早稲田大学大学院 創造理工学研究科

博 士 論 文 概 要

論 文 題 目

RESEARCH ON SLOPE STABILITY AND LANDSLIDE MOBILITY DURING EARTHQUAKES

地震時における斜面の安定性と地すべりの運動特性に関する研究

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The 2008 Wenchuan earthquake with a surface wave magnitude of 8.0 occurred at Yingxiu County in Longmenshan thrust fault belt, southwest China, having triggered a huge amount of slope failures. This catastrophic earthquake induced various disastrous consequences and took more than 80,000 lives, which one third was attributed to slope failures. In order to study on the distribution regularity of slope failures related with seismic parameters, and the influential factors on slope stability and landslide mobility, field investigation, statistical analysis, theoretical derivation and finite element simulation were used. The research aspects included general viewpoint and local viewpoint, qualitative analysis and quantitative analysis. The research procedure obeyed a process of a slope from stability to instability, from the estimation of mobilization ability of sliding debris to the prediction of its travel distance, and then investigated the seismic performance of slope reinforcements so as to take effective countermeasure to protect natural slope from failure in the future.

Firstly, chapter 1 introduced the background of this research, which briefly delineated the causes and results of Wenchuan earthquake, and reviewed previous researches on slope failure distribution related with earthquake parameters, also reviewed previous studies about influential factors on slope stability and its dynamics responses, landslide mobility and its travel distance prediction.

In chapter 2, from the whole viewpoint of Wenchuan earthquake, a detailed inventory with more than 190,000 slope failures and strong ground motion records of 187 seismic stations were used to analyze the qualitative and quantitative relations between slope failure distribution and seismic ground motion in Wenchuan earthquake wholly affected area. The results revealed that slope failure distribution exponentially decreased with the increment of epicentral distance and distance from surface fault rupture; seismic acceleration attenuation and statistical analysis of slope failure distribution gave solid evidences to the existence of hanging-foot wall effect, because peak ground acceleration (PGA) on the hanging wall side was apparently larger than that on footwall side, resulting in slope failures on the hanging wall side was predominantly more than that on footwall side. Linear correlation between slope failure distribution and PGA was demonstrated by regressive analysis, which proposed that 0.18-0.21g horizontal PGA was the threshold value of slope failure occurrence. Furthermore, an empirical model for slope failure distribution attenuation was discussed in Chapter 2.

Thirdly, three kinds of methodologies were used to analyze the numerous influential factors on slope stability and its dynamic responses in chapter 3. In section 3.2, a case study of landslide distribution and slope stability related with five influential factors was implemented based on field investigation of 119 landslides in Wenchuan County. The effectiveness of each influential factor on slope stability was studied by multivariable analysis and demonstrated that slope height, horizontal peak ground acceleration and geological structure had stronger effect on the sliding source area and volume than slope angle and rock type. In order to analyze more influential factors on slope dynamic responses, theoretical derivation was conducted to study the influences of geomechanical parameters and seismic wave parameters in section 3.2. The analytical results revealed that the shape of contour plot of displacement amplification ratio was determined by seismic wave frequency; with the increment of frequency, the contour plot changed from parallel to slope surface to rhythm distribution with multiple peak values; lower frequency induced more dangerous dynamic responses; the maximum displacement amplification ratio relied on Poisson's ratio, input angle of seismic wave and slope angle; mass density had smaller effect on slope dynamic responses than Young's modulus; the thickness of saliently affected region by earthquake become larger with the increment of Young's modulus and seismic wave input angle, and with the decrease of seismic wave frequency. As a supplementary of section 3.2 and 3.3, section 3.4 continued to analyze the effect of topography on slope dynamic responses by finite element simulation. Five simplified slopes with different shapes were analyzed under three typical seismic waves, the results revealed that seismic acceleration was generally amplified with the increment of slope elevation, especially, at the steep section and ground surface curvature sharp changing section; slopes with convex and S-like shape were much more unstable than other three slope types during earthquakes; step-like slope had relatively highest stability; concave slope and inverse S-like slope had medium stability.

