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The perfect mesh for *FLAC^{3D}* to analyze the stability of rock slopes

A. Preh & M. Zapletal
Institute for Engineering Geology, Vienna University of Technology, Vienna, Austria

ABSTRACT: The design of finite difference meshes for solving three-dimensional problems is always a compromise between accuracy and computation time. In order to analyze the stability of rock slopes the mesh has to be detailed enough to calculate the state of limited equilibrium (factor of safety) and to evaluate the possible detached rock volume with acceptable accuracy. The influence of the mesh resolution and the shape of the zones have been investigated in the case of the analysis of a mass movement in Tyrol/Austria. The results varied in the calculated factor of safety, in the formation of the shear band and in the determined moving mass. Some important conclusions derived from this study show how to build up an improved mesh for slope stability analyses.

1 INTRODUCTION

FLAC^{3D} is a powerful tool to analyze the stability of rock slopes and valley flanks. The necessary three-dimensional grid to solve such problems has to be built up and adjusted by the user. This paper tries to investigate the influence of the mesh resolution and the shape of the zones on the calculated state of limited equilibrium (factor of safety) and detached rock volume.

The importance of a well-shaped mesh is illustrated by the stability analysis of a mass movement in Tyrol/Austria. The investigated area is 3.5 km long and 2.5 km wide (Fig. 1) and covers an alpine valley with elevations ranging from 800 m to 1925 m a.s.l..

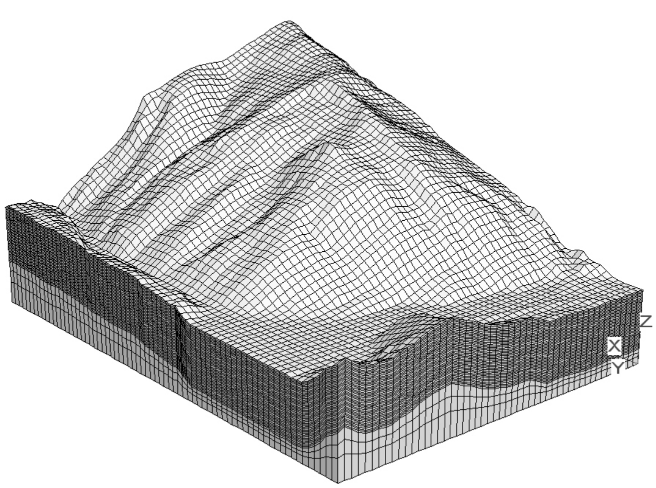


Figure 1. Problem domain.

The meshes of the models are based on a digital terrain model (DTM) with a horizontal grid distance of 50 and 100 meters respectively.

2 GENERAL RULES FOR DESIGNING A MESH

2.1 *Use relatively fine discretizations*

The finite difference zones assume that the stresses and strains within each zone do not differ in position within the zone – in other words, the zones are lowest-order elements. In order to capture stress and strain gradients within the slope adequately, it is necessary to use fine discretizations. The problem is that the solution time increases significantly by increasing the mesh resolution, especially in the case of a three-dimensional analysis. The solution time for a *FLAC^{3D}* run is proportional to $N^{4/3}$, where N is the number of zones.

2.2 *Use uniform zone dimensions*

Large varieties in the dimensions of the zones may influence the solution time considerably and may provide unsatisfying results. Therefore the zoning should be as uniform as possible, particularly in the region of interest. Long, thin zones with aspect ratios greater than 5:1 and jumps in zone size should be avoided. Far away from the region of interest (far-field) the aspect ratios may be 20:1 or more.

3 THREE TYPES OF MESHES TO SOLVE THE PROBLEM

Three different types of meshes were generated to solve the problem:

– *Type A:* Constant number of zones for each column.
– *Type B:* Constant number and height of zones for each column.
– *Type C:* Constant number and height of zones only in the region of interest (fine zoning).

