Structural Safety 49 (2014) 65–74

Contents lists available at ScienceDirect

Structural Safety

journal homepage: www.elsevier.com/locate/strusafe

Slope safety evaluation by integrating multi-source monitoring information

M. Peng [a,b], X.Y. Li [b], D.Q. Li [c], S.H. Jiang [c], L.M. Zhang [b,*]

[a] Key Laboratory of Geotechnical and Underground Engineering of Ministry of Education, Department of Geotechnical Engineering, Tongji University, Shanghai, China
[b] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong
[c] State Key Laboratory of Water Resources and Hydropower Engineering Science, Wuhan University, Wuhan, China

ARTICLE INFO

Article history:
Available online 12 December 2013

Keywords:
Slope stability
Field monitoring
Information fusion
Bayesian network
Reliability analysis
Markov chain Monte Carlo simulation

ABSTRACT

A systematic method is presented for evaluating the slope safety utilizing multi-source monitoring information. First, a Bayesian network with continuously distributed variables for a slope involving the factor of safety, multiple monitoring indexes and their influencing parameters (e.g. friction angle and cohesion) is constructed. Then the prior probabilities for the Bayesian network are quantified considering model and parameter uncertainties. After that, multi-source monitoring information is used to update the probability distributions of the soil or rock model parameters and the factor of safety using Markov chain Monte Carlo simulation. An example of a slope with multiple monitoring parameters is presented to illustrate the proposed methodology. The method is able to integrate multi-source information based on slope stability mechanisms, and update the soil or rock parameters, the slope factor of safety, and the failure probability with the integrated monitoring information. Hence the evaluation becomes more reliable with the support of multiple sources of site-specific information.

1. Introduction

Field monitoring is an important means to evaluate the safety state of slopes, provide basis for slope safety control measures, warn of impending failures and mitigate risks of slope failures [1,2]. Common instruments and measuring indexes in slope monitoring are summarized in Table 1 according to Marr [2]. With appropriate instruments, changes in slope characteristics such as soil stresses, pore water pressures and crack development can be measured and used as a basis for evaluating the slope safety.

Einstein and Sousa [1] emphasized that monitoring results and observations need to be properly interpreted to evaluate slope safety. Numerous studies have been conducted on the interpretation of slope safety based on monitoring information. Some studies aimed to find a relationship between rainfall and slope failure with statistical analysis [3–6] or mechanical analysis [7,8]. It is also believed that slope displacements, especially displacement incremental rates, are important indicators to evaluate slope safety [9,10]. Some advanced methods such as GIS and ground-based radar have been attempted for slope safety evaluation and warning [11–13].

Existing interpretation methods typically use one single index (e.g. surface or underground deformation, pore pressure, or rainfall) as a predictor and hence reveal only one aspect of slope performance. A holistic assessment of the slope safety state may not be achieved. Besides, a large portion of monitoring data is often not utilized in these methods. Slope safety evaluation using multiple sources of monitoring information may be more reasonable, and is the topic of the present research.

Data fusion is a process of integrating multiple sources of data and knowledge representing the same structure into a consistent, accurate and useful representation [14]. Chang et al. [15] and Wong et al. [16] conducted landslide hazard assessment based on the fusion of multisource remote sensing images of the same site. To reduce the errors of monitoring information from human mistakes or faulty equipment, Guo et al. [17] and Peng et al. [18] applied a data-fusion method to filter and extract monitoring information from multiple sensors. Available data fusion methods can improve the quality of monitoring data of the same type (e.g. displacement) by fusing the information from multiple sensors. However, information from different types of monitoring data (e.g. displacement, stress and pore water pressure) may not be integrated easily and applied to evaluate the slope safety in these methods. Artificial neural networks were sometimes used for landslide susceptibility assessment with multiple pieces of information of the influential factors (e.g. slope geometry, soil thickness and drainage) [19]. However, little physical analysis is involved in artificial neural networks; the uncertainties involved are not included explicitly either.

In this study, a systematic method of slope safety evaluation is presented utilizing multi-source monitoring information with Bayesian networks. The method is aimed to (1) integrate multi-

* Corresponding author. Tel.: +852 2358 8720; fax: +852 2358 1534.
E-mail address: cezhangl@ust.hk (L.M. Zhang).

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http://dx.doi.org/10.1016/j.strusafe.2013.08.007

Table 1
Instruments for monitoring global stability of slopes (modified from Marr [2]).

