Slope stability analysis with modified shear strength reduction technique

M. Cala, J. Flisiak & A. Tajdus
Dept. of Geomechanics, Civil Engineering & Geotechnics, AGH University of Science & Technology, Poland

ABSTRACT: This paper deals with the slope stability engineering. Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability analysis. The most popular numerical method of slope stability estimation is shear strength reduction technique (SSR). The factor of safety (FS) for slope may be computed by reducing shear strength of soil (or rock) in stages, until the slope fails. Application of SSR for complex geology slopes is usually restricted to the weakest "link" estimation – part of slope with the lowest FS. Finite Difference Method code FLAC (FLAC, 2000) gives the opportunity to analyse several slip surfaces by using modified SSR technique (MSSR). The method is based on reducing shear properties of soils after identification of first slip surface. MSSR allows performing 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 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).

The analysis of complex geology slopes stability requires suitable numerical modelling.

It must be stated that classical SSR technique has several limitations. Application of SSR requires advanced numerical modelling 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 analyse FS for other parts of the slope. This may sometimes lead to serious mistakes.

2 MODIFIED SHEAR STRENGTH REDUCTION TECHNIQUE (MSSR)

2.1 *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 analyse 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. Program FLAC uses the explicit, Lagrangian calculation scheme. The full dynamic equations of motion are used, even when modelling 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 non-linear or large-strain problems, or to situations in which physical instability may occur. This may lead to identification of several other slip surfaces.

Let's consider benched slope stability (figure 1).

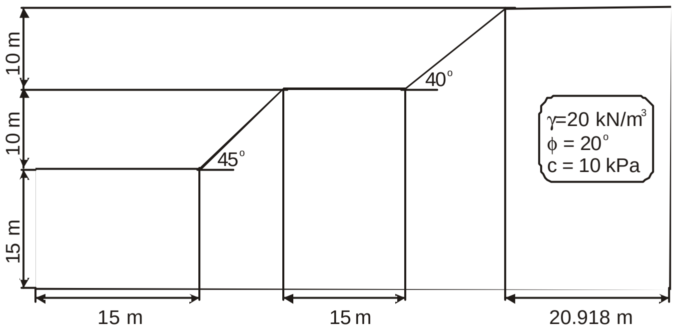

Figure 1. Benched slope case geometry.

Figure 2 shows the displacement vectors for the first identified failure surface. It is (of course) localised in the lower part of the slope. Figure 3 shows the shear strain rate distribution. Failure of the lower part of the slope was detected utilizing FLAC/Slope. $FS_1 = 0.90$ 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.

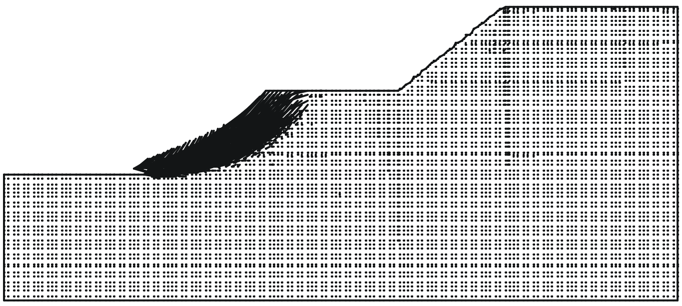

Figure 2.Displacement vectors for the first identified failure surface

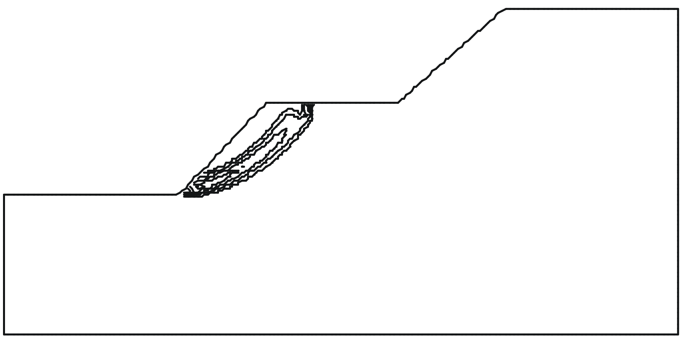

Figure 3. Shear strain rate distribution for the first identified failure surface

However FLAC is created especially for modelling 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 analysed case, next identified failure surface is located in the upper part of the slope. Figure 4 shows the displacement vectors for the second (and first) identified failure surface. Figure 5 shows the shear strain rate distribution for both failure surfaces.

