Complex geology slope stability analysis by shear strength reduction

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ABSTRACT: The stability of slopes may be estimated using 2D limit equilibrium methods (LEM) or numerical methods. Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability engineering. A very popular numerical method of slope stability estimation is the shear strength reduction technique (SSR). It's a well known fact that for a simple slope factor of safety (FS) obtained from SSR is usually the same as FS obtained from LEM. However for slopes of complex geology, considerable differences between FS values may be expected. Application of SSR for such slopes is usually restricted to the weakest link estimation – that part of the slope with the lowest FS. Finite Difference Method code, *FLAC* (Itasca 2000), gives the opportunity to analyze several slip surfaces by using the modified SSR technique (MSSR). The method is based on reducing shear properties of soils after identification of the first slip surface. MSSR allows a complete estimation of stability for any type of slope.

1 INTRODUCTION

The stability of slopes may be estimated using 2D limit equilibrium methods (LEM) or numerical methods. Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability engineering. A very popular numerical method of slope stability estimation is shear strength reduction technique (SSR). In that procedure, the factor of safety (FS) of a soil slope is defined as the number by which the original shear strength parameters must be divided in order to bring the slope to the point of failure (Dawson & Roth 1999).

It's a well known fact that for simple slopes FS obtained from SSR is usually the same as FS obtained from LEM (Griffiths & Lane 1999 Cala & Flisiak 2001). However for complex geology slopes considerable differences between FS values from LEM and SSR may be expected (Cala & Flisiak 2001). Several analyses for the slope with weak stratum were performed to study the differences between LEM and SSR.

It must be also stated that classical SSR technique has several limitations. Application of SSR requires advanced numerical modeling skills. Calculation time, in case of complicated models, can last as long as several hours.

However, the most fundamental limitation of SSR is identification of only one failure surface (in some cases it may identify more than one surface, but with the same FS value). This is not a significant limitation in case of simple geometry slope. But in case with complex geometry (and geology) it's not possible to analyze FS for other parts of the slope. This may sometimes lead to serious mistakes.

2 STABILITY OF SLOPE WITH WEAK STRATUM

To investigate the influence of a weak stratum on FS some 350 models were analyzed. The thickness of the weak stratum was changed from 1.0 to 10.0 m and it was localized from 0 to 50 m from the top of the slope (Fig. 1).

All slopes in this paper were simulated with *FLAC/Slope* (Itasca 2002) or *FLAC* in plane strain, using small-strain mode.

It was assumed that embankment is 25 m high and has a slope angle of 45°. It consists of two different geological units. The soil was given friction angle $\phi = 30°$ and cohesion $c = 75$ kPa. The weak, thin layer had friction angle $\phi = 10°$ and cohesion $c = 25$ kPa. Both soils had unit weight $\gamma = 20$ kN/m^3.

The thickness “*g*” of the horizontal weak layer was changed from 1.0 m to 10.0 m and its distance “*h*” from the top of the slope changed from 0 to 50 m.

Figure 2 shows the FS values for a 1.0 m thick weak layer and figure 3 for a 5.0 thick one. The decrease of FS is quite small if the thin weak layer is located close to the top of the slope.

Increasing the weak layer thickness produces considerable decrease of FS. The differences in FS values are significant especially in case of small thickness (1 m – 3 m) of weak stratum

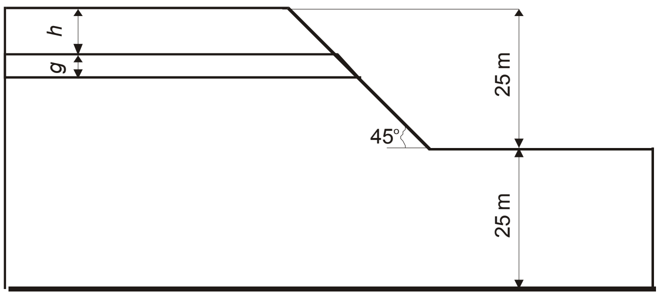

Figure 1. Slope with weak stratum.

