Slope stability analysis with *FLAC* in 2D and 3D

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

ABSTRACT: This paper presents the considerable differences between the factors of safety (FS) of an embankment estimated from 2D and 3D numerical calculations. The presence of a soft subsoil layer of limited dimensions was modeled to investigate its effect on FS values. FS obtained from 2D calculations were much lower than from 3D – the difference even ranged 0.78 for analyzed cases. It seems that, for certain cases, FS obtained from 2D calculations may be underestimated. With the increasing speed of computers, application of Shear Strength Reduction technique (SSR) in 3D seems to be a reasonable alternative to 2D analysis.

1 INTRODUCTION

Due to the rapid development of computing efficiency, several numerical methods are gaining increasing popularity in slope stability engineering. The most popular method of slope stability estimation is shear strength reduction technique (SSR). The factor of safety (FS) for slope may be computed by reducing the shear strength of rock or soil in stages, until the slope fails.

It must also be mentioned that FS for slopes is often estimated by means of Limit Equilibrium Methods (LEM) developed during the last 80 years. In fact, all geo-engineers are familiar with LEM. In spite of the fact that most landslides display not cylindrical but spatial slip surfaces, 2D slope stability analysis are widely used. Application of 2D modeling sometimes forces the user to considerable simplification of the problem.

Using several cross-sections may sometimes provide a reasonable assessment of the 3D effect. However, in some cases 3D calculations are necessary in order to take the complexity of geology under consideration. 3D limit equilibrium methods use columns instead of slices. Application of LEM to solve 3D problems is rather limited due to several simplifying assumptions (Hungr 1987, Chen et al. 2001 & Casamichele et al. 2004). In must be noted, however, that an increasing number of investigators use 3D numerical calculations for estimating slope stability (Dawson & Roth 1999, Zettler et al. 1999, Hürlimann et al. 2002, Koniecky et al. 2004 & Yuzhen et al. 2005).

FLAC^{3D} is widely used for slope stability analysis in Chilean open-pit mining (Karzulovic 2004). Bromhead (2004) simply points it out: "…there are numerous cases where slope failure cannot even approximately be represented by the 2D case, and the analysis of several sections is either impractical or inappropriate". This paper shows the significant differences between the FS values obtained from 2D and 3D analysis.

2 STABILITY OF AN EMBANKMENT

2.1 *Model geometry and material properties of soil units*

The embankment considered in this paper is 10.0 m high, inclined at an angle of 45°. All soils were modeled using conventional Mohr-Coulomb (elastic-ideally-plastic) constitutive model. The details of the modeled geometry are shown in Figure 1. The embankment is assumed to be uniform (unit – fill - c = 20 kPa and ϕ = 28°). The subsoil underlying embankment is characterized by c = 50 kPa and ϕ = 10° (silty clay). The presence of soft clay subsoil layer (c = 6 kPa and ϕ = 5°) of limited width is then assumed. Table 1 shows the mechanical properties assumed in this paper for the soil units.

Due to assumed symmetry of the problem, only one-half of the model was analyzed in the 3D calculations. The width (W) and thickness of the soft subsoil layer were changed. The width of the soft subsoil was changed from 1 m to 50 m (that means from 2 m to 100 m for the full model).

The thickness of the soft subsoil layer was assumed to be 1 m, 2 m and 3 m. 2D calculations were performed for the plane of symmetry.

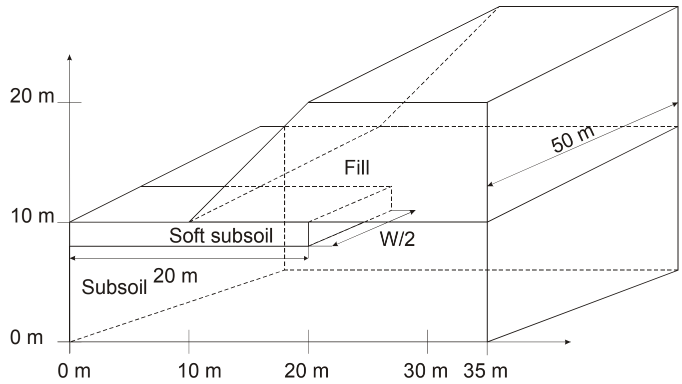

Figure 1. The details of modeled geometry.