3.1 *Type A*

Generating a slope (with big differences in the terrain surface) will result in very plane zones at the toe and comparatively high zones at the top of the slope. Such a mesh has no uniform zone dimensions, especially in the region of interest (Fig. 2).

3.2 *Type B*

By moving the grid points parallel to the surface a mesh with only uniform zones is generated. Calculations to compare this mesh with Type A showed different results in the stability of the slopes. There is a problem with the establishment of the boundary conditions at the base of the model, which is not plane but parallel to the surface (Fig. 3).

3.3 *Type C*

A compromise between Type A and Type B is a model with uniform zones, especially in the region of interest (upper layer, dark grey zones in Fig. 4), and a plane base to allow the right establishment of the boundary conditions. This ideal mesh was generated by moving the zones parallel to the surface in the upper layer and producing a plane base by creating zones of different heights in the lower layer (Fig. 4).

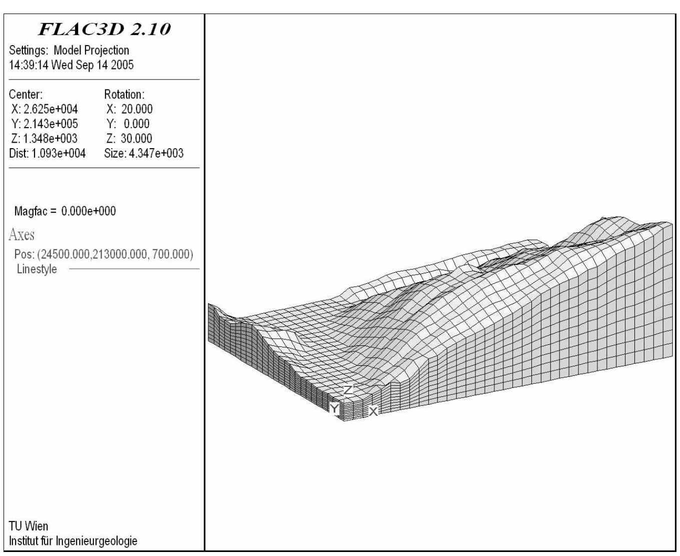


Figure 2. Mesh Type A.

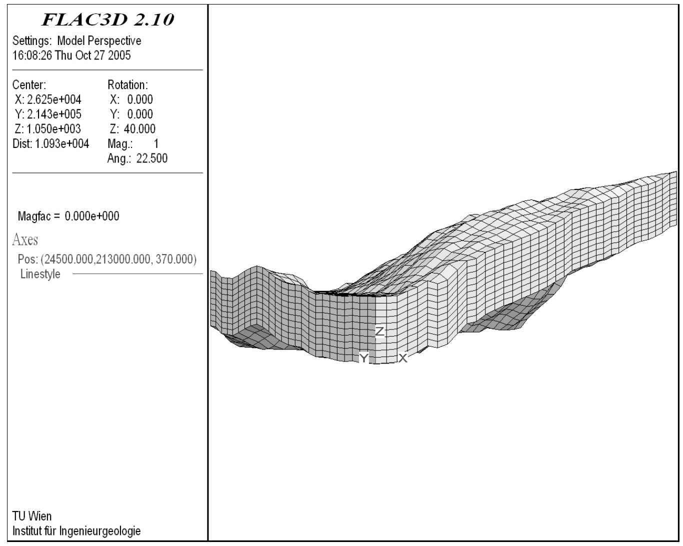


Figure 3. Mesh Type B.