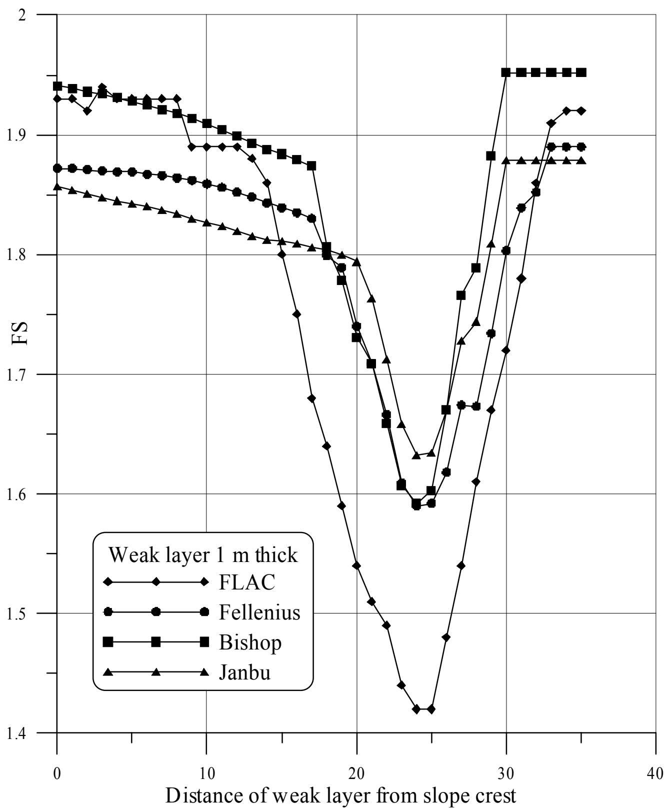

Figure 2. FS values for a 1.0 m thick weak layer.

Increase of weak layer thickness (irrespectively of its localization) reduces differences between FS values from LEM and SSR. Especially FS values estimated with Bishop’s are within 8 % of the FS obtained from SSR.

For the thickness of the weak layer less than or equal to 5 m SSR produces lower FS values than any of the LEM methods. For the weak layer 5 m thick Bishop’s method produces FS = 1.114 and SSR shows FS = 1.07.

Further increase of weak layer thickness (7.5 m and 10 m) produces lowest FS values from Bishop’s method (FS = 0.926 and FS = 0.811 respectively). SSR technique shows respectively FS = 0.95 and FS = 0.87 in this case.

It seems that application of Bishop’s method produces the most reliable results among LEM. These results are simultaneously closest to the FS values obtained from SSR. Application of Fellenius’s method produces unreliable FS values in case of weak layer localization below slope toe. It shows the influence of weak layer on FS values even if the roof of the stratum lays 15 m below the slope toe.

It must be also pointed out that failure surfaces identified by SSR technique are sometimes considerably different than surfaces identified by LEM (Fig. 4). Figure 4 shows the situation when FS computed by SSR is considerably lower and unit volume of failed slope is significantly higher than estimated from LEM.

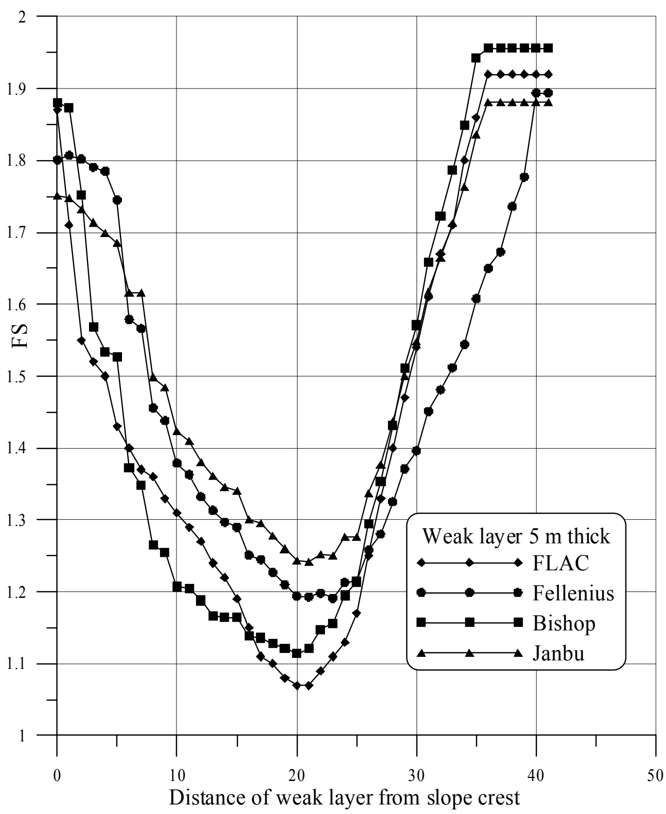

Figure 3. FS values for a 5.0 m thick weak layer.

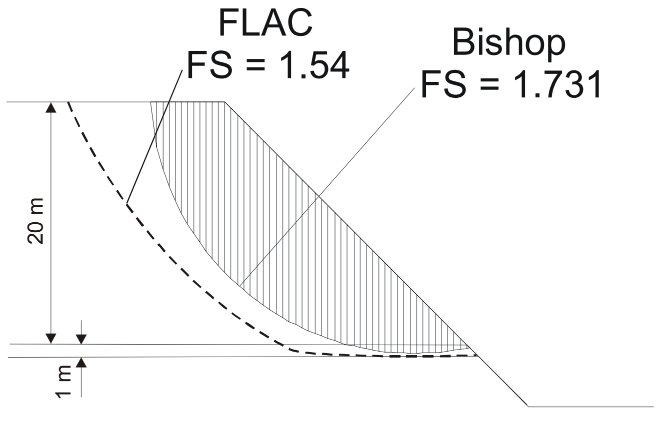

Figure 4. Critical slip surfaces identified by SSR and LEM.

