Review of study on post-earthquake stability of soil slopes

Jinchang Chen¹², Lanmin Wang¹ ²* and Xiaowu Pu¹²

¹Lanzhou Institute of Seismology, China Earthquake Administration, Lanzhou, 730000
²Key Lab of Loess Earthquake Engineering, China Earthquake Administration, Lanzhou, 730000
*Corresponding author’s e-mail: wanglm2304@126.com

Abstract. Under the action of earthquake, the slope will be damaged to varying degrees and the stability will be decreased. The stability of these slopes will be further reduced under the action of succedent rainfall and strong aftershocks, which will evolve into landslides. In addition, the damaged slope, even without the influence of external factors, may slip in a period of time after the earthquake, called progressive landslide or delayed landslide. The losses and casualties caused by the above landslides are often more serious than the coseismic landslides. This paper summarized the research results of post-earthquake stability of soil slopes at domestic and abroad. From the aspects of the damage characteristics, the evolve process of instability and the stability evaluation methods of soil slope, three types of landslides which are progressive landslide, post-rainfall and strong aftershocks induced landslide are analysed. The problems existing in the research and the direction of future research are also been discussed, which can provide some reference for related research work.

1. Introduction

In history, several strong earthquakes have caused a large number of unstable slopes. Under the condition of succedent rainfall and strong aftershocks, the disasters of landslides caused by these unstable slopes slipping often more serious than coseismic landslides.

Through the interpretation of satellite images, it is found that the area of coseismic landslides caused by the Chi-Chi earthquake in Taiwan in 1999 is about 21.85 km², while the area of landslides caused by succedent heavy rainfall induced by typhoon Toraji is about 48.8 km²[1]. It can be seen that the area of landslide caused by rainfall which occurred after earthquake is obviously larger than that caused by earthquake alone.

About 15,000 landslides were triggered by the Wenchuan M8.0 earthquake in China, which caused about 20,000 deaths[2]. Statistical comparison of landslides before and after the Wenchuan earthquake in Maoxian County, Sichuan Province is made[3]. The results show that there are 59 landslides in Maoxian before the earthquake. After the earthquake, 191 hidden landslides which include 91 landslides and 100 unstable slopes were generated. Through the interpreting of SPOT5 satellite images of landslides caused by "5.12" earthquake and "9.24" heavy rainfall in Beichuan County, 828 landslides caused by succedent heavy rainfall, which include 150 landslides caused by the earthquake and the area of these landslides was enlarged by 68.7%[4]. Through investigation and analysis, it is predicted that there will be a large area of geological hazards such as landslides in the earthquake area in five years, and it will be stable after about 10 years[5].

According to the difference of working conditions after the earthquake, the instability of the slope after the earthquake can be divided into the following situations which are the post-earthquake delayed...
instability, strong aftershocks induced instability, succedent rainfall induced instability and the instability caused by the interaction or coupling of rainfall and strong aftershocks. In practice, all of these situations have occurred.

In the 1939 Ojika earthquake in Japan, Akiba and Semba observed that the slope instability caused by the earthquake occurred mostly in the hours or 20 hours after the earthquake and proposed the concept of delayed landslide.

Large landslide occurred in the Kuragasaki area on September 22, 2011. First of all, due to the impact of the Tohoku 9.0 main shock on March 11, 2011, a large number of cracks occurred in the slope, and the vertical displacement reached 1.6m. After 6 months, the area was affected by the typhoon which induced heavy rainfall, three hours after the rain, the disasters of landslides occurred[6].

At 7:45 on July 12, 2013, a magnitude 6.6 earthquake occurred at the junction of Jixian County, Ganyu County, Gansu Province, and a magnitude 5.6 strong aftershock occurred at 9:12. This strong aftershock triggered a landslide disaster in Baozi Village, Weixin Township, Jixian County, and buried more than 100 houses[7].

The Guantan landslide occurred at night on the day of the Wenchuan earthquake. The landslide area was strongly affected when the Wenchuan earthquake occurred. Later, the aftershocks occurred frequently, and the rainstorm happened at that night. Then, the landslide occurred, forming a dammed lake in the next morning and flooding the Liujiaogou Power Station[8].

It can be seen from the above examples that the disaster caused by the instability of the slope after the earthquake is serious and frequently occurs. Therefore, it is necessary to study the damage characteristics, evolve process of instability and the stability evaluation methods of soil slope after earthquake. This paper summarized the research progress, study methods, existing deficiencies and the future directions of domestic and foreign scholars on related issues, which can provide some reference for the disaster prevention and mitigation work about post-earthquake instability of slope.

