# Slope stability analysis with *FLAC* and limit equilibrium methods

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ABSTRACT: The factor of safety for slopes (FS) has been traditionally evaluated using two-dimensional limit equilibrium methods (LEM). However the FS of a slope can also be computed with *FLAC* by reducing the soil shear strength in stages until the slope fails. This method is called the shear strength reduction technique (SSR). Many authors have pointed out several advantages of SSR over the limit equilibrium methods. But usually they checked the effectiveness of SSR on rather small models of simple geometry. In this study, the accuracy of the SSR was investigated through comparisons with limit analysis solutions. FS estimated by SSR was compared with FS obtained from Fellenius, Bishop, Morgenstern-Price and Janbu.

## 1 INTRODUCTION

The stability of slopes is traditionally estimated using 2D limit equilibrium methods (LEM). However these methods have several disadvantages and may neglect some important factors. Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability engineering. Finite Element Method (FEM) and Finite Difference Method (FDM) are very often used for that purpose.

The factor of safety (FS) for slope may be computed by reducing shear strength of rock or soil in stages until the slope fails. This method is called shear strength reduction technique (SSR).

*FLAC* code is often applied for estimating FS for rock slopes (Song & Han 1999, Sjöberg 1999a,b) or even foliated rock slopes (Pant & Adhikary 1999). It is also applied in evaluating stability of soft rock slope perforated by underground openings (Steward et al. 1996). *FLAC* is also widely used for analyzing stability of soil slopes (Zettler et al. 1999, Dawson & Roth 1999, Cala & Flisiak 2000). Sometimes *FLAC* is even used for slope stability engineering in combination with other methods. Thompson (1993), Babu & Bijoy (1999) show examples of the application of *FLAC* combined with LEM. Wang et al. (2000) present possibilities of using *FLAC* with Monte Carlo method.

SSR technique is often used with FEM to solve quite sophisticated problems such as estimating stability of slope reinforces by piles (Cai & Ugai 2000, Ng et al. 2000) or slope with horizontal drains (Cai & Ugai 1999). A good overview of FEM application for slope stability engineering may be found in Fredlund & Scoular (1999).

Advantages and disadvantages of SSR and LEM are presented in Jiang & Magnan (1997), Griffiths & Lane (1999). The majority of investigators prefer using FEM or FDM for estimation of FS for slopes. Griffiths & Lane (1997) even asked in the title of the paper "Why are engineers still drawing circles?"

However the majority of engineers still prefer using LEM mainly due to its simplicity, tradition of application and low price of available codes.

## 2 STABILITY OF SIMPLE GEOMETRY SLOPES

### 2.1 *FS and elastic properties of material*

To check the influence of elastic properties (Young's modulus = E, Poison's ratio = ν) more than 100 numerical simulations for the homogeneous and isotropic slopes were performed. The values of E were changed from 25 MPa to 1000 MPa and ν from 0.1 to 0.4. All the slopes in this paper were simulated with *FLAC* in plane strain, using small-strain mode.

It was found that although the elastic properties have a significant influence on the computed deformations prior to failure, they negligibly influenced FS. The difference in FS was below 1 %. This confirms conclusions of Griffiths & Lane (1999) – they even recommended using nominal values of E = 100 MPa and ν = 0.3 for slope stability analysis with SSR. After preliminary calculations it seems that this statement is also valid for heterogeneous slopes.

## 2.2 *Comparison of SSR and LEM for simple geometry slopes*

### 2.2.1 *Simple, homogeneous slope*

To compare SSR and LEM mode than 200 numerical simulations for the isotropic and homogeneous slopes were carried out. Embankments were simulated with slope angles (α) ranging from 18.43° (1:3) to 63.43° (2:1). The height of the embankment was changed from 15 m to 35 m. The soil was given values of angle of internal friction (ϕ) ranging from 10° to 30° and cohesion (c) from 25 kPa to 75 kPa. Figure 1 shows FS calculated with SSR are within few percent of the FS obtained from LEM.