Instrument type	Instrument	Measured index
Geometric measures	Ground reference point, survey monument	Settlement and movement
	Settlement plate, platform or cell	Settlement
	Vertical inclinometer	Inclination
	Horizontal inclinometer	Inclination
	Tilt meter	Rotation
	Crack meter	Width
	Extensometer	Movement
	Time domain reflectrometry (TDR)	Distance
	Automated total station	Change in position
	Differential Global Positioning System (dGPS)	Movement
	LIDAR (Light Detection and Ranging)	Vertical movement
	InSAR (Interferometric synthetic aperture radar)	Surface map
	Digital camera with reference targets	Movement
	Liquid level gages	Settlement
Water related measures	Observation well	Water level
	Piezometer	Water pressure
	Rain gage	Rainfall
Mechanical measures	Strain gage	Strain/stress
	Load cell	Force
	Accelerometer	Dynamic forces
	Acoustic emission monitoring	Particles sliding
	Fiber optic sensor	Strain or pressure
	Micro-seismic	Energy
Temperature measures	Thermister, thermocouple and TDR	Temperature
	Fiber optic sensor	Temperature

source information based on slope stability mechanisms; (2) update the soil or rock model parameters with the integrated monitoring information; and (3) predict the factor of safety and failure probability of the slope with the integrated monitoring information. An example of a slope with multiple monitoring indexes is presented to illustrate the proposed methodology.

2. Proposed method of slope safety evaluation by integrating multi-source monitoring information

2.1. The Bayesian network

A Bayesian network is a probabilistic graphical model that represents a set of random variables and their conditional dependencies via a directed acyclic graph [20]. A Bayesian network combines the knowledge of graph theory and statistics theory. It consists of nodes (parameters) and arcs/links (inter-relationships) with their (conditional) probabilities, which can be applied to solve uncertainty problems by logic reasoning. Bayesian networks have been proven to be a robust method for reliability analysis and risk analysis, including the integration of multiple sources of information [21–26].

2.2. The framework

Both the factor of safety, F_S, and monitoring information are indicators of the performance of a slope of certain parameters (e.g. cohesion, friction angle etc.), as shown in Fig. 1. A change in the slope parameters will lead to changes in the monitoring information and slope safety. Based on this, the slope safety evaluation with multi-source monitoring information is conducted by updating the slope parameters using the monitoring information (back analysis), and calculating the F_S and the failure probability (P_F) of the slope with the updated slope parameters (inference) as shown in Fig. 1. The main steps of the proposed method are shown in Fig. 2:

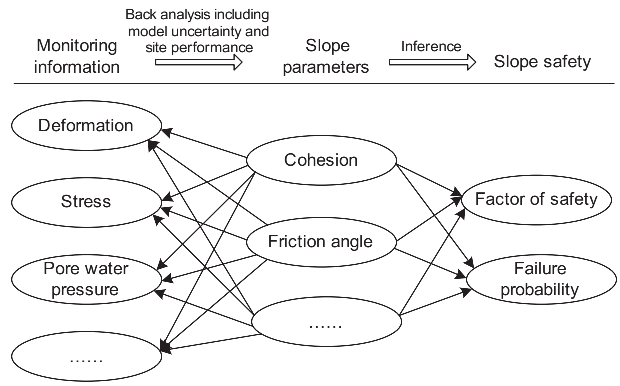

Fig. 1. Principle of fusion of monitoring data from multiple sources.

(1) A causal network is first constructed considering relationships among F_S, monitoring parameters (M) and slope parameters (S).
(2) The F_S and M as response functions of S, namely, $F_S(S)$ and $M(S)$ in Fig. 2, are obtained using finite element analysis and a response surface method.
(3) The prior probabilities of the Bayesian network, namely, the prior probabilities of S, $P(S)$, and the prior conditional probabilities of M given S, $P(M|S)$, and F_S given S, $P(F_S|S)$, are obtained by applying Monte Carlo simulation to the response functions, $F_S(S)$ and $M(S)$, as shown in Fig. 2. The model uncertainties are included in this step.
(4) The posterior probabilities of S, $P(S|m)$, are obtained by updating the prior, $P(S)$, with available monitoring information, $M = m$, as shown in Fig. 2. Markov Chain Monte Carlo (MCMC) simulation is applied in this step since the Bayesian network in this study involves non-normal continuous probability distributions.
(5) Finally, the posterior probability of F_S, $P(F_S|m)$, is calculated with the updated slope parameters as well as the probability of slope failure (Fig. 2).

Actually, the updating of the slope parameters and the updating of the factor of safety, namely, steps (4) and (5), are executed at the same time in the computation program. They are described in two steps here in order to better understand the updating mechanisms. The framework of the proposed method will be introduced step by step later in the paper. An example of a slope with multiple monitoring indexes will be presented to illustrate the proposed framework toward the end of this paper.

2.3. Constructing a Bayesian network by considering F_S and monitoring parameters

As shown in Fig. 3, a simple casual network is built for a soil slope by considering the soil parameters (i.e. cohesion c and friction angle ϕ), two monitoring parameters (i.e. the vertical displacement at point A, D_A and the vertical stress at point B, S_B), F_S and the slope safety state (safe/failed or S/F). In this case, F_S, D_A and S_B are governed by c and ϕ if other parameters are well defined (c and ϕ are the parents of F_S, D_A and S_B); S/F depends on the value of F_S (F_S is the parent of S/F), which means S/F = safe if $F_S > 1$ and S/F = failed if $F_S < 1$. c and ϕ are uncertain and difficult to obtain, while D_A and S_B can be measured using monitoring instruments. Therefore in the Bayesian network, the monitoring information of D_A and S_B can be used to update c, ϕ, F_S and S/F.