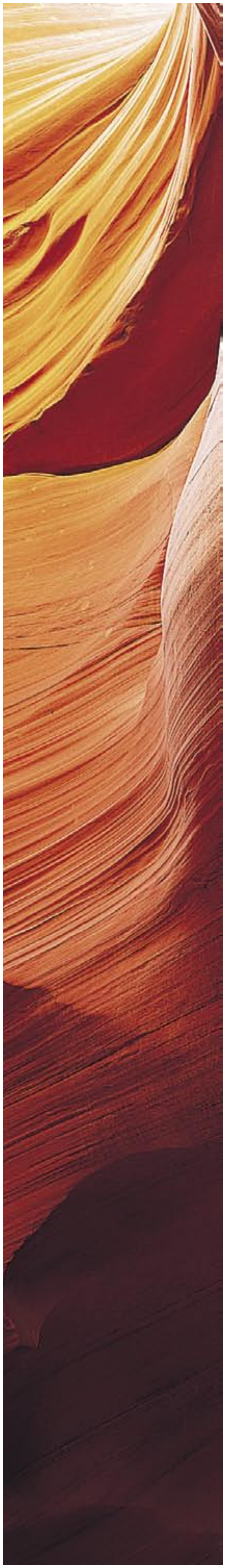


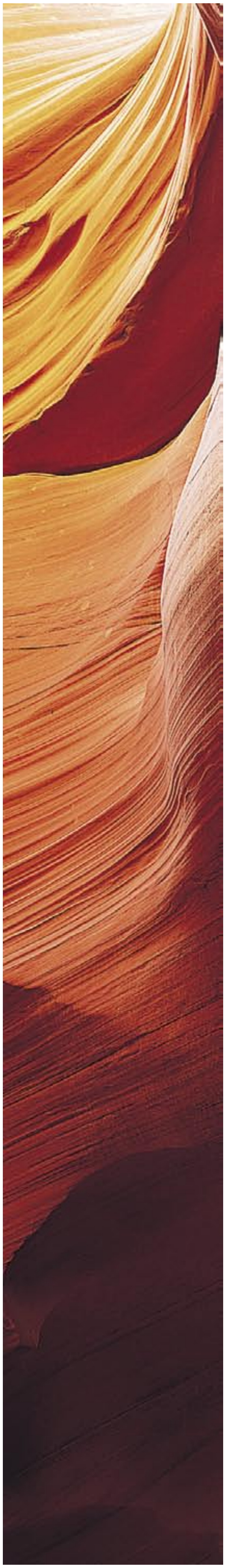
Ready for Prime Time:

Slope Stability Analysis with the Shear Strength Reduction Method

We believe that the SSR method, facilitated by its implementation in software, is ready for prime time, the point at which it can be applied to the practical, routine analysis of slopes. This article provides reasons why this is so, as well as providing practical guidelines for SSR modelling.

Prime time generally refers to the evening hours between 7 and 11 p.m. when the largest audience watches television. Because of what stands to be gained, TV networks fiercely compete for the attention of these viewers. Advertising during this period is powerful. A well executed ad can create positive brand recognition while a bad ad will turn customers off. Networks and advertisers go to great lengths to ensure that shows and ads stand up to the scrutiny of discerning buyers, and it's in this sense that we believe the Shear Strength Reduction (SSR) method of slope stability analysis is ready for prime time: it will stand up to the scrutiny of the discerning geotechnical audience, and is therefore ready for routine slope analysis.

Due to its ability to realistically model a very broad range of problems, the Finite Element Method (FEM) has become tremendously popular since it was first applied to geotechnical engineering in 1966. For various reasons that will be outlined in this article, its primary application in geotechnical engineering, though, had been restricted to stress and deformation analysis of excavations and support. Recent refinements to the SSR method, and advances in computing technology have now altered this landscape.



Brief Description of SSR

The central concept of the SSR method is very simple. Similar to limit-equilibrium analysis, it involves successive reductions (by some factors) in the shear strengths of slope materials until failure occurs. Failure is indicated when the finite element model does not converge to a solution, because equilibrium cannot be maintained. The critical factor at which failure occurs is taken to be the factor of safety.