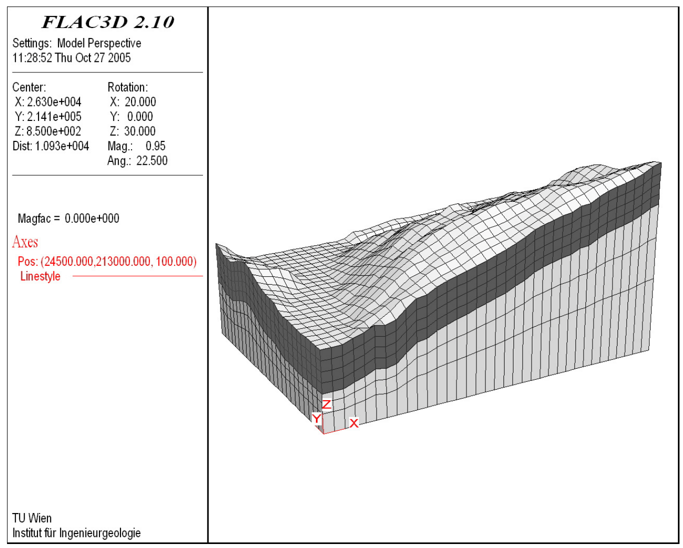


Figure 4. Mesh Type C.

4 INFLUENCE OF THE ZONE DENSITY

The investigations of the influence of the zone density were made by means of mesh Type C. Four different mesh resolutions were developed for a horizontal grid resolution of 100 m as well as 50 m. The depth of the failure zone (transition zone between moving rock mass and rock remaining in place) of the mass movement has been estimated with about 350 m. Therefore the region of interest (upper layer with uniform zones) was modeled as a layer with a thickness of 400 m. The investigated zone densities of the upper layer are specified in Tables 1 & 2.

Table 1. Zone density – 100 m grid distance.

Mesh Resolution	Zone height (m)	Number of zones in the z-direction	Ratio B:H
gross	100	4	1:1
coarse	50	8	2:1
fine	25	16	4:1
very fine	20	20	5:1

Table 2. Zone density – 50 m grid distance.

Mesh Resolution	Zone height (m)	Number of zones in the z-direction	Ratio B:H
gross	50	8	1:1
coarse	25	16	2:1
fine	12.5	32	4:1
very fine	10	40	5:1

4.1 *Modeling procedure*

The behavior of the rock was simulated by a Mohr-Coulomb material model with the parameters listed in Table 3. The in situ stresses were calculated based on pure elastic material behavior. Plastic deformations were prevented by high strength of the rock. After calculating the in situ stresses, the failure was triggered by reduction of the strength parameters according to the values given in Table 3.

Table 3. Material properties.

ρ (kg/m³)	E (GPa)	ν	c (kPa)	φ (°)
2700	8.0	0.25	400	20

The material strength parameters for the limited equilibrium and the factor of safety were determined by using the shear strength reduction technique (Zienkiewcz et al. 1975) and an algorithm using the bisection method implemented in *FLAC^{3D}* (Zettler et al. 1999).

4.2 *Initial failure mechanism and the detached rock volume*

The distributions of the shear strain rate of all investigated models (Figs. 7 & 8) indicate a zone of maximum shear strain rate at a certain depth. Below this shear band there are no displacements and above it they have an approximately constant value. The displacements within the shear band (failure zone) are decreasing continuously with increasing depth. This mechanical behavior of the rock mass identifies the failure mode “slope creep” (Poisel & Preh 2004). The distribution of displacements modeled by *FLAC^{3D}* (Fig. 6) shows the typical course for “block slope creep” as described by Poisel (1998, Fig. 5).

The shear band represents the transition zone between the moving mass and the rock remaining in place. Thus the volume inside the outer boundary of the shear band (failure surface) is the detached rock volume. The investigations show that the width of the shear band decreases by increasing the mesh resolution (Figs. 7 & 8), while the volume of the mass inside the shear band is increasing. The detached rock volume is decreasing insignificantly by increasing the mesh resolution.