2. Damage characteristics and instability process of slope after earthquake

2.1. Damage characteristics of slope after earthquake

From the macroscopic point of view, the damage of soil slope after earthquake mainly manifests in the aspects of loosening and cracking within shaking, from the aspect of mechanical parameters, it manifests in the increase of porosity, the decrease of compactness and strength parameters, from the aspect of physical and mechanical mechanism, it manifests in the decrease of soil sliding resistance force.

The structural integrity of slopes is destroyed and the corresponding mechanical parameters are reduced after the earthquake action. A substance with special structure and engineering properties were formed[9].

The damage effect of earthquake on soil slope should be divided into two aspects: soil material and soil deformation[10]. For the aspect of soil material, it is recommended to use the surface wave to evaluate the damage depth, and use the shaking table to evaluate the acceleration amplification effect. For the aspect of soil deformation, the displacement calculation is proposed by using the Jibson formula to evaluate the soil displacement.

By investigating and measuring the damage depth of the extreme earthquake zone after the Wenchuan earthquake, it is found that the slope damage caused by the earthquake is mostly concentrated within 5 meters of the slope, showing the superficial effect, and the phenomenon is verified by the shaking table test[11]. It is explained that this is due to combination action of tensile stress generated by the uncoordinated movement between the surface layer and the interior and the repeated action of the dynamic shear strain of the surface layer.

The shaking table test is used to simulate the development of cracks under the action of earthquakes. With the increase of the time, the cracks increase gradually with angle about 45°. Then, Using the tank test to simulate the situation under the action of rainfall after the earthquake[12]. The
penetration depth is deeper and the pore water pressure is growing faster than the slope without the earthquake.

A direct shear test was carried out on a soil sample of Pingtong Town which was the hardest hit area after the Wenchuan earthquake[13]. In order to obtain the influence of different rainfall intensity on the shear strength of the soil after the earthquake, the variation of shear strength under different water contents was analysed and compared. It is found that the shear strength of soil decreases with the increase of water content, and the decrease degree of cohesive strength C is greater than theφ.

The above research results show that the crack mainly appears at the surface layer of slope and the overall stiffness decreases under the action of seismic force. Under the later rainfall conditions, the pore water pressure increases, the effective stress decreases and the shear strength parameter decreases. This may be an important reason for the instability of the slope after the earthquake. There are also some insufficient in the research, such as the lack of systematic comparison of soil mechanical parameters under the condition of pre-earthquake, post-earthquake rainfall and strong aftershock.

2.2. The process of slope instability after earthquake

2.2.1. Delayed Instability process of slope
Seed analysed and discussed the delayed instability of landslide induced by earthquake in 1979[14]. He pointed out that the post-earthquake deformation and stress redistribution should be taken into account in the analysis of delayed instability. It is gradually recognized that in earthquakes, liquefied material structures such as soils may be partially damaged, which weakens the overall stiffness and reduces the shear strength. The decrease of local shear strength will cause stress redistribution in soil, which will lead to liquefaction or yield of surrounding soil materials. With the expansion of liquefaction or yield range, the whole slope will be destroyed.

2.2.2. Instability process of slope under rainfall after earthquake
Using a test tank with a certain angle and putting loose deposits from the actual slope, then, by changing the test tank angle under the same rainfall conditions, the process of loose landslide with different slope angle under the condition of rainfall occurred after earthquake in natural situation were simulated[15]. Results show that under the action of rainfall, some fine particles infiltrate into the soil after the earthquake. When these fine particles accumulate at a certain position of the slope, the pore water pressure increases and the effective stress decreases. When the effective stress decreased to zero, the slope slides.

At present, the study of slope instability process under the condition of strong aftershocks and the interaction or coupling action of strong aftershocks and rainfall is still in the blank stage. In fact, after a strong earthquake, aftershocks with a certain magnitude are often followed, so the influence of aftershocks on slope stability cannot be ignored. Aftershocks have a cumulative damage effect on structures, which is bound to exist on slopes[16]. However, few previous studies have mentioned this effect. Therefore, it is urgent and necessary to carry out relevant research.