Recent Advances in the SSR Method

In the past, a number of factors limited application of the SSR technique for routine slope stability analysis. These included:

- Lengthy modelling, compute, and results analysis times
- Lack of automated tools for performing the successive changes to shear strength
- A perceived hunger for material input data, which were not collected in routine site investigations, at least not with reasonable accuracy
- Restriction to linear material strength (Mohr-Coulomb model), and
- Unproven reliability of SSR results

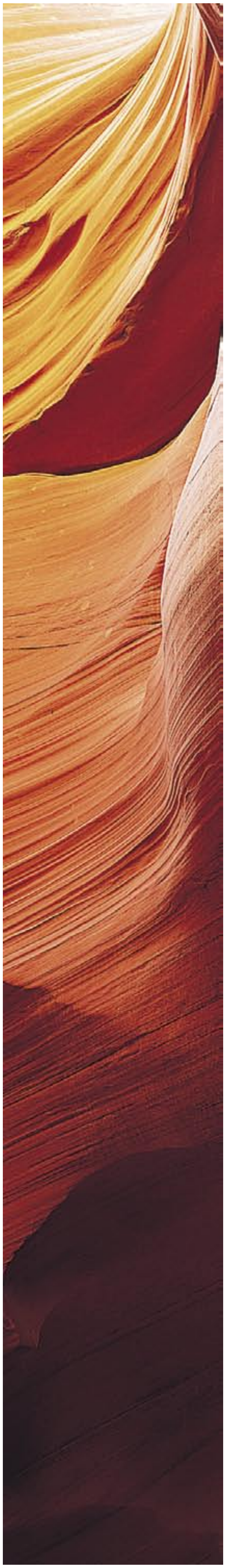
As was discussed in an article in the Summer 2004 issue of RocNews,

> *Will Finite Elements Replace Limit-Equilibrium in Slope Design?*

powerful programs, which enable routine geotechnical finite element analysis, are available today. *Phase*^{2}, Rocscience's two-dimensional FEM program, is a leader in this market. The program significantly reduces the amount of time required to build, compute and interpret models.

Version 6 of *Phase*^{2} highly automates the SSR procedure for calculating a factor of safety. In some cases, it is even easier to use than conventional limit-equilibrium analysis. In addition, the new *Phase*^{2} can read *Slide* (Rocscience's limit-equilibrium slope stability program) files, and automatically convert them into fully meshed, finite element equivalents. The version includes algorithms, which make it possible to perform SSR analysis for non-linear material strength models, a capability missing in practically all the other competing products. For more detail, see the article:

> *Stability Analysis of Rock Slopes using the Finite Element Method*



The previous article explained that the additional data required for the SSR method is routinely collected for other forms of geotechnical analysis. As a result the need for additional data does not overly complicate finite element slope stability analysis.

The Summer 2004 RocNews article also addressed the question of the reliability of SSR results, and listed references, which report good agreement between SSR and limit-equilibrium results. To further increase confidence in the SSR technique, we tested the method on 33 benchmark slope examples. These cases, which cover a broad range of material and slope behaviours, have been used to verify the results of slope stability programs, including *Slide*.

The results of our study were published in a paper,

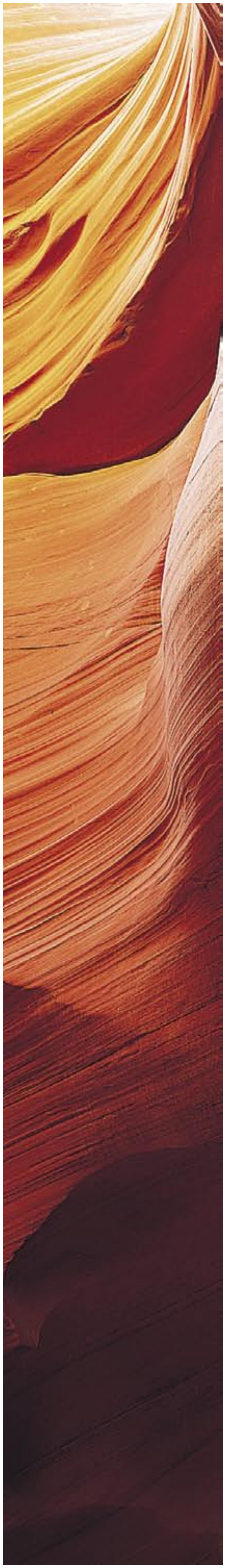
> *A Comparison of Finite Element Slope Stability Analysis with Conventional Limit-Equilibrium Investigation*

presented at the recently concluded 58th conference of the Canadian Geotechnical Society (CGS) in Saskatoon. The study confirmed what had been previously reported; in all the cases, the SSR gave answers that agreed very well with limit-equilibrium results.

Guidelines for SSR Modelling

In the course of verifying the reliability of the SSR method, we studied various aspects of finite element slope stability analysis and compiled a set of modelling guidelines. These guidelines are especially useful, since FEM slope stability analysis is still new to many geotechnical engineers, and generally requires more modelling know-how than limit-equilibrium analysis.

We studied the impact of Young's modulus, Poisson's ratio, and dilation angle on computed factor of safety values. Because the SSR factor of safety is determined based on the occurrence of non-convergence, aspects of finite element modelling such as stopping rules (convergence criteria), number of iterations and tolerance, which influence solution convergence, were also investigated. Although the compiled set of guidelines is by no means an exhaustive list of how to perform SSR analysis, it is still very helpful to both experienced users and novices.