Figure 4. Displacement vectors for the second (and first) identified failure surface

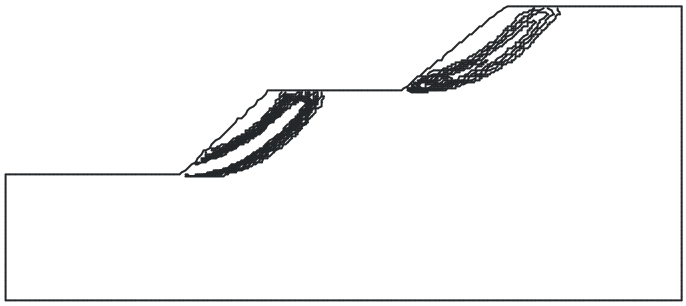

Figure 5. Shear strain rate distribution for both identified failure surfaces

$FS_2 = 1.00$ 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 shows the slip surfaces identified in benched slope by MSSR and LEM.

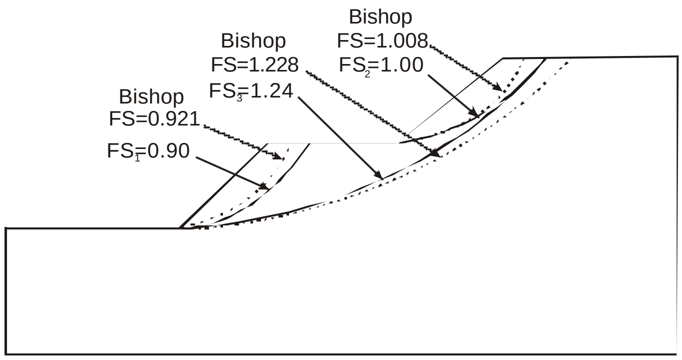

Figure 6. Several slip surfaces identified in benched slope by MSSR and LEM.

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.

All the calculations were performed on meshes with essentially square elements. According to Shukha & Baker (2003) this assumption gives more reasonable results in FS value and failure mode estimation.

Modified Shear Strength Reduction with FLAC may be summarized as follows:

1. apply classic SSR with FLAC/Slope to calculate FS_1,
2. export *.dat file to FLAC; calculate the initial, stable situation by operating *c* and ϕ,
3. find the representative number of steps (N_r) which characterizes the response time of the system (use $1.1N_r$ for further calculations),

4. calculate situation for FS_1 (check out for communication between FLAC and FLAC/Slope and elimination of any mistakes),
5. reduce *c* and ϕ to find further FS_i (prepare *.dat file manually or using Excel; each time start from the initial, stable *.sav file).

2.2 *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 shows geometry and geology of the analysed slope. The overall sloping angle was equal $\alpha = 7.477°$.

Figure 8 presents the all the slip surfaces 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.

Factor of safety for an overall slope failure surface is equal $FS_5 = 1.29$. 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 slope cases.

Figure 9 shows shear strain rate distribution for the third ($FS_3 = 1.02$) identified failure surface. Figure 10 shows the shear strain rate distribution for the fourth $FS_4 = 1.17$) identified failure surface and figure 11 presents shear strain rate distribution for the fifth ($FS_5 = 1.29$) identified failure surface. It is the final failure surface for the entire slope. Analysing figures 9-11 it may be concluded that identification of failure surfaces is not very easy. It requires understanding of origin of following failure surfaces. The user must rely on experience and intuition to understand the ability of the numerical model to predict the behaviour of the real physical model of the slope.