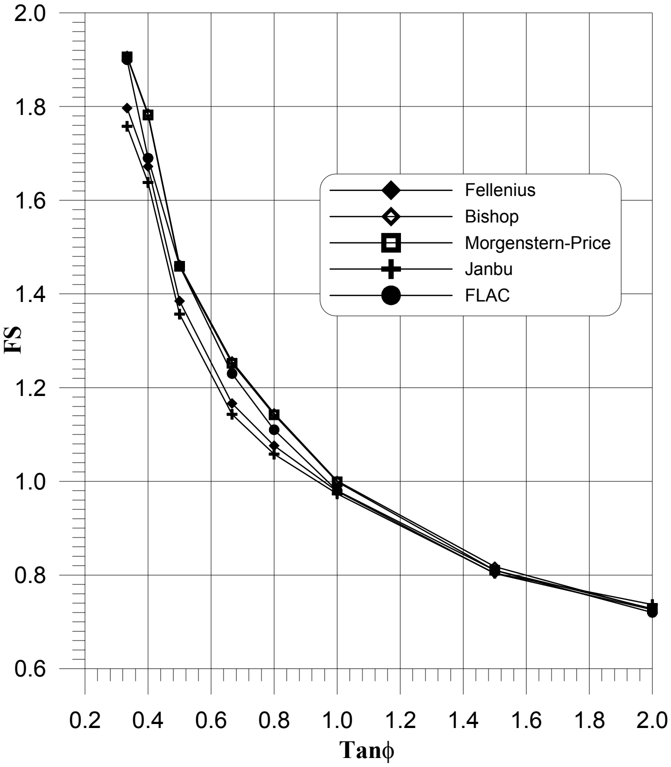

Figure 1. FS for embankment of height 25 m, friction angle $\phi = 20^o$, cohesion c = 30 kPa for several sloping angles with SSR and LEM.

### 2.2.2 *Slope consisting of two geological units*

The next task was to compare FS from SSR and LEM for a slope consisting of two different geological units. The soil below the embankment (foundation layer) was given friction angle $\phi = 10°$ and cohesion c = 0. The stability embankment of height 25 m, friction angle $\phi = 20°$ and cohesion c = 30 kPa for several sloping angles was analyzed.

Figure 2 shows FS calculated with SSR are within a few percent of the FS obtained from LEM for sloping angles from 18.43° to about 41°. For sloping angles from 41° to 64.43° FS calculated with SSR are even 20% lower than FS from LEM. This may be explained by the fact that slip surfaces obtained from SSR are localized deeper than slip surfaces from LEM. That may suggest that the complex geology of the slope has a significant influence on the value of FS predicted by LEM and SSR. Two different cases were studied to verify this hypothesis.

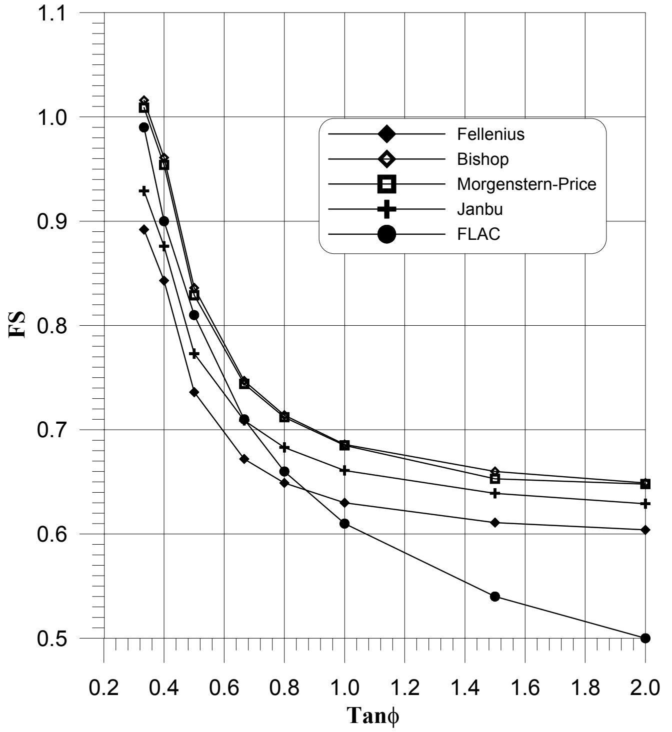

Figure 2. FS for embankment of height 25 m consisting of two geological units for several sloping angles with SSR and LEM

## 3 SMALL SCALE COMPLEX GEOLOGY SLOPE

The slope consisted of six different geological units. The mechanical properties of the soil units involved in the slope are given in Table 1. Figure 3 shows the geometry of slope and its geology after failure.

Table 1. Mechanical properties of soil units.

| Unit Number | c kPa | ϕ degrees |
|---|---|---|
| 1 | 8 | 9 |
| 2 | 15 | 14 |
| 3 | 16 | 15 |
| 4 | 5 | 6 |
| 5 | 0 | 37 |
| 6 | 50 | 11 |

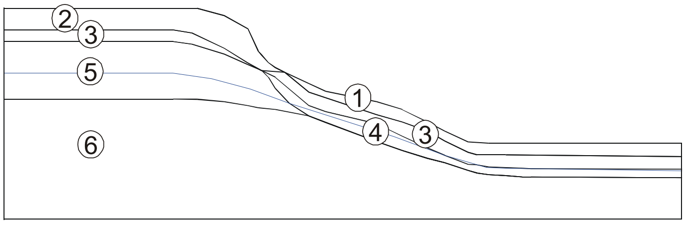

Figure 3. Geometry and geology of the slope after failure.