The rules of thumb for replicating limit-equilibrium slope analysis with the SSR method can be summarized as follows:

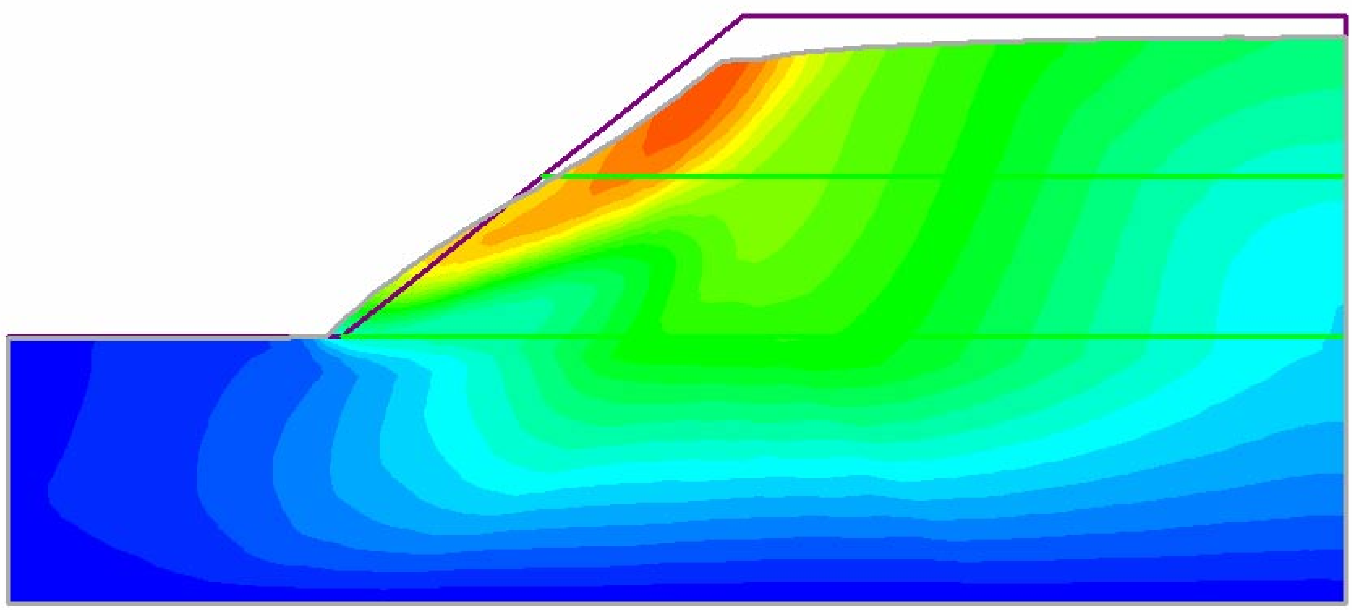
- Assume a single Young's modulus and a single Poisson's ratio for slope materials
- Assume a zero dilation angle
- Assign all materials elastic-perfectly plastic behaviour
- Use six-noded triangular or other higher-order elements. For a given number of nodes higher-order elements are generally more efficient (produce results that are closer to the 'true' solution)
- Begin with smaller number of elements. Refine model (increase number of elements) once you've obtained a good handle on a slope problem, and
- Check the sensitivity of results to number of elements

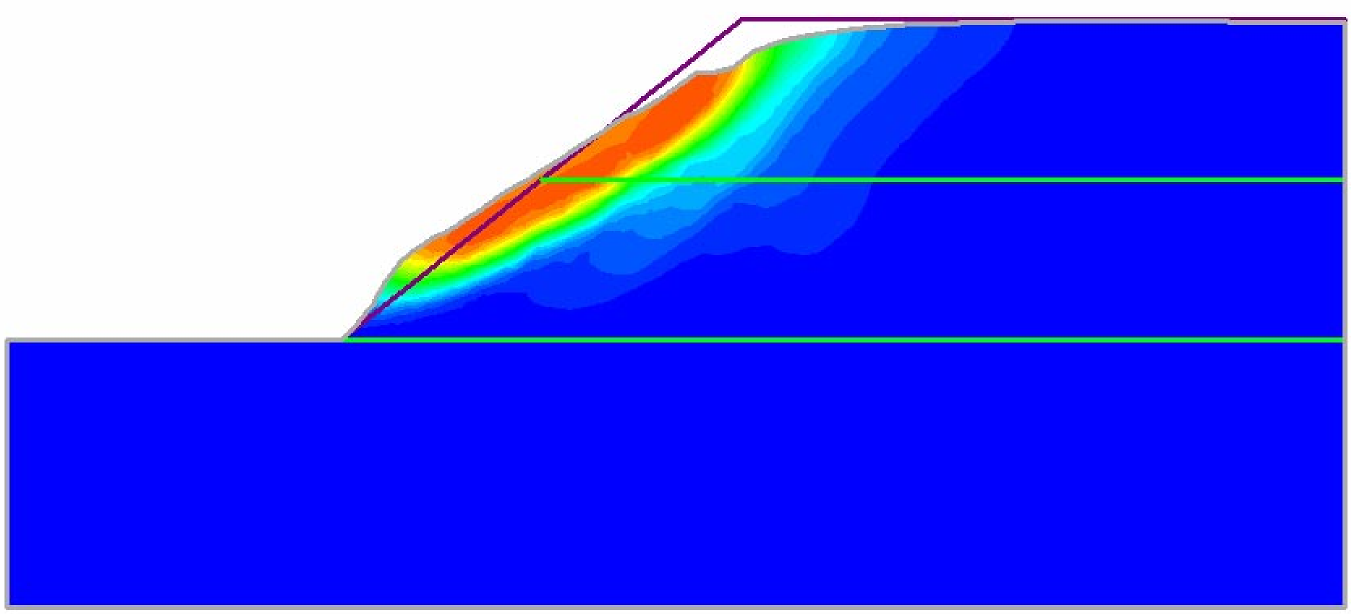
We would like to note that the deformation parameters (Young's modulus, Poission's ratio and dilation angle) influence the magnitudes of computed deformations. If deformations at failure are therefore required in addition to factor of safety values, then effort must be made to specify the right estimates of these properties.

