Available online at www.sciencedirect.com
SCIENCE DIRECT®
Engineering Geology 83 (2006) 217–235
ENGINEERING GEOLOGY
www.elsevier.com/locate/enggeo

Developments in the characterization of complex rock slope deformation and failure using numerical modelling techniques

D. Stead [a,*], E. Eberhardt [b], J.S. Coggan [c]

[a] Department of Earth Sciences, Simon Fraser University, Burnaby, BC, Canada
[b] Geological Engineering/Earth and Ocean Sciences, University of British Columbia, Vancouver, BC, Canada
[c] Camborne School of Mines, University of Exeter in Cornwall, Penryn, Cornwall, U.K.

Accepted 24 June 2005
Available online 10 November 2005

Abstract

Recent advances in the characterization of complex rock slope deformation and failure using numerical techniques have demonstrated significant potential for furthering our understanding of both the mechanisms/processes involved and the associated risk. This paper illustrates how rock slope analyses may be undertaken using three levels of sophistication. Level I analyses include the conventional application of kinematic and limit equilibrium techniques with modifications to include probabilistic techniques, coupling of groundwater simulations and simplistic treatment of intact fracture and plastic yield. Such analyses are primarily suited to simple translational failures involving release on smooth basal, rear and lateral surfaces where the principle active damage mechanisms are progressive failure and/or asperity breakdown. Level II analyses involve the use of continuum and discontinuum numerical methods. In addition to simple translation, Level II techniques can be applied to complex translational rock slope deformations where step-path failure necessitates degradation and failure of intact rock bridges along basal, rear and lateral release surfaces. Active damage processes in this case comprise not only strength degradation along the release surface (e.g., asperity breakdown) but also a significant component of brittle intact rock fracture. Level III analyses involve the use of hybrid continuum–discontinuum codes with fracture simulation capabilities. These codes are applicable to a wide spectrum of rock slope failure modes, but are particularly well suited to complex translation/rotational instabilities where failure requires internal yielding, brittle fracturing and shearing (in addition to strength degradation along release surfaces). Through a series of rock slope analyses the application of varied numerical methods are discussed. Particular emphasis is given to state-of-the-art developments and potential use of Level III hybrid techniques.

Keywords: Rock slopes; Numerical modelling; Continuum; Discontinuum; Hybrid techniques; Brittle fracture damage

1. Introduction

Numerical modelling of rock slopes is now used routinely in the civil and mining engineering sectors as well as in academic research. Given the wide scope of numerical applications available today, it is essential for the engineer and geoscientist to fully understand the varying strengths and limitations inherent in each of the different methodologies. The use of limit equilibrium methods still remains the most common adopted solution method in surface rock engineering although in many cases, major rock slope instabilities often involve complex internal deformation and fracturing bearing little resemblance to the 2-D/3-D rigid block assump-

* Corresponding author.
E-mail address: dstead@sfu.ca (D. Stead).

0013-7952/$ - see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.enggeo.2005.06.033

tions adopted in most limit equilibrium back-analyses. Initiation or trigger mechanisms may involve sliding movements that can, in the most idealized of cases, be analyzed as a limit equilibrium problem. The processes leading up to this initial slip are however invariably far more complex than a simple balance of disturbing and resisting forces.

In recognition of the controlling influence jointing has on complex rock slope deformation, numerical discontinuum techniques are being increasingly used in practice. It must be recognized however that conventional discontinuum models also have inherent limitations. Failure is frequently followed or preceded by creep, progressive deformation (fatigue damage processes), and extensive internal disruption of the slope mass (brittle/plastic damage). The factors controlling initiation and eventual sliding may be complex and are not easily allowed for in a simple static analysis. Addressing these challenges, the authors suggest that a new phase of slope stability analysis is warranted that utilizes recent advances in computing software and hardware development. In many cases, this may involve the combined use of limit equilibrium and numerical modelling techniques to maximize the advantages of both. As engineers are increasingly required to undertake landslide hazard appraisals and risk assessments, they must address both the consequence of slope failure and the hazard or probability of failure; a critical component of both is an understanding of the underlying processes/mechanisms driving the instability so that spatial and temporal probabilities of failure can be addressed. Limit equilibrium concepts alone cannot answer these questions. This paper will discuss and provide examples of the slope analysis tools that are available to the engineer, emphasising recent developments in numerical methods in the analysis of complex rock slope deformations.

2. Kinematic and limit equilibrium analysis of rock slopes

2.1. Conventional applications

Conventional rock slope analyses in current practice invariably begin with engineering geological investigations of the discontinuities, leading to kinematic and limit equilibrium stability assessments. Table 1, modified after Coggan et al. (1998), provides a summary of conventional methods, together with their advantages and limitations. Several commercial programs are available which may be used to assess rock slope stability using either daylight envelopes (e.g., Dips — Rocscience, 2004) or keyblock theory (e.g., SAFEX — Windsor and Thompson, 1993; Kblock — Pantechnica, 2001). These stereographic techniques can be used as input for deterministic or probabilistic limit equilibrium calculations to determine a factor of safety

Table 1
Conventional methods of analysis (modified after Coggan et al., 1998)

Analysis method	Critical input parameters	Advantages	Limitations
Stereographic and kinematic	Critical slope and discontinuity geometry; representative shear strength characteristics.	Simple to use and show failure potential. Some methods allow analysis of critical key-blocks. Can be used with statistical techniques to indicate probability of failure and associated volumes.	Suitable for preliminary design or for non-critical slopes, using mainly joint orientations. Identification of critical joints requires engineering judgement. Must be used with representative joint/discontinuity strength data.
Limit equilibrium	Representative geometry, material/joint shear strength, material unit weights, groundwater and external loading/support conditions.	Much software available for different failure modes (planar, circular, wedge, toppling, etc.). Mostly deterministic but some probabilistic analyses in 2-D and 3-D with multiple materials, reinforcement and groundwater profiles. Suitable for sensitivity analysis of FofS to most inputs.	FofS calculations must assume instability mechanisms and associated determinacy requirements. In situ stress, strains and intact material failure not considered. Simple probabilistic analyses may not allow for sample/data covariance.
Rockfall simulation	Representative slope geometry and surface condition. Rock block sizes, shapes, unit weights and coefficients of restitution.	Practical tool for siting structures and catch fences. Can utilize probabilistic analysis. 2-D and 3-D codes available.	Limited experience in use relative to empirical design charts.