The results have an important implication in practice, since possible identification of all failure surfaces is necessary in order to perform a sensible prediction of slope

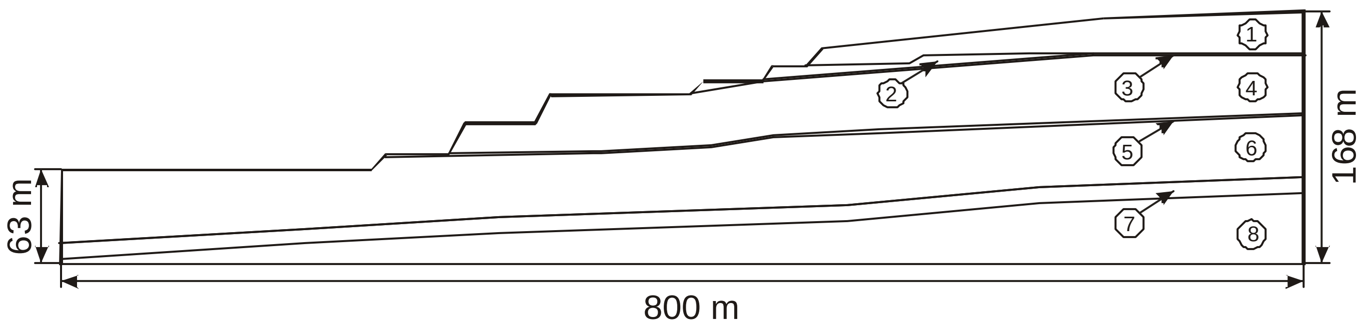

Figure 7. Slope geometry and geology.

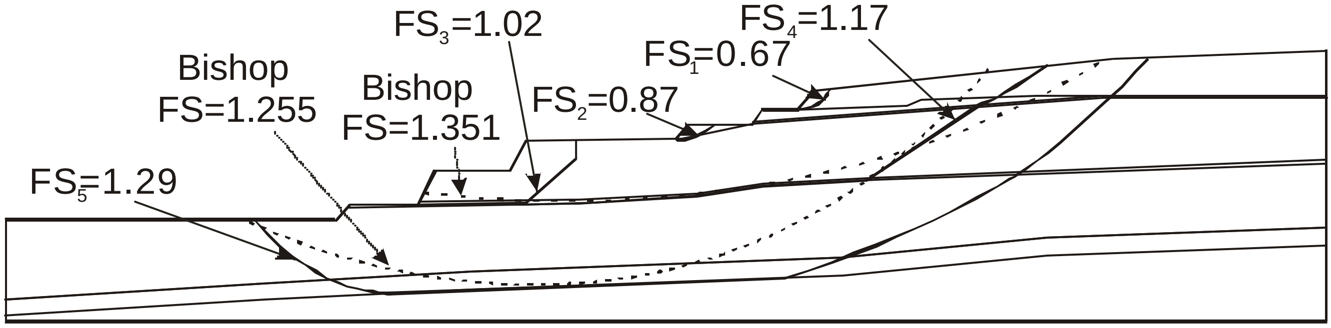

Figure 8. FS values and critical slip surfaces identified with MSSR and LEM.

stability.

3 SUMMARY

Many authors pointed out the necessity of considering several possible failure surfaces. Usually they used LEM to analyse such cases.

The use of MSSR has some serious advantages over LEM calculation. It's 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 analysed soil determines shape and location of following slip surfaces. Application of MSSR can provide considerable insight into the behaviour of slopes.

It also seems that MSSR is much more "sensitive" than LEM in the case of complex geometry and geology slopes.

The method is sufficiently general, it can deal not only with complicated geology but also with complex loading sequence. Such a powerful tool as MSSR with FLAC can be well applied to perform complete stability analysis for any slope.

It must be however noted that MSSR has also several limitations. Correct interpretation of several slip surfaces is not very easy and requires understanding of failure mechanism.