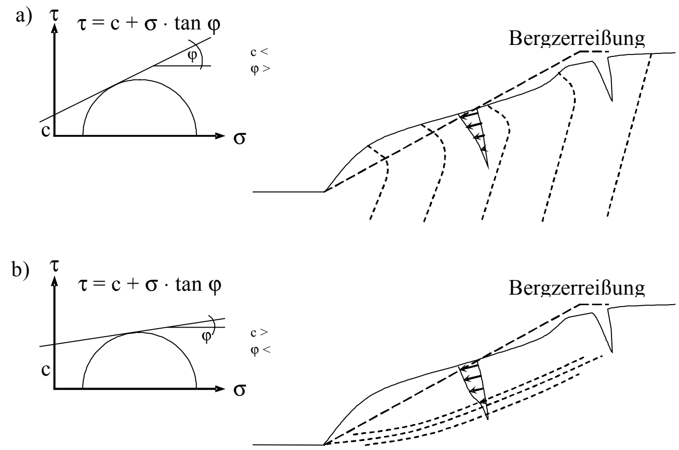


Figure 5. Diagram of slope creep mechanism and characteristic distribution of displacement rates; a) small part of cohesion in rock mass strength (outcrop bending); b) great part of cohesion in rock mass strength (block slope creep) (Poisel 1998).

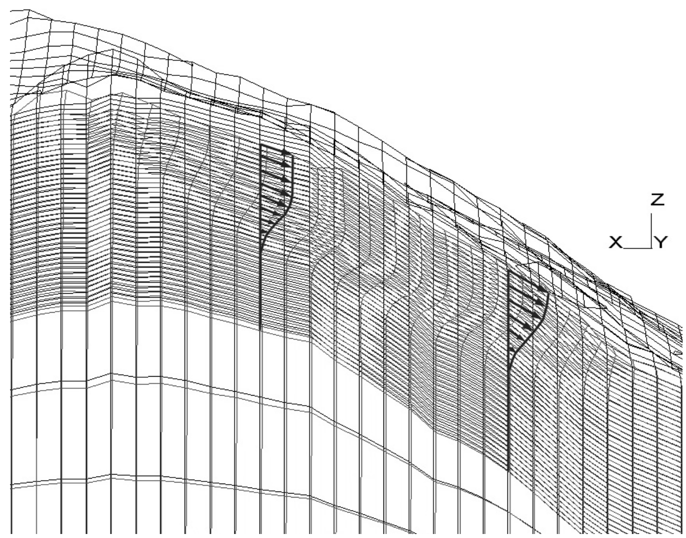


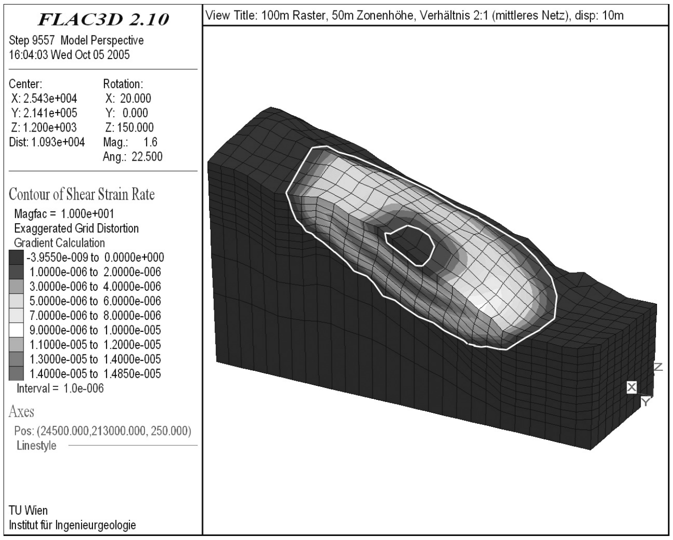
Figure 6. Characteristic distribution of displacement rates modeled by *FLAC^{3D}*, illustrated by the comparison of the undeformed and deformed mesh.