3. Stability evaluation methods of slope after earthquake

3.1. Stability evaluation methods of delayed instability slope
Poulos[17] put forward the theory of stable state in 1981. He believed that sand and other materials were in stable state when the effective stress, shear stress, volume and deformation rate reached a constant value. McRoberts and Sladen[18] put forward a new strength theory based on the steady state theory in 1990, and found the possible relationship among the failure surface, Hough surface and transition stage in p-q space. W. H. Gu[19] on the basis of this strength theory, assuming that liquefiable materials will not drain, established a simplified strength theory in 1993 and established an elastic-plastic constitutive relationship under undrained conditions, and used incremental finite element method to carry out post-earthquake analysis of Lower San Fernando dam. Compared with
the research results of the Lower San Fernando dam done by Seed et al.[20] in 1975, two results are consistent, which proves the correctness of the method proposed by W. H. Gu. Since then, K. Zhang [21] has used strength reduction method to analyse and evaluate the stability of delayed instability slope. Zhao Yanan et al.[22] established the damage evolution equation of loess. Based on this, the evaluation of the delayed instability loess slope was made. It is considered that the damage degree can be used to replace the safety factor.

3.2. Stability evaluation methods of rainfall after earthquake and strong aftershocks induced landslide

3.2.1. Rigid limit equilibrium method

Based on the limit equilibrium theory of rigid body, the formula for calculating the safety factor of slope body is as follows:

$$FS = F_r + F_w + F_c$$

(1)

Iverson [23] deduced its composition in dimensionless form in 1991:

$$F_r = \frac{\tan \phi}{\tan \theta}$$

(2)

$$F_w = -\frac{\Psi(D,t)\rho_w g \tan \phi}{\rho_s g D \sin \theta \cos \theta}$$

(3)

$$F_c = \frac{C}{\rho_s g D \sin \theta \cos \theta}$$

(4)

In the formula: $C$ cohesive strength of soil, $\theta$ slope angle, $\rho_s$ density of soil, $\rho_w$ density of water, $g$ acceleration of gravity, $D$ vertical height of soil, $\phi$ friction angle of soil, $\Psi(D,t)$ function of vertical height of water head in soil layer changing with time.

Assuming that the vertical height of water head does not change with time, Hammond [24] proposed a formula for calculating the safety factor of slope under one-dimensional seepage in 1992:

$$SI = C_r + C_s \cos^2 \theta \rho_s g (D - D_w) + (\rho_s - \rho_w) g D_w \tan \phi$$

(5)

In the formula: $C_r$ for the cohesive strength of the bottom of the slide, $C_s$ for the cohesive strength of the soil, $D_w$ for the vertical height of the water head in the soil layer.

R.T. Pack [25] proposed its dimensionless form in 1998:

$$FS = \frac{C + \cos \theta [1 - Wr] \tan \phi}{\sin \theta}$$

(6)

In the formula: Relative humidity $w = D_w / D = h_w / h$, $C = (C_r + C_s) / (\rho_w g)$, water-soil density ratio $r = \rho_w / \rho_s$.

Based on this, SINMAP model was established for slope stability analysis after earthquake.

Zhihua Yang et al.[26] used SINMAP model to analyse the influence of different rainfall conditions (light rain, moderate rain, heavy rain, heavy rain) on slope stability after earthquakes. Through the stability analysis of shallow landslide after Lushan earthquake under rainfall conditions, it is found that the method is in good agreement with the actual situation.

HE Siming [27] introduced Darcy’s law and inertia force on the basis of predecessors. According to the calculation model shown in Fig. 1, a formula for calculating the safety factor of slope stability under aftershocks and rainfall is proposed:

$$K = \frac{C + D \rho_s (g \cos \theta - a \sin \theta) \tan \phi}{D \rho_s (g \sin \theta + a \cos \theta)} - \frac{D \rho_s g \cot \theta \tan \phi}{Th_p g (\sin \theta + a \cos \theta)}$$

(7)

In the formula: $\tau$ for Permeability coefficient, $I$ for rainfall intensity.

Thus, when $K = 1$ the formula for calculating the critical value of rainfall intensity under the action of rainfall alone after an earthquake can be obtained:
This is same as the formula for calculating the critical rainfall intensity proposed by David R. Montgomery[28] in 1994. Similarly, the formula for calculating the critical value of acceleration under a single aftershock is as follows:

$$a_{cr} = \frac{1}{\sin\theta \tan\phi + \cos\phi} \left[ \frac{C}{D\rho_s} + g \cos\theta (\tan\phi - \tan\theta) \right]$$  \hspace{1cm} (9)

The formula for calculating rainfall safety factor of slope after earthquake based on rigid body limit equilibrium theory is complex when considering the change of seepage depth with time, and there is a gap between theoretical value and actual value. When the change of seepage depth with time is not considered, the seepage depth should be assumed in advance. The formula for calculating the safety factor of slope after strong aftershocks based on rigid body limit equilibrium theory needs to know the seismic acceleration on the slope surface, which is often difficult to obtain. Considering the magnification effect of seismic acceleration on the slope surface, the value can only be measured or obtained by experience. Permanent displacement cannot be calculated by this method.

