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Review article

A critical review of rock slope failure mechanisms: The importance of structural geology

Doug Stead [a], Andrea Wolter [b, *]

[a] Simon Fraser University, 8888 University Dr., Burnaby, BC, Canada
[b] ETH Zurich, 5 Sonneggstrasse, Zurich, Switzerland

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ABSTRACT

Geological structures such as folds, faults, and discontinuities play a critical role in the stability and behaviour of both natural and engineered rock slopes. Although engineering geologists have long recognised the importance of structural geology in slopes, it remains a significant challenge to integrate structural geological mapping and theory into all stages of engineering projects. We emphasise the importance of structural geology to slope stability assessments, reviewing how structures control slope failure mechanisms, how engineering geologists measure structures and include them in slope stability analyses, and how numerical simulations of slopes incorporate geological structures and processes.

1. Introduction

Our understanding of rock slope failure mechanisms has increased considerably during the last decade in response to continued development of urban populations in mountainous areas and to the challenges faced by engineers and geoscientists in the exploitation of large open pit mines. Design in such large-scale rock masses necessitates consideration of structural geology from the micro-scale to the regional tectonic scale. In this paper, we critically review rock slope failure mechanisms with an emphasis on how knowledge of the structural geological environment influences all stages in the slope characterisation or design process. We discuss the impacts of broad structural feature types on rock slopes, highlighting important aspects using relevant case studies. We then summarise how structures are characterised in engineering geological projects, and finally review how structural geology is incorporated into numerical modelling of slopes, a useful technique in slope design. Our objective is to demonstrate the critical role of structural features and processes in controlling rock slope stability and failure type, style, and mechanism.

* Corresponding author.
E-mail addresses: dstead@sfu.ca (D. Stead), awolter@ethz.ch (A. Wolter).

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2. Effects of structural geology on rock slope stability

Structural features, such as folds, faults, and discontinuities, control rock mass (i.e., intact rock dissected by discontinuities) behaviour and contribute to either the stabilisation or destabilisation of rock slopes, depending on their orientations and the intensity of associated tectonic damage. Glastonbury and Fell (2000) demonstrated how the geometry and composition of a rock slope and its structures determine the potential mechanism of a landslide, ranging from translational to complex multi-mechanism failure (Fig. 1 and Fig. 2). Stead et al. (2006) referred to the importance of structure in determining the complexity of failure mechanisms. In this section, we review the importance of tectonic environment and damage and common brittle and ductile structures related broadly to lithology, with examples drawn from the published rock slope literature. Table 1 summarises the structural and lithological features of the cited case studies and additional examples. Specific structural features are discussed in relation to each lithological rock type; however, this does not imply they are exclusive to that lithology.

2.1. Tectonic environment and damage

The tectonic environment and history, or inheritance, of a given slope can determine if and how it fails; *in situ* stress conditions are