4.3 *Factor of safety*

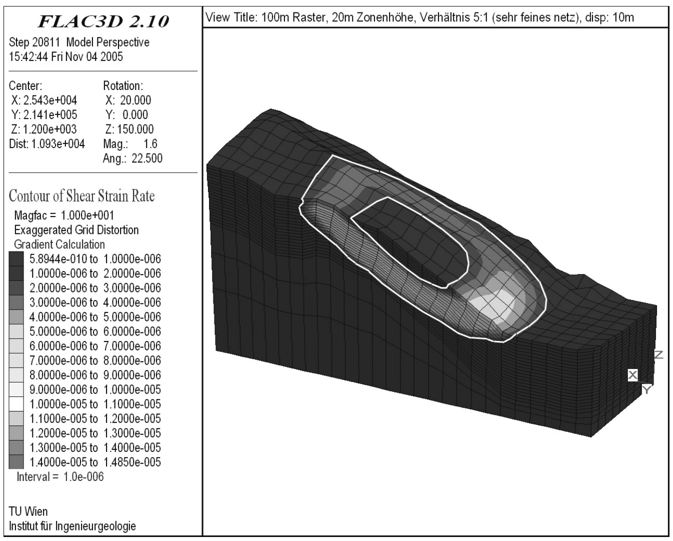
The investigation shows that the mesh resolution (grid size) affects the calculated factor of safety. The factor of safety is decreasing by increasing the mesh resolution and converges to a value of $\eta = 1.25$. The factor of safety and the critical values of the shear strength depending on the mesh resolution are listed in Table 4.

Table 4. Mesh resolution and factor of safety.

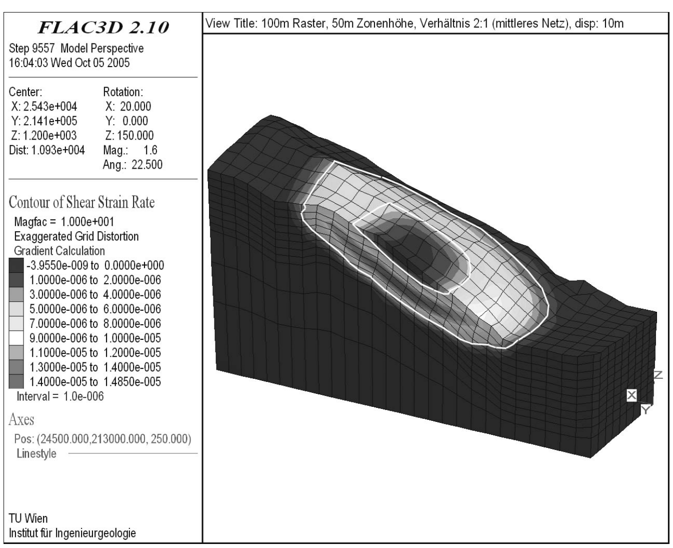
Mesh Resolution	Factor of safety	c_{crit} (kPa)	φ_{crit} (°)
gross	1.34	299	23.3
coarse	1.29	310	24.1
fine	1.27	316	24.4
very fine	1.25	320	24.8



a) Contour of shear strain rate for the coarse mesh.

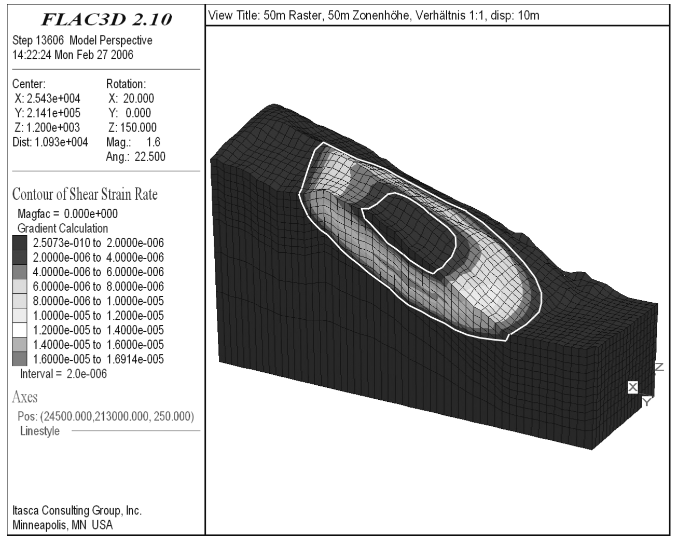


b) Contour of shear strain rate for the very fine mesh.