To investigate the effectiveness of SSR and LEM both methods were applied for predicting slope stability for initial geometry of the slope. The overall size of the grid was 40 m in length by 20 m in height. The overall sloping angle was equal $\alpha = 26.16°$. The vertical planes were fixed in the horizontal direction by applying a zero constant velocity. The model base was fixed in both directions assuming that displacements were insignificant deep beneath the slope. The water table was modeled by increasing density of saturated rock mass.

Figure 4 presents the slip surface identified by SSR and LEM. The critical slip surfaces identified with *FLAC* and LEM (Bishop method) are almost the same. The differences in FS calculated with SSR and LEM are negligible.

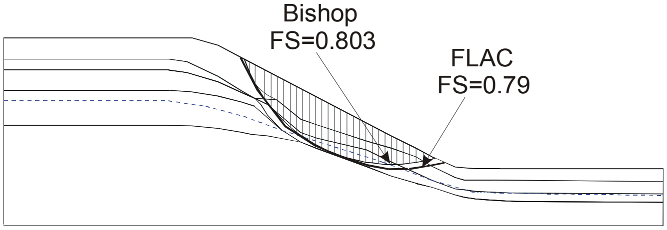

Figure 4. FS and critical slip surfaces for slope of height 10 m consisted of six geological units with SSR and LEM.

## 4 LARGE SCALE COMPLEX GEOLOGY SLOPE (BENCH EXCAVATION)

The slope consisted of seven different geological units (from a Polish lignite open pit mine). The mechanical properties of the soil units involved in the slope are given in Table 2.

Table 2. Mechanical properties of soil units.

| Unit number | c kPa | $\phi$ degrees |
|---|---|---|
| 1 | 38.2 | 9.3 |
| 2 | 112.0 | 18.1 |
| 3 | 154.7 | 33.0 |
| 4 | 154.7 | 33.0 |
| 5 | 59.4 | 16.29 |
| 6 | 60.0 | 0.0 |
| 7 | 239.0 | 14.1 |

The overall size of the grid was 1500 m in length by 170 m in height (grid consisted of 164344 zones). The overall sloping angle was equal $\alpha = 10.38°$. The boundary conditions were the same as in the previous section.

Figure 3 presents the slip surface identified by SSR and LEM. LEM analysis showed that minimum FS was equal to 2.115 (Morgenstern-Price method). SSR analysis showed considerably (80%) lower FS (1.18). The location (Fig.1) of identified slip surface was completely different than that obtained from LEM (!). All critical slip surfaces identified with several LEM were located on the left side of the slope on its upper part. SSR identified critical slip surface located on the right side of the slope on its lower part. Why are the results so different?

*FLAC* identified the critical slip surface in the region with the sharpest sloping angle. One of the most important reasons for localizing SSR slip surface in the lower part of slope was the interaction with the upper part. This interaction forced movement of the soil down. Limiting of size of the numerical model only to the upper part of the slope probably would lead to FS values close to those obtained from LEM.

After discussing these results with the geotechnical engineers from the mine it turned out that they had experienced some slope stability problems in the region (Fig. 5) pointed out by *FLAC* (!). That seems to be quite a good reference for application of SSR for complex geometry problems.

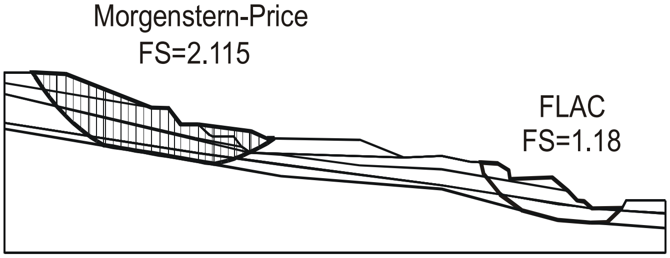

Figure 5. FS and critical slip surfaces for slope of height 170 m consisted of seven geological units with SSR and LEM.

## 5 CONCLUSIONS

It has to be taken under consideration that FS is a function of mechanical properties of rock or soil. The input data is the key factor for reliable FS analysis. An excellent and worth studying example of reliability analysis of FS for submerged slope is given by Duncan (2000).

SSR technique gives the opportunity to investigate very complex systems in order to get the value of FS without assuming a failure mode in advance. With the increasing speed of computers SSR technique seems to be a quite reasonable alternative to the LEM.

For a simple, homogeneous slope FS calculated with SSR are usually the same as FS obtained from LEM. In the case of a simple geometry slope consisting of two geological units, FS calculated with SSR may be considerably different than FS from LEM. On the other hand, for a simple geometry, small-scale slope consisting of six units, FS calculated with SSR is almost the same as FS from LEM.

It must also be stressed that *FLAC* proved to be an effective tool in analyzing the stability of complex geology slopes. In the case of bench excavation (slopes of complex geometry and geology) SSR technique is much more “sensitive” than LEM.

Application of SSR with *FLAC* may be recommended for the large-scale slopes of complex geometry.

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