Journal of Rock Mechanics and Geotechnical Engineering 7 (2015) 493–508

CSRME

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full length article

Microseismic monitoring and numerical simulation on the stability of high-steep rock slopes in hydropower engineering

Chun'an Tang [a,*], Lianchong Li [a], Nuwen Xu [b], Ke Ma [c]

[a] School of Civil Engineering, Dalian University of Technology, Dalian, 116024, China
[b] State Key Laboratory of Hydraulics and Mountain River Engineering, Sichuan University, Chengdu, 610065, China
[c] Institute of Mechanics, Chinese Academy of Sciences, Beijing, 100190, China

ARTICLE INFO

Article history:
Received 17 November 2014
Received in revised form
1 June 2015
Accepted 17 June 2015
Available online 6 August 2015

Keywords:
Rock slope
Stability analysis
Damage
Microseismic monitoring
Numerical simulation

ABSTRACT

For high-steep slopes in hydropower engineering, damage can be induced or accumulated due to a series of human or natural activities, including excavation, dam construction, earthquake, rainstorm, rapid rise or drop of water level in the service lifetime of slopes. According to the concept that the progressive damage (microseismicity) of rock slope is the essence of the precursor of slope instability, a microseismic monitoring system for high-steep rock slopes is established. Positioning accuracy of the monitoring system is tested by fixed-position blasting method. Based on waveform and cluster analyses of microseismic events recorded during test, the tempo-spatial distribution of microseismic events is analyzed. The deformation zone in the deep rock masses induced by the microseismic events is preliminarily delimited. Based on the physical information measured by in situ microseismic monitoring, an evaluation method for the dynamic stability of rock slopes is proposed and preliminarily implemented by combining microseismic monitoring and numerical modeling. Based on the rock mass damage model obtained by back analysis of microseismic information, the rock mass elements within the microseismic damage zone are automatically searched by finite element program. Then the stiffness and strength reductions are performed on these damaged elements accordingly. Attempts are made to establish the correlation between microseismic event, strength deterioration and slope dynamic instability, so as to quantitatively evaluate the dynamic stability of slope. The case studies about two practical slopes indicate that the proposed method can reflect the factor of safety of rock slope more objectively. Numerical analysis can help to understand the characteristics and modes of the monitored microseismic events in rock slopes. Microseismic monitoring data and simulation results can be used to mutually modify the sensitive rock parameters and calibrate the model. Combination of microseismic monitoring and numerical simulation provides a more objective basis for the numerical model and parameters and a solid mechanical foundation for the microseismic monitoring.

1. Introduction

Among the stability analysis methods for geotechnical engineering, the development of slope stability analysis method is the most remarkable. Especially, the stability of high-steep rock slopes has always been a problem that many researchers have been trying to solve but not satisfactorily solved yet. With the development of computers, a number of numerical methods have been proposed and widely applied to slope stability analysis, such as finite difference method (FDM), finite element method (FEM), boundary element method (BEM), element free method, meshless method, discrete element method (DEM), discontinuous deformation analysis (DDA) method, fast Lagrange interpolation method, and manifold method. Among these methods, the FEM is a relatively mature numerical method. Its application to stability analysis of rock and soil slopes can be dated back to 1967 and it is also one of the most widely used numerical methods at present. Although it cannot well deal with the problems of large deformation and discontinuous displacement, the FEM has a rigorous theory system that considers the stress–strain relationship of sliding mass and can simulate the interaction between the sliding mass and supporting structure. The FEM also has great advantages in coupling of deformation and seepage of sliding mass. The slope stability analysis based on FEM can be generally divided into three categories. The first is the slip surface stress analysis (SSA), which combines the limit equilibrium theory and the FEM results (Duncan, 1996). Based

---

* Corresponding author. Tel.: +86 13840899558.
E-mail address: tca@mail.neu.edu.cn (C. Tang).

Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2015.06.010

on the finite element stress analysis, the most probable slip surface can be determined by various optimization methods. The computation process is simple and practical. However, the theoretical defects also exist, i.e. the SSA is unable to reflect the region where slip most probably occurs and the evolution process of failure. The second is the strength reduction method (SRM), which is a direct method proposed by Zienkiewicz et al. (1975). Its fundamental principle is to combine the strength reduction concept, the limit equilibrium principle and the finite element principle. First, the slope strength parameters are reduced and a new pair of strength parameters is obtained as the input parameters for FEM calculation. The corresponding strength reduction coefficient is the minimum factor of safety. A great amount of research work on this method has been conducted (Dawson et al., 1999; Lian et al., 2001; Zheng and Zhao, 2004). The third method based on FEM is the centrifugal loading method (or the gravity increase method) (Swan and Seo, 1999; Xu and Xiao, 2007; Li et al., 2009). The principle of the centrifugal loading method is opposite to that of the SRM. The shear strength parameters of rock or soil, c and φ, remain constant. Finite element analysis is performed with increasing gravitational acceleration g until the critical failure state is reached. The ratio between the corresponding gravitational acceleration g_{lim} and the real gravitational acceleration g_0 (g_0 is usually taken as 9.81 m/s^2) is the factor of safety of the slope. Increasing the gravitational acceleration is in fact equivalent to increase of rock or soil gravity. Therefore, this method is named as the centrifugal loading method or the gravity increase method.

