

## **Modelling the Effects of Joints on Slope Behaviour with Finite Element Analysis**

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### **ABSTRACT**

The strength and deformation modulus, and the accompanying responses to loading, of rock masses, as well as the stability of excavations, especially in low stress environments, are significantly affected by joints. Due to their generally brittle (strain softening) stress-strain behaviour, joints can cause significant departures from stress distributions predicted by elastic or elasto-plastic analysis of homogeneous continua. They play a principal role in progressive failure.

One approach of incorporating the influence of joints on rock mass strength in numerical analysis is through specification of reduced deformation and strength properties. Although the concept is straightforward and simplifies analysis, establishment of the equivalent reduced properties is not so easy. As well the approach has the drawback of eliminating the effects of excavation size relative to jointing density (spacing). For example, when the size (height) of a slope is quite large compared to joint spacing, the failure mode tends to be rotational – the failure mechanism characteristic of continua. However, if the rock mass joint spacing is wide relative to the slope height, failure surfaces are controlled by the joints.

The second approach of accounting for joint influence in a numerical analysis is to model a rock mass as an aggregate of discontinuities and intact material. Explicit representation of joints allows for the simulation of more generalized rock mass behaviour. For example, it accounts for scale effects. Just as important, it more realistically captures the broad range of behaviours caused by interactions between the different moduli and strengths of intact rock, joints and support.

In the opinion of the authors, in order to apply the second approach through the most versatile numerical analysis method, the finite element method (FEM), two primary techniques were required:

- i) A method for simulating the stress-strain behaviour of joints, and
- ii) An approach for automatically generating joint sets

Specialized joint elements for the FEM were first formulated in the late 1960s, while routines for generating joint sets that fit certain statistical patterns were developed in the 1970s. For the modelling of rock slopes, a third important tool was required: a technique that enabled the FEM to be applied to the determination of the stability of slopes. The basics of the shear strength reduction (SSR) method, which allows this end to be attained, were laid down in the mid to late 1960s.

Although all these foundation blocks were laid decades ago, it is only recently that computing advances have allowed the FEM to be used for practical rock slope analysis. In this paper, the authors will demonstrate the capabilities of modern FEM programs, which combine automatic generation of joint sets, joint elements and SSR analysis, in solving a broad range of rock slope stability problems.

The problems covered in the paper will vary from those controlled wholly by sliding along discontinuities to those involving the rotational failure mechanisms commonly encountered in soils (continua). Through these examples, the authors will show how the FEM captures the change in failure mechanisms with slope scale. They will also demonstrate how different combinations of joint and intact rock strength and deformation characteristics result in different failure mechanisms. The critical failure mechanisms determined by the FEM will include stepped (en-echelon) failure paths that combine slip along joints with shearing through intact rock.

The paper will underline the greatest benefit of FEM analysis—generality at highly reasonable computational cost. Unlike limit equilibrium methods which require *a priori* specification of failure modes, FEM analysis with explicit representation of joints can uncover several failure modes without special assumptions or treatment.