High mobility landslide was a severe harzard to endanger the area along travel path due to time limitation of evacuation. It is essential to evaluate the effects of numerous influential factors on landslide mobility, so as to better understand the movement of landslide. Hence, chapter 4 qualitatively studied the relations between the equivalent coefficent of friction ($\mu=H_{\max}/L_{\max}$) and other 6 parameters of 46 landslides, such as topographical factors, landslide volume, horizontal PGA and rock type, by means of simplified plots. The effectiveness of each factor on landslide mobility ($1/\mu$) and its travel distance was revealed by multivariable analysis and proposed that rock type, landslide volume, slope transition angle and slope height had predominant effect on landslide mobility and its travel distance. Furthermore, two statistical models for predicting equivalent coefficent of friction and travel distance were developed, respectively, intending to serve relocation and rehabilitation; their validities were verified by satisfactory agreement between observations and predictions, and further compared with previous statistical models.

In order to learn from seismic damage and take effective countermeasures to enforce slope stability, chapter 5 reported the field survey about seismic performance of four slope reinforcements along National Road 213 and Dujiangyan-Wenchuan expressway, that is, anchor cable, frame beam, soil nailing wall and shotcrete with bolts. The result of damage comparison suggested that anchor cable, frame beam and soil nailing wall had good anti-seismic property, however, shotcrete with bolts had limited ability to enhance slope stability during earthquake.

Finally, the chapter 6 summarized the findings in this research and discussed the future research topics.

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Journal Paper	
○1)	Deping Guo, Masanori Hamada, 2013. Qualitative and Quantitative Analysis on Landslide Influential Factors During Wenchuan Earthquake: a Case Study in Wenchuan County. Engineering Geology, 152, 202-209. (SCI)
○2)	Deping Guo, Masanori Hamada, 2012. Observed Stability of Natural and Reinforced Slopes During the 2008 Wenchuan Earthquake. Journal of Japan Society of Civil Engineers, Ser. A1 (Structural Engineering & Earthquake Engineering (SE/EE)), 68(2) 481-494. (JSCE)
○3)	Deping Guo, Masanori Hamada, Chuan He, Yufeng Wang, Yulin Zou. An Empirical Model for Landslide Travel Distance Prediction in Wenchuan Earthquake Area, Landslides. (SCI, Accepted)
○4)	Deping Guo, Masanori Hamada, Chong Xu, Chuan He. Analysis of the Relations Between Slope Failure Distribution and Seismic Ground Motion During the 2008 Wenchuan Earthquake. Soil Dynamics and Earthquake Engineering. (SCI, Major revision)
Conference paper	
○1)	Deping Guo, Masanori Hamada, Hongyu Jia, 2013. Influential Factors on Slope Stability and Landslide Mobility. The 2nd IACGE International Conference on Geotechnical and Earthquake Engineering. (ASCE-GSP, In press)
○2)	Deping Guo, Masanori Hamada, 2013. Susceptibility Analysis on Landslide Triggering Factors During the 2008 Wenchuan Earthquake. Seventh International Conference on Case Histories in Geotechnical Engineering, Chicago.
○3)	Deping Guo, Masanori Hamada, 2012. Lessons Learnt From Seismic Damage Induced by the 2008 Wenchuan Earthquake. 2012 International Conference on Vibration, Structural Engineering and Measurement, Applied Mechanics and Materials, Vols. 226-228, pp.889-896, (EI, Oral Presentation)

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Conference paper	
○4)	Deping Guo, Masanori Hamada, 2012. Landslide Distribution Related with Seismic Ground Motion during the 2008 Wenchuan Earthquake. Proc. of the First International Symposium on Earthquake Engineering, JAEE, Vol.1, 115－124, Tokyo. (Parallel session, Oral presentation)
○5)	Deping Guo, 2012. Theoretical Analysis on Dynamic Responses of Single Surface Slope during Earthquake, 15th World Conference on Earthquake Engineering, Lisbon. (e.poster).
○6)	Deping Guo, Masanori Hamada, 2012. Statistical Analysis of Landslides Triggered by Wenchuan Earthquake, 14th International summer Symposium of JSEC, Nagoya. (Parallel session, Oral Presentation)
7)	Deping Guo, Chuan He, Jimin Zhou, Ping Geng, 2009. Discussion on Anti-upward Moving Calculation Method of Submarine Shield Tunnel during the Construction and Service Stages, Proc. of the Fifth China-Japan Conference on Shield Tunneling, 152-158. (In Chinese with English abstract)
8)	Jimin Zhou, Chuan He, Deping Guo, Zhun Tan, 2009. Research on Mechanical Behavior of Lining Structure Influenced by Embedded Depth of Submarine Shield Tunnel, Proc. of the Fifth China-Japan Conference on Shield Tunneling, 131-136. (In Chinese with English abstract)