Besides numerical analysis, in situ monitoring and analysis are also necessary for evaluating slope stability. Due to the complexity in geological conditions and various influencing factors, stability analysis of rock slopes has to rely on monitoring techniques for verification. Currently, the traditional monitoring devices and methods for slopes include: (1) Slope surface geodetic survey (e.g. theodolite, level gauge, range finder, total station); (2) GPS monitoring; (3) Displacement meter; (4) Infrared remote monitoring method; (5) Laser micro-displacement monitoring; (6) Synthetic aperture radar interferometry (e.g. SAR interferometry, INSAR); (7) Time-domain reflectometry (TDR) technique; (8) Borehole inclinometer, anchor dynamometer and pressure monitoring device inside the slope; (9) Acoustic emission (AE) and microseismic monitoring technique. Among these monitoring devices and methods mentioned above, items (1)–(7) are mainly used to monitor the slope surface, and items (8) and (9) mainly to monitor the sliding mass at a certain depth. With the development of science and technology, the non-contact, fully remote-controlled, highly intelligent, high-precision integrated monitoring techniques from slope surface to interior are the future development trend for slope monitoring.

As a tempo-spatial dynamic monitoring method, the microseismic (AE) monitoring technique can capture the damage or microcracks initiated in the rock mass in time, which has been gradually applied to qualitative analysis of slope stability in recent years (Dixon and Spriggs, 2007; Cheon et al., 2011). The microseismic monitoring technique is currently used to understand the slope deformation characteristics and microseismicity parameters, e.g. the relationship between major microseismic events, the accumulative events and energy rate, and to determine the position of the potential slip surface (zone). For example, the microseismic monitoring technique was applied to high slopes of Guanyin Mountain in 1983. Both displacement and groundwater level were monitored for prediction of slope stability (Hou, 1989). In mountainous Switzerland, microseismic monitoring networks have been installed since 2001 in a number of mountains where potential landslides may occur. The monitoring network was provided by Swiss Seismological Service, with frequency in the range between 1 Hz and 200 Hz (Eberhardt et al., 2004; Spillmann et al., 2007); For Suusammyr road slopes in Kyrgyzstan, a microseismic monitoring network with the frequency ranging from 10 Hz to 100 Hz was adopted to predict the landslide mode (Arosio et al., 2009). The microseismic monitoring technique has been widely applied in highway slopes in recent years in developed countries such as USA and Japan (Shiotani, 2006). More applications to slope hazards prediction for open mines in USA, Canada, South Africa and Australia have been reported (Glazer and Hepworth, 2004; Yang and Hou, 2008). As for slope monitoring for water resources, hydropower and reservoir bank, a landslide of 40–70 million cubic meter in volume was estimated at the Aaknes reservoir bank in Norway. In order to provide early warning information for landslide hazards, a microseismic monitoring system with 8 three-phase transducers was installed in 2005 to detect the microseismic events in real time during the progressive deformation process (Ganerød et al., 2008). In China, microseismic monitoring was implemented for the high slope of the double-line five-stage ship lock of the Three Gorges Project, the Mabukan high slope, the left bank slope of Jinping I Hydropower Station, and the right bank slope of Dagangshan Hydropower Station, etc. (Yan et al., 1998; Li and Wang, 2001; Wan et al., 2003; Xu et al., 2011; Ma et al., 2013).

For any sources triggering landslides (including excavation unloading, cavern excavation in slope, blasting, grouting, and extreme environment during the service lifetime, such as earthquake, rainstorm, rapid rise or drop of reservoir water level), the essence of potential slip surface formation process is a process of damage initiation and accumulation. It has been recognized that the landslide evolution is a process of continuous to discontinuous deformation or even separation. Therefore, the slope stability is essentially a dynamic stability state, i.e. during excavation and service lifetime of slope, the physico-mechanical properties of rock masses within the slip surface zone always change dynamically. Therefore, the factor of safety of a slope varies with elapsed time (Zhou et al., 2004; Li and Qian, 2010). The meaning of “dynamic stability” includes two aspects. One is the dynamic development of an objective target. Its stability has to be traced and monitored so as to provide objective conditions for data acquisition and analysis of “interactive monitoring and simulation”. The other is the objective understanding of the dynamic change of slope in the entire service lifetime. The boundary condition and parameters for simulation need to be modified constantly and thus the stability assessment is dynamic.

The meaning of dynamic stability provides a good opportunity for combination of microseismic monitoring and numerical modeling. If a three-dimensional (3D) geomechanical model is built for numerical analysis of slope stability, the reliability and applicability of the model and corresponding parameters should be verified by real physical information. If the slope slip surface is identified only by AE monitoring, the evolution process of slip surface cannot be represented elaborately either. In this study, the intrinsic effects and relationship between the stress field, development of the slip surface, and microseismic information (tempo-spatial coordinates, source size, energy dissipation and other physical information) of 3D geomechanical model are considered. The numerical and monitoring methods are integrated and supplementary for each other. The numerical analysis can help to understand the characteristics and modes of microseismic events monitored. The monitored microseismic physical information can be mutually used for modification of sensitive parameters and calibration of numerical model. Taking the left bank slope of Jinping I Hydropower Station and the right bank slope of Dagangshan Hydropower Station for examples, microseismic monitoring and numerical simulations are performed for slope stability analysis in this study.