3 MODIFIED SHEAR STRENGTH REDUCTION TECHNIQUE (MSSR)

3.1 *Benched slope stability case*

Application of SSR for complex geology slopes is usually restricted to the weakest "link" estimation – part of the slope with the lowest FS. However the Finite Difference Method code *FLAC* gives the opportunity to analyze several slip surfaces using modified shear strength reduction technique – MSSR (Cala & Flisiak 2003a, b).

This method is based on reducing shear properties of soils *after* identification of first slip surface (FS_1). It is simply the continuation of classic SSR, but after first instability occurrence. It is possible only using Finite Difference Method. The *FLAC* program uses the explicit, Lagrangian calculation scheme. The full dynamic equations of motion are used, even when modeling systems that are essentially static. This enables *FLAC* to follow physically unstable processes (i.e. several processes simultaneously!) without numerical distress. In fact, *FLAC* is most effective when applied to nonlinear or large-strain problems, or to situations in which physical instability may occur. This may lead to identification of several other slip surfaces. The same criterion is used to identify secondary (and further) failure surfaces. The primary and the following identified failure modes are constantly active (not suppressed) during entire calculation process. Let's consider benched slope stability (Fig. 5).

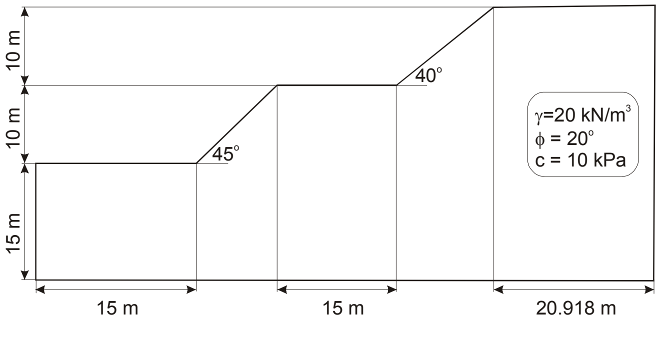

Figure 5. Benched slope case geometry.

Figure 6 shows the slip surfaces identified in benched slope by MSSR and LEM. Failure of the lower part of the slope was detected first. $FS_1 = 0.90$ calculated by SSR is very close to FS = 0.921 given by Bishop's method. And precisely here ends the range of classical SSR technique – especially with application of any Finite Element Method code. However *FLAC* is created especially for modeling physical instability (in this case - physical instabilities would be better term).

This allows to continue shear strength reduction and to identify another possible slip surfaces. In analyzed case, next identified failure surface is located in the upper part of the slope. $FS_2 = 1.00$ calculated by MSSR is again very close to FS = 1.008 given by Bishop's method. And finally application of MSSR allowed to evaluate FS for entire slope – $FS_3 = 1.24$ is also very close to FS = 1.228 given by Bishop's method.

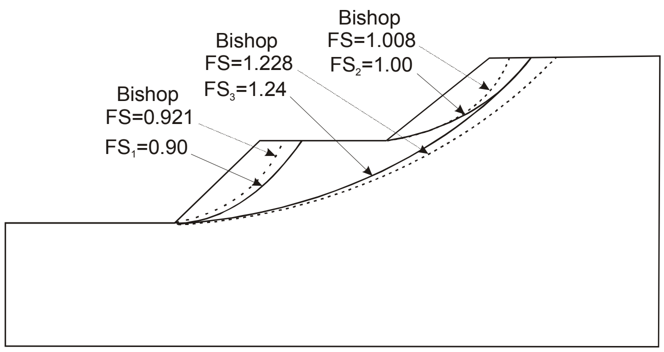

Figure 6. Several slip surfaces identified in benched slope by MSSR and LEM.

It seems that FS calculated with MSSR are within a few percent of the FS obtained from LEM for simple cases. It must be however underlined that effectiveness of MSSR must be verified on real cases.

3.2 *Large scale, complex geology slope stability case*

Let's consider a slope consisted of eight 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 1.

Table 1. Mechanical properties of soil units.