3.2.2. Insite monitoring method

Insite monitoring of slope mainly includes surface deformation monitoring, deep deformation monitoring, stress monitoring and so on. Reasonable evaluation of slope stability is made by real-time variation of deformation and stress.

Zeng Peng et al.[29] through monitoring the deformation of Tieyicun landslide before and after earthquakes, the mechanism of the landslide was analysed. Before Wenchuan earthquake, the annual horizontal deformation of the old landslide was 0.1-0.2 m, and the vertical deformation was 0.05-0.1 m, which was in a local creep state. After the Wenchuan earthquake, there were many small cracks on the surface of the slope, with irregular direction, width between millimetres and centimetres, depth between centimetres and meters. Under the action of water infiltration, the stability of the slope was further weakened. Later, under the effect of aftershocks, the number of cracks increased, and the crack be measured with the value ranged from 10 cm to 30 cm in width and vertical displacement, which further enhanced the infiltration capacity of water and weakened the stability of slope body. Finally, the slope is damaged by slipping, and the slip surface with a shape of circular.
Wang Jialin et al. [30] monitored and analysed the stability of soil-rock accumulations in front of Zipingpu left bank dam before and after earthquakes. The results show that after the Wenchuan earthquake, there are obvious dislocations at the soil-rock boundary of the soil-rock accumulation body. The maximum relative dislocations are 61.46 mm. In the 42 aftershocks with magnitude 5.0 or more, the maximum relative dislocations at the soil-rock boundary are 3.83 mm, which is smaller than that of the main shock, indicating that aftershocks have little influence on the soil-rock boundary dislocations. The maximum displacement is 220 mm, and there is no obvious change in the aftershocks. Therefore, it is determined that the soil-rock accumulation body is in a stable state.

Zhang Hua et al. [31] used borehole inclinometer to monitor the internal displacement of a slope in Panzhihua. By comparing the data before and after the earthquake of August 30, 2008 in Panzhihua City, it was found that the displacement of the slope caused by the earthquake was obvious. The maximum displacement of soil borehole was located on the slope surface, the value was about 27 mm, and it tended to decrease along the depth. The post-earthquake data are also analysed. It is found that the displacement increases gradually and reaches the peak value 300 days after the earthquake, then reaches stable state.

After the Wenchuan earthquake, Wang Yunsheng et al. [32] placed strong seismograph on three different elevations of a slope body in Jiulong area to monitor the acceleration response of the slope body in aftershocks, so as to analyse and evaluate the stability of the slope body in aftershocks.

The insite monitoring data are reliable, but the investment cost is high, so it is difficult to cover comprehensively.

3.2.3. Test method

At present, the main test methods of slope stability after earthquake are centrifuge test, shaking table test and centrifuge shaking table test.

Zhang Hua et al. [31] simulated the displacement of slope after earthquake with centrifuge, and evaluated the stability of slope by the change rules of displacement. It assumes that the depth of soil slope affected by earthquakes is 10 m and the similarity ratio is 100. The compactness of soil in the depth affected by earthquakes is set at 0.90, 0.85 and 0.8, and the compactness of other soils is 0.95, so as to figure out the variation law of soil displacement under different degrees of seismic loosening. The experimental results show that under its assumed conditions and test scheme, the displacement adjustment will go through three stages: 1) acceleration stage 2) primary consolidation stage 3) secondary consolidation stage. The adjustment time of displacement field after earthquake is about one year. As the compaction coefficient decreases, the main crack gradually approaches the free surface and the size of the crack gradually increases.

M. H. Wu et al. [33] through centrifuge shaking table test, the relationship between the volume of sliding caused by slope instability failure, earthquake intensity and rainfall intensity after earthquake was studied. The experiment is divided into two groups: light rain and heavy rain. The peak acceleration of horizontal earthquake is 0 g, 0.05 g, 0.1 g and 0.15 g, respectively. There are eight centrifuge shaking table tests. Finally, it is found that the larger the peak value of the earthquake is, the larger volume of the landslide body will be. Under the same intensity of the earthquake, the larger the rainfall intensity after the earthquake, the larger volume of the landslide body will be.

Hari Woli et al. [34] [35] of the University of California, USA, used shaking table tests to simulate the rainfall of slopes after earthquakes. The slopes did not lose stability under the condition of rainfall after earthquakes. The experimental results show that the permeability rate and pore water pressure in the soil of the rainfall slope after earthquake are lower than those of the slope under rainfall alone. It is believed that this is due to the effect of vibration, which makes the void ratio of soil decrease. The experimental results also explain why there are no landslides in Nepal during the rainy season after the earthquake.

