Engineering Geology 154 (2013) 56–63

Contents lists available at SciVerse ScienceDirect

Engineering Geology

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

Reliability-based design of rock slopes — A new perspective on design robustness

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ARTICLE INFO

Article history:
Received 7 July 2012
Received in revised form 5 December 2012
Accepted 8 December 2012
Available online 30 December 2012

Keywords:
Rock slopes
Reliability-based design
Failure probability
Robustness
Uncertainty
Optimization

ABSTRACT

Traditional reliability-based rock slope designs, in which the lowest-cost design is selected from all designs meeting target reliability requirements, are often sensitive to variations in noise factors such as rock shear properties. Consequently, a design that was initially judged acceptable may not satisfy reliability requirements if the variation of rock properties has been greatly underestimated. The authors present a Robust Geotechnical Design (RGD) approach for purposes of addressing this dilemma, by considering the robustness *explicitly* in the design process. In the context of rock slope design, this proposed RGD approach aims to make the response (i.e., failure probability) of a rock slope system insensitive to, or robust against, the variation of rock shear properties by adjusting design parameters (i.e., such as slope angle and height). Compared to traditional reliability-based design, the RGD approach adds design robustness as one of its design objectives. Thus, multi-objective optimization, considering both cost and robustness, is needed to select optimal designs in the acceptable design space where safety is guaranteed by a constraint on the reliability. In this paper, the concept of the Pareto Front, a collection of optimal designs that reflect the trade-off between cost and robustness, is implemented in the RGD approach. The proposed RGD approach is demonstrated with an example of a rock slope design.

1. Introduction

In recent years, risk-based approaches have been increasingly used in the analysis and design of rock slopes. This approach necessitates qualification of the probability of failure of the rock slope, which explicitly includes consideration for uncertainties in the underlying input parameters in a systematic manner (Vanmarcke, 1980; Oka and Wu, 1990; Christian et al., 1994; Duncan, 2000; Ching et al., 2009). Many investigators have contributed to the subject of reliability or failure probability of rock slopes (e.g., Low and Einstein, 1992; Low, 1997; Juang et al., 1998; Park and West, 2001; Duzgun et al., 2003; Park et al., 2005; Hoek, 2006; Low, 2007; Low, 2008; Duzgun and Bhasin, 2009; Li et al., 2011; Lee et al., 2012; Park et al., 2012). Traditional reliability-based rock slope designs, however, are often sensitive to variations in noise factors such as rock shear properties. In this paper, the authors propose a reliability-based robust design approach to achieve design robustness, while also meeting safety and cost requirements.

The shear strength of discontinuities, which is a key parameter that controls the stability of rock slopes, is often difficult to ascertain and has to be modeled as a random variable. A proper statistical characterization of this random variable often requires testing of a large number of samples extracted from a wide range of sites that contain the same roughness profile of the rock discontinuities in question. However, budgetary constraints for site investigation and field and laboratory tests often limit the amount of data available to an engineer. Thus, uncertainty is often inherent in the derived statistical parameters of rock properties because of a small sample size and imperfect knowledge. Unfortunately, traditional reliability-based designs are usually sensitive to the estimated variation of shear strength properties. As such, an initially acceptable reliability-based design may not satisfy the target reliability index or failure probability requirement if the variation of the rock properties is underestimated. The proposed reliability-based Robust Geotechnical Design (RGD) approach presented herein is aimed at addressing this dilemma by considering robustness *explicitly* in the design process. In the context of rock slope design, the proposed approach is aimed at making the response (i.e., failure probability) of a geotechnical system insensitive to, or robust against, the variation of noise factors (i.e., rock properties and their statistical characterization). Here, the design robustness is achieved by adjusting design parameters (i.e., slope angle and height, and protection measures) that can be controlled by the engineer.

The robust design concept was first proposed by Taguchi (1986) for improving product quality and reliability in industrial engineering, the early applications of which are closely related to the product design to avoid the effect of the uncertainty from environmental and operating conditions. More recent applications are found in various fields such as mechanical design, structural design, and aeronautical design (e.g., Chen et al., 1996; Chen and Lewis, 1999; Sandgren and Cameron, 2002; Lagaros and Papadrakakis, 2007; Jamali et al.,

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0013-7952/$ – see front matter
http://dx.doi.org/10.1016/j.enggeo.2012.12.004

2010). Robust design methodology differs from the traditional design approaches primarily in the treatment of variation in the system response caused by noise factors.

In the proposed RGD framework, the computed failure probability of rock slope is modeled as the response of the system. The variation in the computed failure probability caused by the uncertainty in the estimated variation of rock properties is evaluated using statistical methods. The robustness for reliability-based design is achieved if the variation of the failure probability (i.e., the system response) can be minimized by manipulating design parameters of the rock slope. However, higher design robustness is often achieved at a higher cost. Thus, a multi-objective optimization considering cost and robustness is needed to select the optimal designs among those in the acceptable design space.