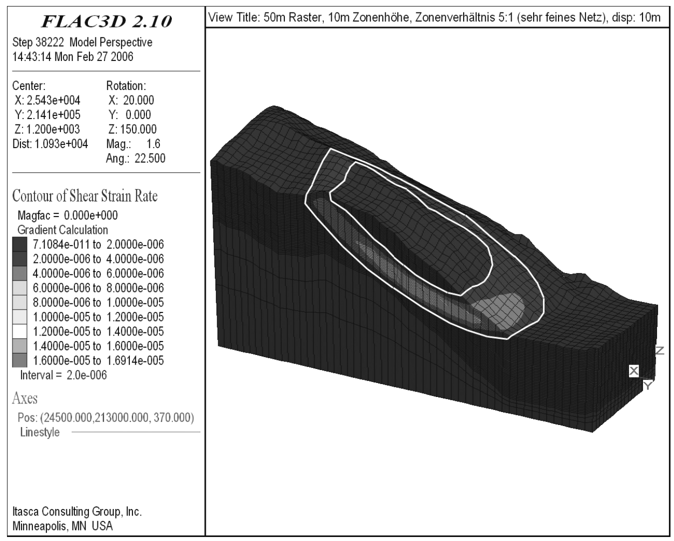


c) Comparison between coarse and very fine mesh (the white line represents the shear band of the very fine mesh).

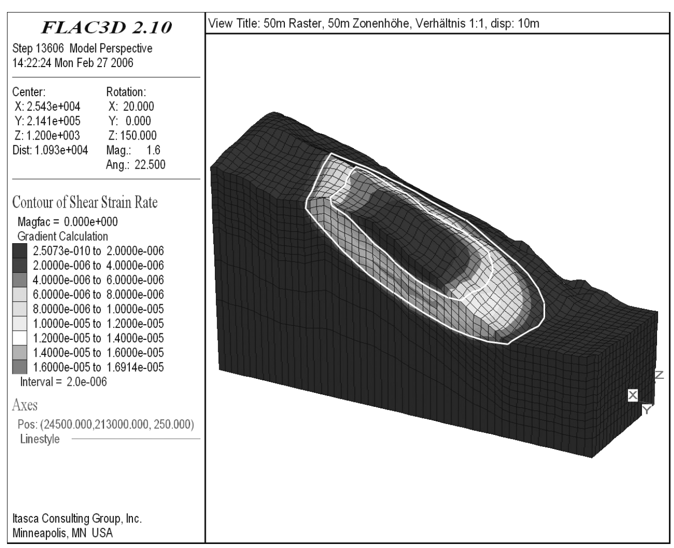
Figure 7. Mesh resolution and shear strain rate; horizontal grid distance 100 m.



a) Contour of shear strain rate for the gross mesh.



b) Contour of shear strain rate for the very fine mesh.



c) Comparison between gross and very fine mesh (the white line represents the shear band of the very fine mesh).

Figure 8. Mesh resolution and shear strain rate; horizontal grid distance 50 m.

5 CONCLUSION

Calculations using a coarse mesh result in a relatively high factor of safety. Consequently the stability of the slope is overestimated. This is a dangerous factor, because everyone is tended to use coarse meshes to shorten the solution time.

Fine meshes reproduce the failure mechanism and the width of the shear band in a more accurate way than coarse meshes. Furthermore the volume of the mass inside the shear band is increasing by using fine meshes.

Mesh size investigations are always necessary if numerical models based on grids, like finite element or finite difference codes, are used.

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