Wang Lanmin and Pu Xiaowu [36] also used shaking table to simulate the stability of slope rainfall after earthquakes, and described the process of slope failure in detail caused by rainfall after earthquakes. Through the measurement of horizontal displacement and vertical seismic subsidence,
the slope stability is analysed accordingly. It is also observed that during the process of rainfall after earthquakes in experiments, cracks in shallow layers will be filled and the stability of slope will be improved on the contrary. In addition, Wang Lanmin also studied the slope stability under the coupling effect of rainfall and earthquake. Through field investigation and experimental study on Yongguangcun landslide caused by Minxian-Zhangxian earthquake and rainfall before earthquake in Gansu Province[37], the physical and mechanical mechanism of the landslide is analysed[38], and the stability evaluation method of loess slope under coupling action of earthquake and rainfall is put forward[39]. The results show that rainfall before earthquakes is more disadvantageous to slope stability than rainfall after earthquakes.

At present, there are relatively many experimental focuses on the evaluation of slope stability under post-earthquake rainfall, but the test results are different, and the evaluation of slope stability under strong aftershocks is almost in the blank stage.

3.2.4. Numerical method

3.2.4.1 Finite element method
Pingyuqi et al.[40] used the extended finite element method[41] to simulate the development degree of cracks in the slope, and then used the vector method proposed by Academician Ge shurun[42] to calculate the safety factor of the slope after the earthquake, so as to evaluate the stability of the slope after the earthquake. The extended finite element method uses the shape function as a decomposition function, thus creating a discontinuous displacement model. This method does not need to divide more grids at the cracks. However, the crack propagation simulated by the extended finite element method artificially prescribes the mode of crack propagation, so there is a gap with the actual situation.

Pei Laizheng et al.[15] used finite element software Geo-Slope to analyze the stability of the seismic cracked slope under rainfall. By adding a regular crack to the top of the slope artificially, the safety factor under different crack depths was calculated and the stability of the slope was evaluated.

He Zhuan[43] used Geo-slope finite element software to evaluate the stability of slope under the condition of foreshock-main shock and main-aftershock. He links the foreshocks with the mainshock’s time histories, as a complete seismic time history. By inputting them into the dynamic files of Quake/w module for dynamic calculation. Then, imports the results into Slope/w module to evaluate the slope stability by calculating the stability coefficient and permanent displacement.

3.2.4.2 Finite difference method
Wenjie et al.[44] used the finite difference software FLAC3d to analyze the stability of the slope under the action of rainfall occurred after seismic. The potential slip surface was found by shear strain increment band, and the strength parameters of the soil above the slip surface were reduced. Then, the stability analysis under rainfall condition was carried out to evaluate the stability of the actual shaking loose slope under the condition of succedent rainfall. Finally, it is concluded that the possibility of deep slipping of slope is increased under the condition of rainfall after earthquake.

3.2.4.3 Discrete element method
By selecting the landslide near the critical state, Ding Jianhui et al.[45] used the discrete element software PFC2d to analyze the stability of slope under succedent rainfall conditions. Through the analysis and comparison of displacement field, velocity field, stress field and porosity, the stability of slope under rainfall after earthquake was evaluated.

3.2.4.4 Coupling method
Zhang Hua et al.[31] used the coupling method of finite difference and discrete element to simulate the stability calculation of soil-rock accumulation slope after earthquake. The loose accumulated material on the slope surface is simulated by uniformly distributed and parallel connected disc discrete element, the rest of the slope is simulated by finite difference method, and then the time history of
earthquake motion is applied to the bottom of the slope. By comparing the displacement been acquired by the actual monitoring data, the stability of the slope is evaluated.

The difficulty of using numerical method to evaluate the slope stability after earthquake is to simulate the seismic crack and the seismic loosening effect. At present, the simulation of the crack is usually manmade, the simulation of the seismic loosening effect is usually to change the relevant mechanical parameters. There are some limitations in practical application.

3.2.5 Probability analysis method
Yang Zongxi[46] introduced the Binarylogistic regression model, and then used the conditional probability, combined with the predicted rainfall probability to study the probability of geological disasters such as landslides under rainfall conditions in the area around Longmenshan, Chengdu after Wenchuan earthquake.

3.2.6 Mathematical Statistics method
Yang Z H et al.[47] used the mathematical statistics method to analyze the landslide sensitivity of the Laoshan earthquake-stricken area in Sichuan Province. Firstly, 5688 catalogues of landslides were obtained through field investigation, remote sensing image interpretation and historical data, and 10 typical disaster-causing factors (rainfall being one of them) were selected. Then, the sensitivity of each factor was analyzed by AHP method[48], and the sensitivity value and weight of each factor were obtained. Finally, the factors were weighted, and then, through GIS, the risk assessment of landslide is made which provide a reference for the stability evaluation of slope. [49-51]also used the same method to study and evaluate the stability of slopes in different regions.