Unit	cohesion c, kPa	friction angle ϕ, deg	unit weight γ, kN/m^3
1	14.0	6.5	18.3
2	90.0	10.9	19.5
3	11.4	7.9	19.5
4	90.0	10.9	19.5
5	11.4	7.9	19.5
6	90.0	10.9	19.5
7	28.0	8.5	20.0
8	1000	30.0	23.0

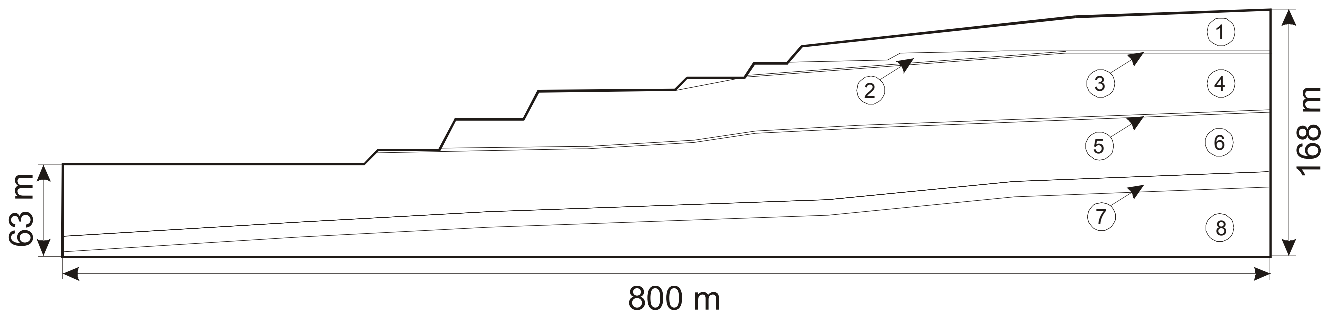

Figure 7. Slope geometry and geology.

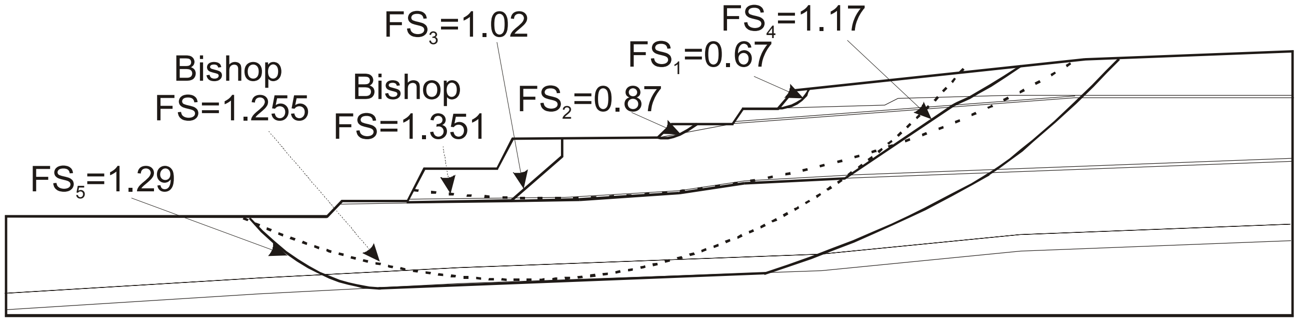

Figure 8. FS values and critical slip surfaces identified with MSSR and LEM.

Figure 7 shows geometry and geology of the analyzed slope. The overall sloping angle was equal $\alpha = 7.477°$.

Figure 8 presents the slip surface identified by MSSR and LEM. Again SSR finds the location of the lowest safety factor $FS_1 = 0.67$. Application of MSSR identifies four new slip surfaces in several parts of the slope. $FS_2 = 0.87$ also shows the local failure surface which, in fact, does not affect the overall slope stability (precisely like previous one). Another possible failure surface with $FS_3 = 1.02$ is based on layer 5 (very thin and weak one) and broken line upward.

Further analysis showed development of previous failure surface with $FS_4 = 1.17$ occurring mainly in layer 5. Bishop's method applied to the upper part of the slope shows cylindrical failure surface with $FS = 1.351$.

It must be noted that due to cylindrical shape Bishop's slip surface covers a little more soil volume. $FS = 1.351$ is however considerably higher than $FS_4 = 1.17$ from MSSR.

And finally an overall slope failure surface with $FS_5 = 1.29$ is identified. Bishop's method shows $FS = 1.255$, but it covers considerably lower soil volume. Generally, the results obtained from LEM are not that close to MSSR as in the simple case discussed before.

It's a well-known fact that application of LEM requires assumption about shape and location of slip surface. Circular failure surfaces were assumed here for calculation purposes. Critical slip surface with lowest FS value was estimated from 20,000 circles.

In MSSR there is no need for such assumptions. Stress and strain field in analyzed soil determines the shape and location of the slip surfaces.

4 CONCLUSIONS

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.

In the case of complex geometry and geology slopes SSR technique is much more "sensitive" than LEM. Another step forward is the modified shear strength reduction technique – MSSR. Application of SSR with *FLAC* may be recommended for the large-scale slopes of complex geometry.

Such a powerful tool as MSSR with *FLAC* gives the opportunity for the complete stability analysis for any slope.

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