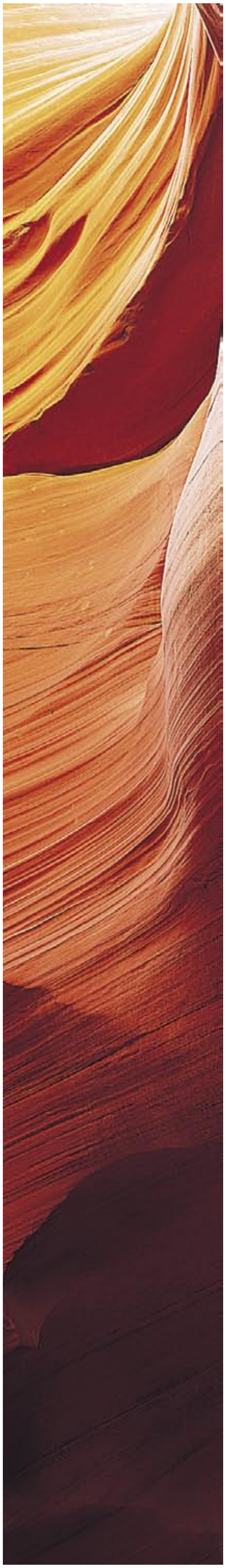
In addition, for multiple material slope models the ratios of the different Young's moduli can affect deformation patterns. In some instances different stiffness ratios can produce failure mechanisms that differ from limit equilibrium solutions. The images on the following page show the different shear deformation contours at failure that arise in a slope for two different sets of Young's moduli for the material layers. Although the factor of safety values are very similar for the two cases, the failure mechanisms differ.

This has implications for the design (location and capacity) of support or other remedial measures for multiple material slopes. For example, if support deformations are required, then it is important to assign adequate estimates of Young's moduli and Poisson's ratios.

These contours of maximum shear strain indicate two different failure mechanisms for a multi-material slope. The difference in failure mode is caused by changing the Young's moduli of the material layers.







Prime Time Ready

We believe that SSR technology has improved to the point where it is ready for prime time use, the practical, routine analysis of slopes. As has been reported by others and as confirmed by our tests on several slope cases, the SSR method produces reliable and consistent results over a wide range of slope problems. It matches powerful limit-equilibrium features such as the ability to model non-linear strength, and accommodate multiple slope materials and support types. In programs like *Phase*^{2}, the SSR has been automated to the same levels as those found in premier slope stability programs.

The SSR enjoys several advantages over conventional limit-equilibrium analysis. Among many desirable attributes, SSR slope analysis can produce insights into failure mechanisms, and their formation, in ways that may not be as evident in limit-equilibrium analysis. SSR analysis can better model the behaviour of support elements, the interactions caused by the relative stiffnesses of slope materials and support elements, and can indicate deformations at failure.

The SSR method has been found to work in cases in which limit-equilibrium analysis either produces misleading results or does not work well. One such example involves analysis of the stability of slopes in which excavations such as tunnels and caverns have been made. Whereas limit-equilibrium methods, due to their inability to model stress-strain behaviour, encounter difficulties on such problems, the SSR method smoothly analyzes these cases.

We advocate for greater use of the SSR, since it powerfully complements conventional limit-equilibrium analysis. The tools for performing such slope analysis are available. Why not use them?

We encourage readers to send their comments and views on this topic to RocNews Feedback.