For the analysis of landslide risk, the method which been used is to identify and analyse the disaster-causing factors through historical data (usually landslide catalogue), and assign weights according to the ratio of each factor which caused the landslide. Then, through GIS, the risk analysis of a certain area is carried out. This method is called heuristic method [52]. With the re-emergence of artificial intelligence, especially the artificial neural network, it has been applied to various fields. Similarly, it has also been applied to seismic landslide risk analysis. Artificial Neural Network (ANN) is used to predict the risk of landslide by establishing the relationship between landslide events and disaster-causing factors. [53] used this method to carry out risk analysis of slope, and achieved satisfactory results. If the influence of aftershocks can be considered as a disaster-causing factor and the relationship between aftershocks and landslide events can be established in this method, it will be an important supplement for slope hazard analysis.

4. Conclusion
1. When earthquake occurred, in addition to causing a large number of coseismic landslides, it may also cause more unstable slopes, which will evolve into landslides under the condition of strong aftershocks and rainfall in the later period. The losses and casualties caused by the instability of slope after earthquake would be more serious than coseismic landslides.

2. When a slope is subjected to earthquake action, the area around shallow surface of slope has the greatest destructive effect, which is mainly reflected in the generation and propagation of cracks, and the degree of damage is proportional to the intensity of the ground motion it encounters. When cracks occur in slope, the stress near cracks will redistribute and form a stress concentration area, causing crack propagated and new cracks generated. With the change of stress, the failure range will increase until the whole slope failure. Post-earthquake rainfall and the effects of strong aftershocks will accelerate this process.

3. At present, the evaluation methods of slope stability after earthquake mainly include theoretical or empirical formula method, numerical calculation method, monitoring method, test method, probability analysis method and mathematical statistics method. Both the theoretical method and the numerical method were used to evaluate the stability of slope after earthquake by calculating the safety factor or permanent displacement through certain simplifications and assumptions. The
monitoring method and the test method mainly through the change rules of displacement to evaluate the stability of slope. For the numerical calculation method, how to simulate the seismic loosening and cracking effect of slope after earthquake and the generation of surface runoff in the process of rainfall infiltration is an important problem to be solved.

4. From the current research situation at domestic and abroad, although the cumulative damage effect of aftershocks on structures has been recognized, the evaluation method of slope stability under the influence of aftershocks is seldom mentioned, and the related experimental research is seldom carried out. Therefore, the research in this field should be a main direction in the future.

5. With the development of artificial intelligence, the evaluation method of seismic landslide risk based on artificial neural network is gradually mature and perfect, and has been well applied in practice, which provides a new idea for the evaluation method of post-earthquake landslide stability.

Acknowledgments
This paper is financially supported by National Natural Science Foundation of China (No.51478444).