Table 1. Mechanical properties of soil units.

Unit	cohesion c, kPa	friction angle ϕ, deg	unit weight γ, kN/m^3
Fill	20.0	28.0	20.0
Subsoil	50.0	10.0	20.5
Soft Subsoil	6.0	5.0	20.5

2.2 *Results of slope stability analysis*

The computer codes, *FLAC* (Itasca 2005) and *FLAC^{3D}* (Itasca 2002) were used for numerical calculations and SLOPE/W (Krahn 2004) for LEM analysis. Table 2 presents the results of 2D calculations performed with LEM and SSR.

Table 2. Comparison of the results for 2D calculations.

Case	LEM (Bishop)	*FLAC*
no soft subsoil	1.531	1.52
soft subsoil 1 m thick	0.997	0.91
soft subsoil 2 m thick	0.801	0.75
soft subsoil 3 m thick	0.729	0.71

Application of LEM produced higher FS values than application of SSR. The main reason is probably small sensitivity of LEM on complex geological situation – especially the presence of thin and soft strata (Cala & Flisiak 2003 and Dolezalova et al. 2001). It must be also pointed out that failure surfaces identified by SSR technique are sometimes considerably different than surfaces identified by LEM. FS computed by SSR may be considerably lower and unit volume of failed slope significantly higher than estimated from LEM (Cala & Flisiak 2003). Increasing the thickness of soft subsoil layer over 3 m did not produce further decrease in FS values.

Three series of analyses were performed using *FLAC^{3D}*. In the first series the factor of safety was calculated for the thickness of soft subsoil equal to 1 m. In the second and third series, thickness of soft subsoil was increased to 2 m and 3 m, respectively.

Figure 2 shows 2D and 3D FS values for several widths of soft subsoil stratum. It was assumed that the thickness of soft subsoil is 1 m. The value of FS = 1.52 is constant up to the width of soft subsoil equal to 8 m. Increasing the width above 8 m results in decrease of FS values. FS = 1.3 (a factor of safety of 1.3 is a value that is frequently used in the design of slopes for open-pit mines) is obtained for the width of soft subsoil equal to W = 14 m. The slope is at incipient failure (i.e. safety factor of 1) for the W = 60 m. For the soft subsoil width W < 60 m slope had FS > 1. That shows considerable difference between 2D and 3D results. Further increase of width produces slow decrease of FS values. FS slowly tends to the factor of safety value obtained from 2D calculations (FS_{2D} = 0.91).

The example picture of failure mode for the width of the subsoil W = 12 m (thickness 1 m) is presented in Figure 3. The contours of shear strain rate and direction of velocity vectors are clearly identifying 3D failure surface.

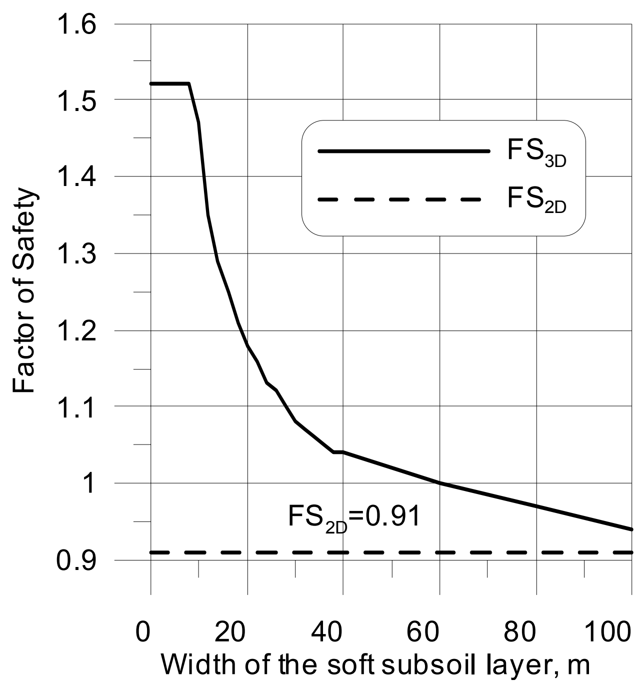

Figure 2. 2D and 3D FS values for several soft subsoil widths (thickness – 1 m).