4 ACKNOWLEDGEMENTS

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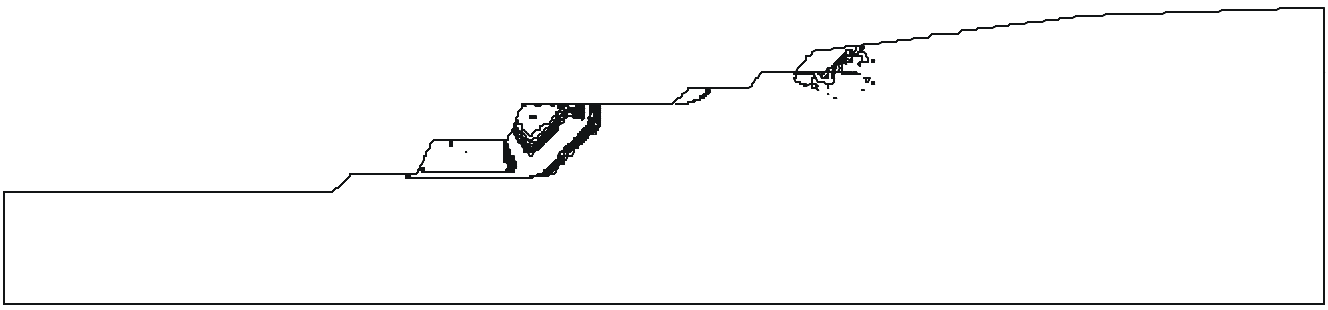

Figure 9. Shear strain rate distribution for third (FS_3 = 1.02) identified failure surface.

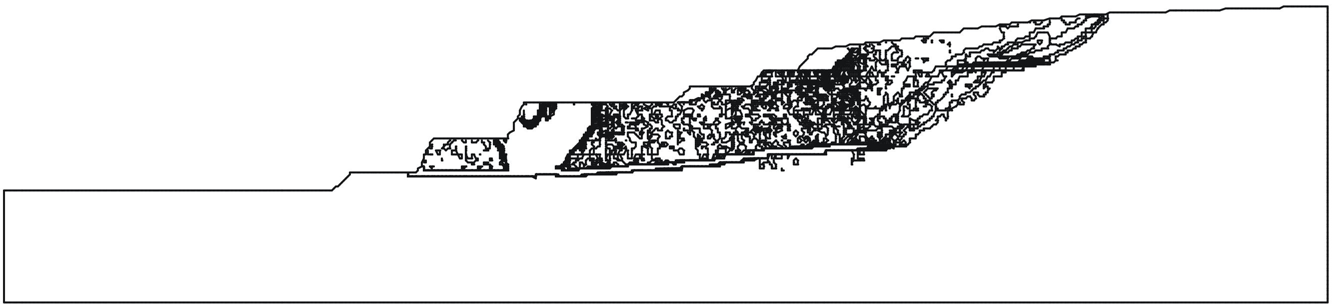

Figure 10. Shear strain rate distribution for fourth (FS_4 = 1.17) identified failure surface.

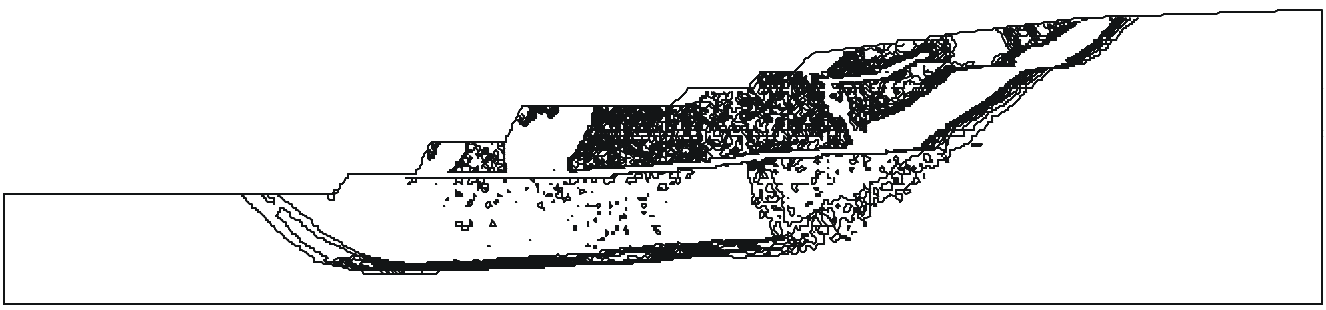

Figure 11 Shear strain rate distribution for fifth (FS_5 = 1.29) identified failure surface.

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