Multi-objective optimization does not usually produce a single best design with respect to all design objectives. Rather, the result is often expressed in a “Pareto Front” (Ghosh and Dehuri, 2004), which is a set of optimal designs that are “non-dominated” (Deb et al., 2002) by any other designs in all aspects. In our case, the points on the Pareto Front collectively express a trade-off relationship between robustness and cost. Thus, the Pareto Front may be used as a design aid for selecting the best design considering the desired cost range and/or target level of design robustness.

To illustrate the proposed RGD approach and its significance, the authors studied the Sau Mau Ping rock slope in Hong Kong, which is composed of unweathered granite with sheet joints (Hoek, 2006). By conducting and comparing reliability-based designs, both with and without consideration of robustness, the authors demonstrated the significance of the RGD approach.

2. Framework for reliability-based Robust Geotechnical Design (RGD)

The authors propose a methodology for the reliability-based robust geotechnical design (RGD) of a rock slope, which is a modification of the authors' recent work (Juang et al., 2012; Juang and Wang, 2013). In reference to Fig. 1, this design methodology consists of five steps:

(1) Establish the deterministic computational model for stability analysis of rock slope.
In a deterministic stability analysis of rock slope, design methods are often selected based upon the design situation

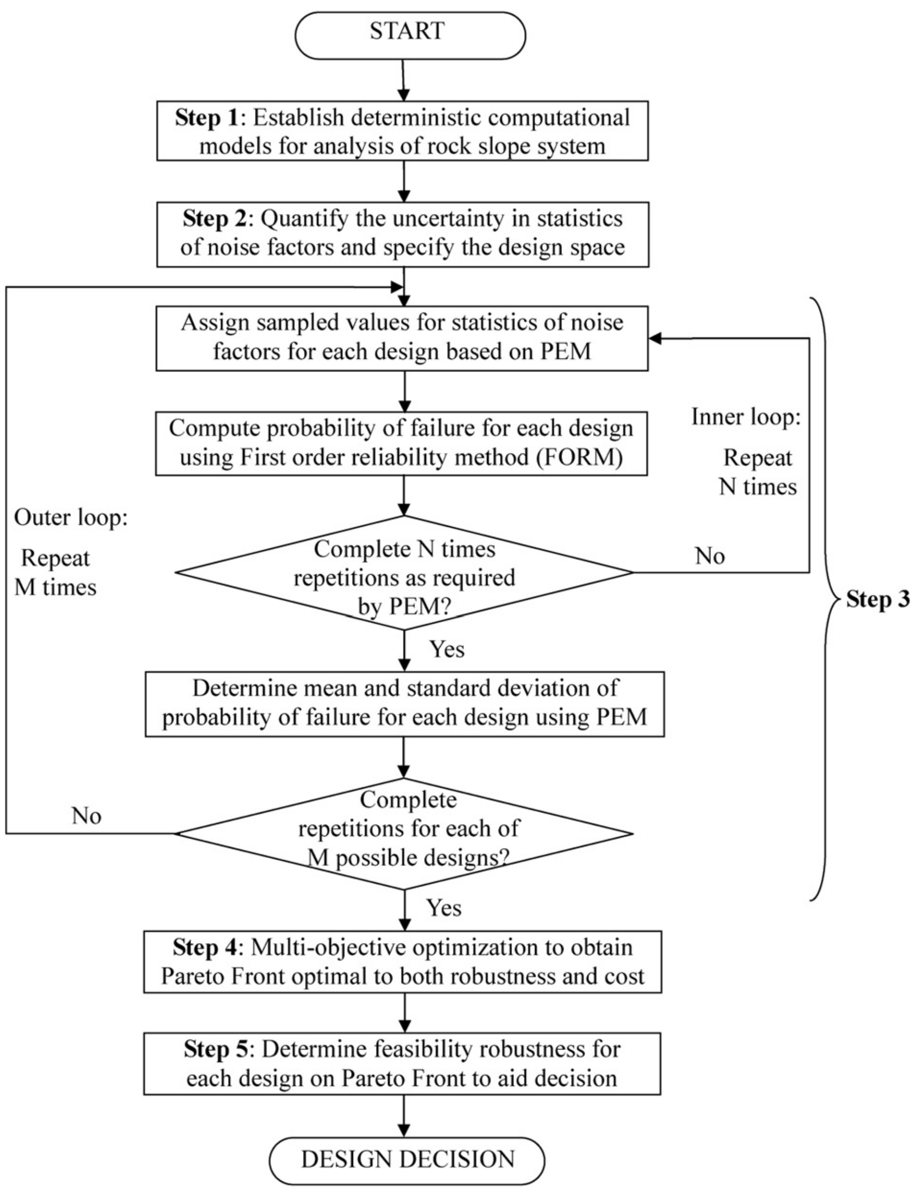

Fig. 1. Flowchart illustrating reliability-based robust geotechnical design of rock slopes (modified after Juang and Wang, 2013).