References
[1] Yin Y. (2009) Features of landslides triggered by the wenchuan earthquake[J]. Journal of Engineering Geology. Commun.,17(1):29-38.
[2] Cui Peng., Zhuang Jianqi., Chen Xingchang. (2010) Characteristics and countermeasures of debris flow in Wenchuan area after the Earthquake[J]. Journal of Sichuan university. Commun., 42(5):10-19.
[3] Qi Xin., Tang Chuan., Chen Zhoufeng. (2012) Coupling analysis of control factors between earthquake induced landslides and subsequent rainfall-induced landslides in epicenter area of WENCHUAN earthquake[J]. Journal of Engineering Geology. Commun., 20(4):522-531.
[4] Wang Li. (2011) The characteristics of wenchuan earthquake induced landslide[J]. Technology of highway transportation. Commun., (10):190-193.
[5] Zhao Jianjun., Ju Nengpan., Li Guo. (2010) Failure mechanism analysis of Guantan landslide induced by wenchuan earthquake[J]. Journal of geological hazards and environment preservation. Commun.,21(2):92-96.
[6] Chen Xiaoning., Cui Peng., LI Yong. (2010) Mountain hazard induced by wenchuan earthquake and its long-term development trends of ganxi gully, beichuan[J]. Journal of Sichuan university. Commun.,42(S1):22-32.
[7] Usui Y., Shimada H., Innami H. (2013) Case Study on Heavy Rainfall-Induced Reactivation of Seismically Disturbed Slope Caused by the 2011 off the Pacific Coast of Tohoku Earthquake[M]. Earthquake-Induced Landslides. Springer Berlin Heidelberg.
[8] Lin C W., Liu S H., Lee S Y. (2006) Impacts of the Chi-Chi earthquake on subsequent rainfall-induced landslides in central Taiwan[J]. Engineering Geology Commun.,86(2-3):87-101.
[9] Pei Lai-Zheng., Zhou Xiaojun., FANG Hua. (2012). Type active characteristics and development trend of rainfall-induced landslides after wenchuan earthquake[J]. Bulletin of soil and water conservation. Commun.,32(5):113-116.
[10] Hun Zhixu. (2010) Study on Soil Damage Effect in Strong Earthquake Area of Wenchuan Earthquake[D]. Southwest Jiaotong University.
[11] Jiang Liangwei., Yao Lingkan., Hu Zhixu. (2010) Experiment study on slope’s superficial dynamic effect and anchoring prevention mechanism under earthquake disturbance[J]. Journal of Sichuan university. Commun.,42(5):164-174.
[12] Qiu H., Kong J., Wang R. (2017) Response mechanism of post-earthquake slopes under heavy rainfall[J]. journal of seismology. Commun., 21(4):869-884.
[13] Zhu Zhiming., Zhou Kairui. (2013) Experimental research on cross external prestress reinforcing concrete beam[J]. Shanxi architecture. Commun.,39(33):37-39.
[14] Seed, H. B. (1979). "Nineteenth Rankine lecture: Consideration in the earthquake resistance design of earth and rockfill dam." Gotechnique, 29, London, England. Commun., 215-263.
[15] Pei Laizheng (2011) Research on the Landslide Mechanism of Damaged Soil Triggered by Rainfall After Wenchuan Earthquake[D].
[16] Wang Gaohui. (2017) Research on the quantification methods for water footprint of crop production[J]. Shuili xuebao. Commun., (6).
[17] Poulos, S. J. (1981). "The steady state of deformation." J. Geotech. Engrg. Div. ASCE, Commun., 107(5), 5513-5562.
[18] McRoberts, E. D., and Sladen, J. A. (1990). "Observations on static and cyclic sand liquefaction methodologies." Prediction and Perf. in Geotech., 43th Can. Geotech.Conf., Canadian Geotechnical Society. Commun., 215-226.
[19] GU W H., MORGESTERN N R., ROBERTSON P K. (1993) Progressive failure of lower San Fernando Dam[J]. J Geotechnical Engineering, ASCE. Commun., 119(2):333—347.
[20] Seed, H. B., Idriss, I. M., Lee, K. L., and Makdisi, F. I. (1975). "Dynamic analysis of the slide in the lower San Fernando dam during the earthquake of February 9, 1971." J. Geotech. Engrg. Div., ASCE. Commun., 101(9), 889-911.
[21] Ke Zhang., Ping Cao., Rui Bao. (2013) Progressive failure analysis of slope with strain-softening behavior based on strength reduction method[J]. Zhejiang Univ-Sci A (Appl Phys & Eng). Commun., 14(2): 101—109.
[22] Zhao Yanan. (2015) Study on progressive failure of loess and loess slope based on damage theory[D].
[23] Iverson, R.M. (1991). Sensitivity of stability analyses to groundwater data. In Landslides, Bell, ed. (Rotterdam: A.A. Balkema). Commun., pp. 451–457.
[24] Hammond C, Hall D, Miller S, et al. (1992) Level I Stability Analysis (LISA) documentation for version 2.0[J]. General technical report INT. Commun., 285.
[25] PACK, R. T. (1998) The SINMAP approach to terrain stability mapping[J]. Congress of the International Association of Engineering Geology. Commun., 21–25.
[26] Zhihua Yang, Hengxing Lan, Hongjiang Liu. (2015). Post-earthquake rainfall-triggered slope stability analysis in the lushan area. Journal of Mountain Science, 12(1). Commun., 232-242.
[27] He S , Li D , Wu Y , et al. (2011) Study on the rainfall and aftershock threshold for debris flow of post-earthquake[J]. Journal of Mountain Science. Commun., 8(5):750-756.
[28] Montgomery D R, Dietrich W E. (1994). A physically based model for the topographic control on shallow landsliding[J]. Water Resources Research. Commun., 30(4):1153–1171.
[29] Zeng Peng, Liu Sheng, Li Haiping. (2012) Study on Deformation and Failure Mechanism of Earthquake-Induced Landslide[J]. ChengShi Jianshe LiLun Yan Jiu. Commun., (11).
[30] Wang Jialin, XU Xiangtao, WANG Xianliang. (2009) Monitoring analysis of influence of WENCHUAN 8.0 Earthquake on talus slope stability at left bank in front dam of ZIPINGPU hydraulic project[J]. Chinese journal of rock mechanics and engineering. Commun., 28(6):1279-1287.
[31] Zhang Hua. (2011). Study on earthquake induced behaviors of slopes covered by deposits[D]. Southwest Jiaotong University.
[32] Wang Y, Luo Y, Wang F, et al. (2012) Slope seismic response monitoring on the aftershocks of the Wenchuan earthquake in the Mianzhu section[J]. Journal of Mountain Science Commun., 9(4):523-528.
[33] Wu M H, Wang J P, Yeh J C. (2017) Centrifuge Modeling of Relationships Between Earthquake Intensities and Scales of Post-quake Triggering Rainfall and Landslide[J].
[34] Woli H. (2015) Effect of post-earthquake rainfall on slope stability. Dissertations & Theses – Gradworks.
[35] Tiwari B, Ajmera B, Tran D. (2017) Influence of Post-Earthquake Rainfall on the Stability of Clay Slopes-IPL-192[C]// Workshop on World Landslide Forum. Springer, Cham.
[36] Pu Xiaowu. (2016) Study on the instability of loess slope under earthquake and rainfall coupling action based on large shaking table model test[D]. Lanzhou Institute of seismology.
[37] Wang Lanmin, Wang qian. (2017) Loessial Landslides Induced by the Minxian–Zhangxian Ms6.6 Earthquake of China in 2013[M]// Geotechnical Hazards from Large Earthquakes and Heavy Rainfalls. Springer Japan.