Figure 4 presents 2D and 3D FS values for several widths of soft subsoil stratum. It was assumed that the thickness of soft subsoil is 2 m. The value of FS = 1.52 is constant up to the width of soft subsoil equal to 4 m. Increasing the width above 4 m results in decrease of FS values. The width of soft subsoil equal to W = 10 m gives FS = 1.3. The failure of the slope (FS = 1) is observed for W = 22 m. For the soft subsoil width W < 22 m slope had FS > 1. Increasing the thickness of soft subsoil stratum produces faster decrease of FS values. Again, FS slowly tends to the factor of safety value obtained from 2D calculations (FS_{2D} = 0.75).

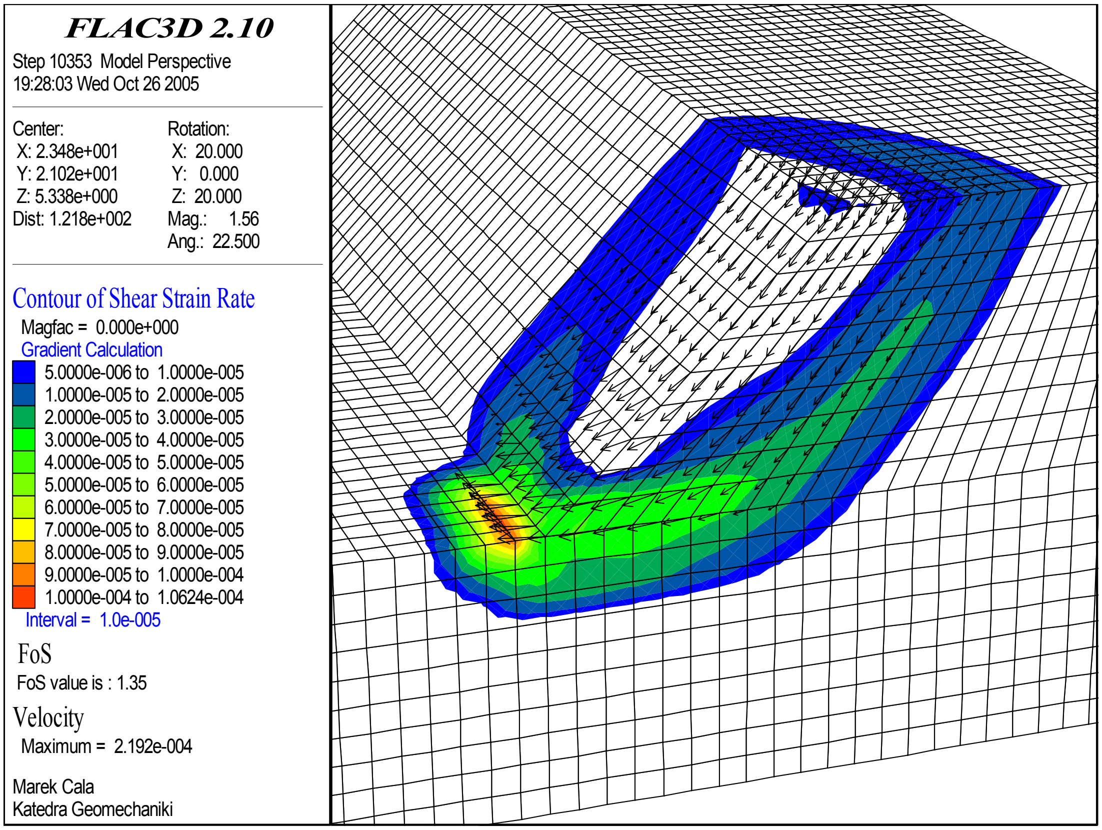

Figure 3. *FLAC^{3D}* model showing failure mode for the width of the subsoil W = 12 m (thickness 1 m).

