

Haneberg W C (2006). Effects of digital elevation model errors on spatially distributed seismic slope stability calculations: an example from Seattle, Washington. *Environ Eng Geosci*, 12(3): 247–260

Hsieh S Y, Lee C T (2011). Empirical estimation of the Newmark displacement from the Arias intensity and critical acceleration. *Eng Geol*, 122(1–2): 34–42

Jibson R W (1993). Predicting earthquake-induced landslide displacements using Newmark's sliding block analysis. *Transp Res Rec*, 1411: 9–17

Jibson R W (2007). Regression models for estimating coseismic landslide displacement. *Eng Geol*, 91(2–4): 209–218

Jibson R W, Harp E L, Michael J M (1998). A method for producing digital probabilistic seismic landslide hazard maps: an example from the Los Angeles, California area. *US Geological Survey Open-File Report98–113*, 17

Jibson R W, Harp E L, Michael J M (2000). A method for producing digital probabilistic seismic landslide hazard maps. *Eng Geol*, 58(3–4): 271–289

Jibson R W, Keefer D K (1993). Analysis of the seismic origin of landslides: examples from the New Madrid seismic zone. *Geol Soc Am Bull*, 105(4): 521–536

Keefer D K, Wartman J, Ochoa C N, Rodriguez-Marek A, Wiczorek G F (2006). Landslides caused by the M 7.6 Tecomán, Mexico earthquake of January 21, 2003. *Eng Geol*, 86(2–3): 183–197

Newmark N M (1965). Effects of earthquakes on dams and embankments. *Geotechnique*, 15(2): 139–160

Pradel D, Smith P M, Stewart J P, Raad G (2005). Case history of landslide movement during the Northridge earthquake. *J Geotech Eng ASCE*, 131(11): 1360–1369

Sarma S K (1981). Seismic displacement analysis of earth dams. *J Geotech Eng ASCE*, 107: 1735–1739

Saygili G, Rathje E M (2008). Empirical predictive models for earthquake-induced sliding displacements of slopes. *J Geotech Eng ASCE*, 134(6): 790–803

Wilson R C, Keefer D K (1983). Dynamic analysis of a slope failure from the 6 August 1979 Coyote Lake, California, earthquake. *Bull Seismol Soc Am*, 73: 863–877

Xu X W, Wen X Z, Han Z J, Chen G H, Li C Y, Zheng W J, Zhnag S M, Ren Z Q, Xu C, Tan X B, Wei Z Y, Wang M M, Ren J J, He Z T, Liang M J (2013). Lushan Ms 7.0 earthquake: a blind reserve-fault event. *Chin Sci Bull*, 58(28–29): 3437–3443

Yin Y P (2009). Features of landslides triggered by the Wenchuan Earthquake, *J Eng Geol*, 17: 29–38 (in Chinese)

AUTHOR BIOGRAPHIES



Renmao Yuan received a Bachelor degree in Engineering Geology from Hebei Geological College (China, 1995), a Master of Science degree from the Peking University (China, 2002) and a PhD in Geological Engineering from the Institute of Geology and Geophysics, CAS (China, 2006). His major fields of research are engineering geology, tectonics and geological hazards.

He was the Leverhulme Trust Fellow in Cardiff University (UK, 2007–2008), the invited associated professor in Taiwan University (China, 2011/03–2011/07), and the visiting scholar in University of Leicester (UK, 2012–2013), and is now employed at Institute of Geology, China Earthquake Administration as an associate professor of geology. He has published papers widely on earthquake-induced landslides, engineering geology, active faults. His current research interests are focused on earthquake-induced landslides, fault gouge analysis and geomorphology.

Professor Yuan is the member of the international association for engineering geology and the environment (IAEG).

E-mail: yuanrenmao@ies.ac.cn



Qinhai Deng received a Master degree in engineering geology from School of Resources and Environment, Henan Polytechnic University (China, 2003), and a PhD in geological engineering from Institute of Geology and Geophysics, CAS (China, 2007). His major fields of research are engineering geology, groundwater, geo-hazards, and geological information system.

He is now an associate professor in College of Earth sciences and Engineering, Shandong University of Science and Technology, China. He has published many papers on mine geological hazards, groundwater and numerical simulation. His current research interests focus on geo-hazards evaluation, groundwater and numerical model.

E-mail: dqh2004@163.com



Dickson Cunningham received a Bachelor degree in Earth Sciences from Dartmouth College (USA, 1982), a Master of Science degree from the University of Arizona (USA, 1986) and a PhD in Geological Sciences from the Univer-

sity of Texas at Austin (USA, 1993). His major fields of research are structural geology, tectonics, remote sensing and geological hazards.

He worked at the University of Leicester (UK) as a Lecturer and Senior Lecturer from 1994–2012 and is now employed at Eastern Connecticut State University (USA) as Professor of Geology. He has published widely on the tectonic evolution of Central Asia (Mongolia, China), Brazilian Highlands, southernmost Andes, and geological applications of airborne LiDAR. His current research interests are focused on intracontinental mountain building processes, crustal evolution, active fault systems and earthquake hazards.

Professor Cunningham is a member of GSA, AGU, and EGU and serves on the editorial board of the Journal of Asian Earth Sciences.

E-mail: cunninghamw@easternct.edu



ZhuJun Han received a Bachelor of science from Peking University of China in 1986, a Master and a PhD in seismogeology from Institute of Geology, China Earthquake Administration in 1987 and 1997, respectively. His major

fields of research are earthquake engineering, tectonics, and seismogeology.

He is now a professor in Institute of Geology, China Earthquake Administration. He has published many papers on earthquake engineering and active fault. His current research interests: earthquake engineering and active fault.

E-mail: zjhan0904@163.com



Dongli Zhang received a Master in structural geology from Institute of Seismogeology, Lanzhou, China Earthquake Administration in 2000, and received a PhD in geotechnical engineering from Institute of Engineering Mechanics, China Earthquake Administration in 2005. Her major fields of research are seismogeology and strong ground movement.

She is now an associate professor in Institute of Geology, China Earthquake Administration. She has published papers on earthquake engineering and strong ground movement. Her current research interests are earthquake hazards and recorded data of acceleration analysis.

E-mail: zhdl@ies.ac.cn



Bingliang Zhang received his B.S. in geochemistry from the University of Science and technology of China in 1976.

He is a professor in Institute of Geology, China Earthquake Administration. He has published many papers on the structural geology and fault gouges. His current research interest is microstructural analysis of fault gouges.

E-mail: zhangbl15@126.com