[38] Wang Lanmin, Sun Junjie. (2017) Physical mechanism and prevention method of loess slope failure induced by the coupling effect of earthquake and rainfall[C]. 16th World Conference on Earthquake.

[39] Wang Lanmin, Pu Xiaowu, et al. (2017) A performance-based design method of loess slopes under the coupling effects of earthquakes and rainfalls[C]. PBD III VANCOUVER Earthquake Geotechnical Engineering.

[40] Ping Tongqi, Luo Xianqi, Zheng Anxing. (2015) Analysis of influence of cracks on rock slope stability under seismic loading[J]. Rock and Soil Mechanics. Commun., (2):600-606.

[41] Belytschko T, Black T. (1999) Elastic crack growth in finite elements with minimal remeshing[J]. International Journal for Numerical Methods in Engineering. Commun., (45): 601–620.

[42] Ge Xiurun. (1987) Finite Element Analysis of Rock Mass Engineering Subject by PC Microcomputer[C]// Papers of the First National Symposium on Computational Geotechnical Mechanics.chengdu. Southwest Jiaotong University press. Commun.,74-85.

[43] He Zhuan. (2009) Study on Stability Assessment and Analysis Method of Slope under Special Working Conditions[D]. southwest Jiaotong University press.

[44] Wen Jie. (2016) Analysis of Formation Mechanism of Loess Landslide under Earthquake and Rainfall[D].

[45] Ding Jianhui. (2013) Study on Formation Mechanism and Dynamic Model of Earthquake Rainfall Landslide[D].

[46] Yang Zongjie, Qiao Jianping,Tian Hongling. (2010) Prediction of regional geological hazards induced by rainfall after earthquakes[J]. Journal of Sichuan university. Commun.,42(S1):38-42.

[47] Yang Z H, Lan H X, Gao X, et al. (2015) Urgent landslide susceptibility assessment in the 2013 Lushan earthquake-impacted area, Sichuan Province, China[J]. Natural Hazards Commun., 75(3):2467-2487.

[48] Saaty TL. (1997) A scaling method for priorities in hierarchical structures. J Math Psychol 15:234–281.

[49] Tang C, Zhu J, Qi X. (2011a) Landslide hazard assessment of the 2008 Wenchuan earthquake: a case study in Beichuan area. Can Geotech J. Commun.,48:128–145.

[50] Yoshimatsu H, Abe S. (2006) A review of landslide hazards in Japan and assessment of their susceptibility using an analytical hierarchical process (AHP) method. Landslides Commun., 3:149–158.

[51] Kamp U, Growley BJ, Khattak GA, Owen L. (2008) GIS based landslide susceptibility mapping for the 2005 Kashmir earthquake region. Geomorphology. Commun., 101:631–642.

[52] Casagli N, Catani F, Ermini L. (2005) Artificial Neural Networks Applied To Landslide Hazard Assessment[J]. Geomorphology. Commun.,66(1):327-343.

[53] Lee S, Evangelista D G. (2006) Earthquake-induced landslide-susceptibility mapping using an artificial neural network[J]. Natural Hazards & Earth System Sciences. Commun., 6(5):687-695.