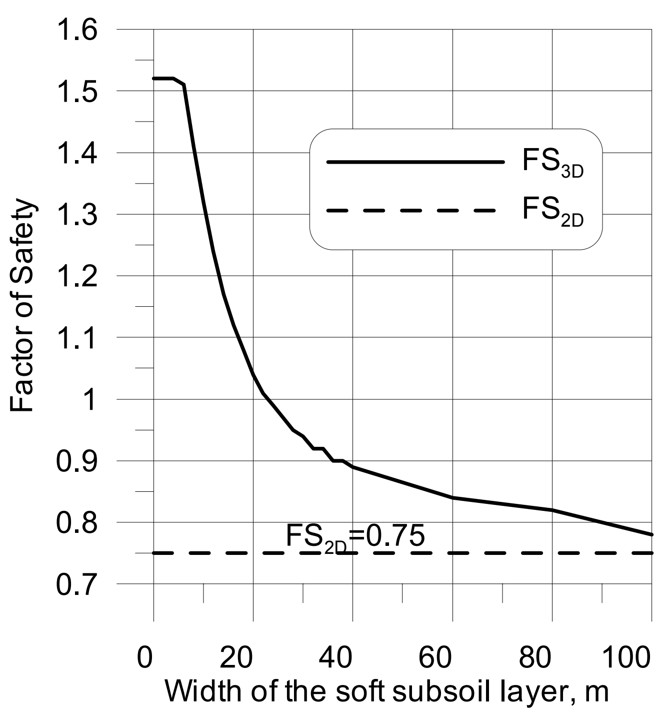

Figure 4. 2D and 3D FS values for several soft subsoil widths (thickness – 2 m).

Figure 5 shows 2D and 3D FS values for different widths of soft subsoil stratum assuming 3 m thick soft subsoil. The value of FS = 1.52 is constant only to the width of soft subsoil W = 4 m. As in the two previous cases, increasing the width above 4 m results in decrease of FS values. The factor of safety FS = 1.3 is obtained for the width of soft subsoil W = 10 m. The failure of the slope (FS = 1) is observed for W = 20 m. For the soft subsoil width W < 20 m slope had FS > 1. Further increasing of the thickness of soft subsoil stratum produces decrease of FS values tending to the factor of safety value obtained from 2D calculations ($FS_{2D} = 0.71$).

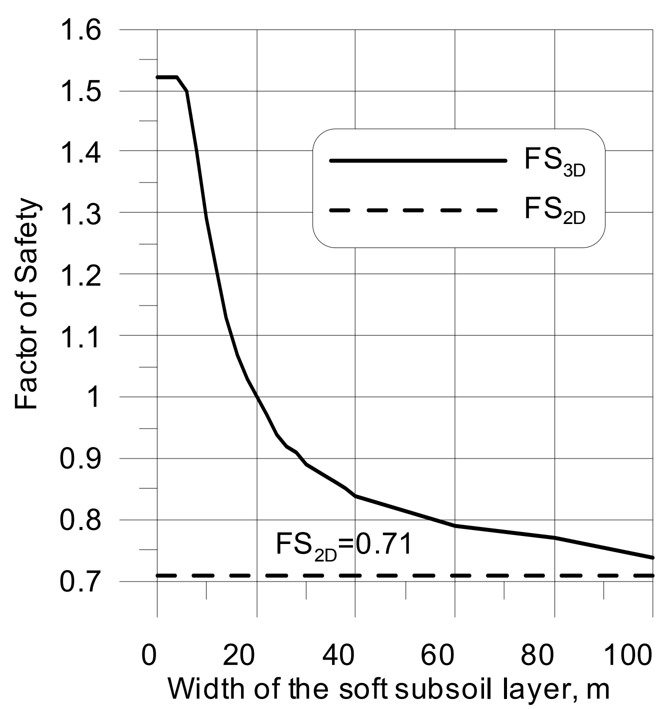

Figure 5. 2D and 3D FS values for several soft subsoil widths (thickness –3 m).

3 SUMMARY

Application of 2D models, for certain cases, may lead to a very conservative approach. In case of the limited width of soft subsoil layer, FS obtained from 2D calculations may be seriously underestimated. Application of SSR in 3D may produce a reasonable value of FS for most cases. This refers not only to convex or concave slopes but also to complex geology cases (thinning out of layers, faults, folds etc.). The examples presented in this paper clearly showed that 3D analysis were required to determine realistic value of FS.

The effect of 3D is often considered as an additional safety reserve. But on the other hand, one must find a reasonable equilibrium between safety and economy. Numerical modeling with *FLAC*^{3D} showed sensitive reaction of the system to small changes of soil parameters.

It seems that there is a widespread opinion that considering problem in 2D is always conservative and that engineering design doesn't need the third dimension. Do we really have to be that conservative?

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