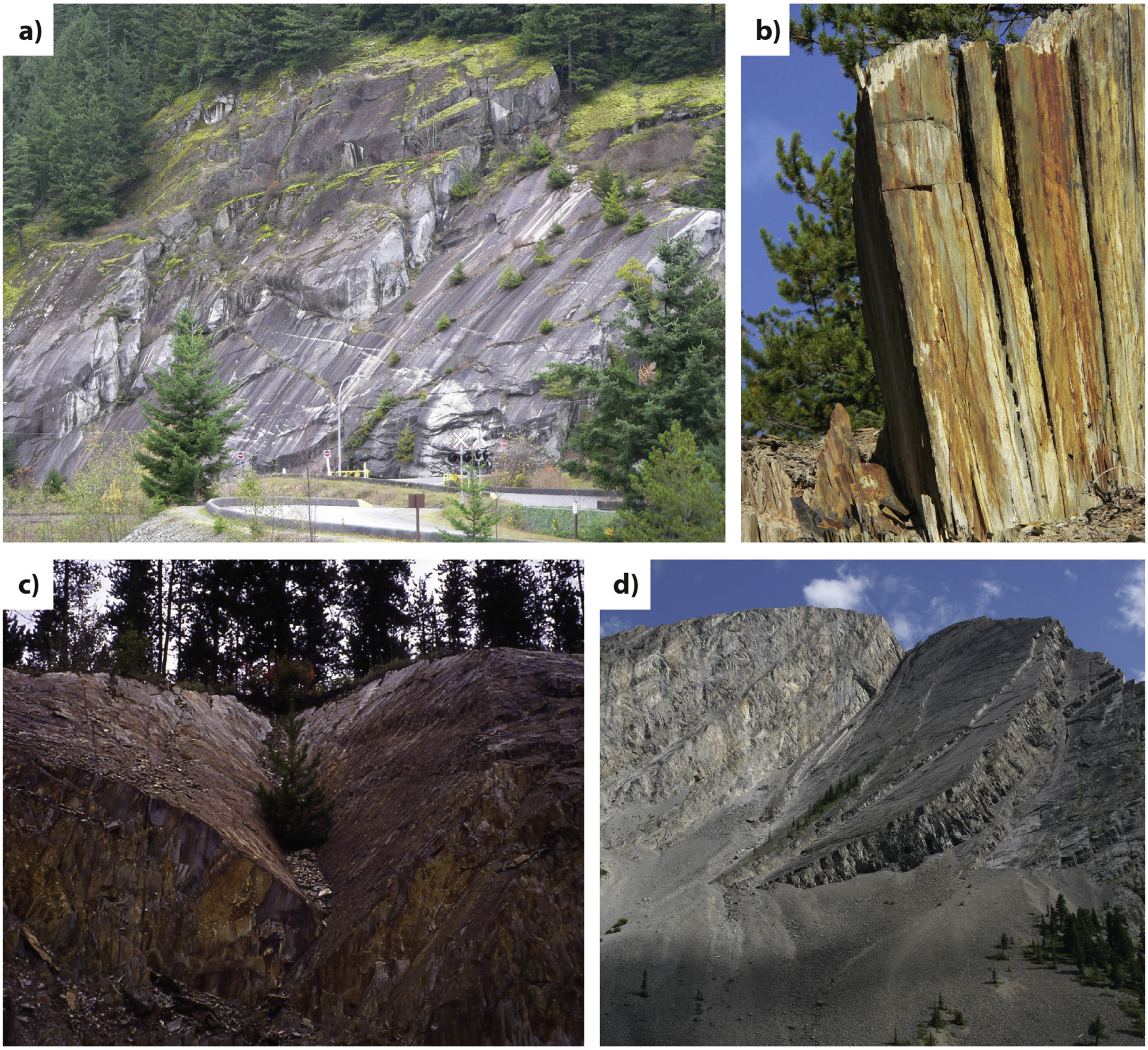

Fig. 1. Key rock failure modes considered in slope stability analysis: a) planar/translational sliding, b) toppling, and c) wedge sliding. d) Multi-planar translational failure (Palliser rockslide), demonstrating the complexity slope engineers may encounter.

important to consider when assessing rock mass behaviour. Hoek et al. (2009) discussed the role of *in situ* stresses in influencing the design of large open pits. They demonstrated numerically that *in situ* stresses are typically not significant as compared to uncertainties related to the geological model, strength and deformation properties, and groundwater pressures within the rock masses of a given pit slope. Thus, gravitational stress usually dominates slope stability in open pits. The exception is in areas of high horizontal stress (compressional regime), where stresses can influence open pit performance and should be considered. Kinakin and Stead (2005) demonstrated the importance of *in situ* stress conditions in the formation of sackung-type slope failures (or Deep-Seated Gravitational Slope Deformations (DSGSDs)). Also investigating natural slopes, Ambrosi and Crosta (2011) emphasised the interaction between geomorphological processes and *in situ* stress conditions and slope geometry. They demonstrated that these factors influence slope failure type and behaviour. The World Stress Map (Zoback, 1992) is a useful tool in assessing general *in situ* stress conditions.

Past and present seismicity is also important to slope stability. Not only does each earthquake have the capability of triggering slope failures, but the cumulative effect of regional seismicity may also damage and weaken slopes. Moore et al. (2011), for example, illustrated the production of slope amplification effects at the 1991 Randa instability in Switzerland due to seismicity. Damjanac et al. (2013) discussed the simulated stability of large open pits in relation to seismic activity and showed that open pits are less susceptible to seismically induced failure than natural slopes. Brian et al. (2014) examined the role of microseismicity in producing fatigue and damage in slopes, concluding that microseismic