Failure Modes of Rock Slopes Demonstrated with Base Friction and Simple Numerical Models

By Andreas Goricki and Richard E. Goodman

Usually a slope failure is a very complex kinematic and dynamic process. For evaluating slope instability it is necessary to identify the involved mechanisms. The knowledge of the failure modes is essential for all further investigations of the stability or instability of a slope.

The goal of this paper is to show possible modes for the failure of rock slopes. Physical models are shown with a base friction machine, and compared to the results of numerical modelling with the code DDA. Due to the base friction model laws it is generally difficult to get exact results but failure modes can be shown very clearly. Thus, for studying the basic mechanisms physical models are very helpful.

First a description of the base friction machine, the basic principles of base friction modelling, and a brief introduction to Discontinuous Deformation Analysis (DDA) will be given. Then different simple failure modes involving sliding, rotating, and cracking are shown. Finally a few selected more complex combined failure modes are demonstrated.

Base Friction

Principle

The basic principle of the base friction model is the replacement of the gravity forces by analog horizontal friction forces in the two dimensional model. The model represents a horizontally turned, thin vertical slice of the natural rock slope. The discontinuous model is bounded by a fixed frame and an endless belt is dragged along

Versagensarten von Felsböschungen dargestellt mit Base Friction Versuchen und einfachen numerischen Modellen

Die anschauliche Darstellung der Versagensmechanismen von Felsböschungen ist das vorrangige Ziel dieser Arbeit. Dazu werden sowohl ein physisches als auch ein numerisches Modell verwendet.

Die Modellversuche werden mit einer Base Friction Maschine durchgeführt. Prinzipiell beruht das Base Friction Konzept auf der Analogie der Gravitation zu einer horizontalen Reibungskraft, die durch Ziehen eines endlosen Bands unter dem Modell erzeugt wird. Das in einem fixierten Rahmen eingebaute Modell besteht aus einer Mischung aus Sand, Mehl und Öl und hat den Vorteil der möglichen Bruchneubildung des Modellmaterials. Base Friction Modelle eignen sich ausgezeichnet zur Modellierung von Böschungen in geklüftetem Fels. Neben einem Überblick über die Entwicklung des Base Friction Konzepts werden Vorteile und Einschränkungen kurz beschrieben. Zusätzlich werden die Versagensmechanismen mit einer Discontinuous Deformation Analysis (DDA) numerisch ermittelt und dargestellt.

Um anschauliche Ergebnisse zu erhalten, werden die grundsätzlich komplexen Vorgänge des Versagens von natürlichen Böschungen auf singuläre Versagensmechanismen reduziert. Dabei wird vorrangig auf die Beurteilung und Darstellung des Nachbruchverhaltens Wert gelegt. Am Beginn stehen Modelle mit Gleit- und Kippversagen von Blöcken und Schichten, wobei sich die unterschiedlichen Mechanismen primär aufgrund geänderter geometrischer Verhältnisse einstellen. Zusätzlich werden Modelle mit unvollständig durchtrenntem Gebirge gezeigt. Durch die mögliche Bildung von Neubrüchen im Modellmaterial erweist sich das Base Friction Konzept als sehr brauchbares Hilfsmittel zur qualitativen Untersuchung der Versagensmechanismen solcher Böschungen. Abschließend werden an einigen ausgewählten komplexeren Modellen kombinierte Versagensmechanismen gezeigt.

The purpose of this paper is to illustrate different failure mechanisms in rock slopes. A physical and a numerical model are used to demonstrate the most important failure modes.

For physical modelling of rock slope instabilities the base friction machine is used. The main principle of the base friction concept is to replace the effect of gravity by the friction force of a dragging belt. The models are built horizontally with a mixture of sand, flour, and oil which allows the development of new cracks. These base friction models are very convenient for modelling discontinuous rock slopes. An overview of the development of the base friction concept is presented and its advantages and limitations are described briefly. Additionally discontinuous deformation analysis (DDA) is used to demonstrate the failure modes numerically.

To obtain demonstrative results, the often complex combinations of failure mechanisms in natural slope failures are reduced to singular failure modes. The focus of the presented models is set on the post failure behaviour of the slopes. The models presented first show simple sliding, slumping, and toppling of blocks, layers or columns. The different failure modes are the result of changing geometrical conditions of the discontinuities cutting through the rock mass. In addition to basic failure modes, the influence of rock bridges within a fractured rock mass is highlighted in further models. Due to the possibility of the development of new cracks, the base friction concept proves to be a helpful tool for studying the mechanisms of such rock slopes. Finally combined failure modes are demonstrated with a few selected more complex models.

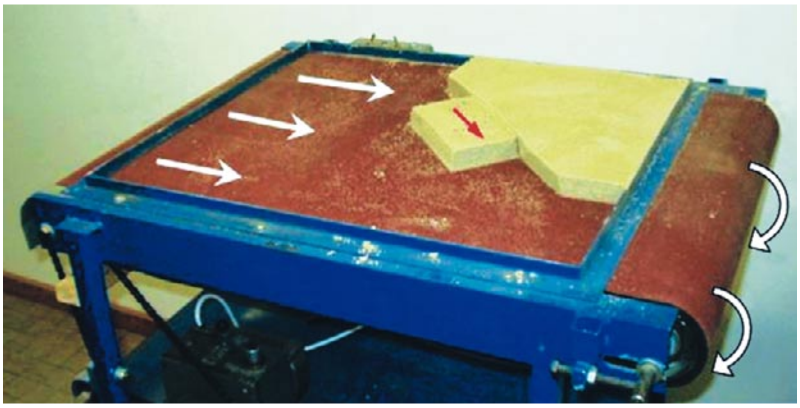

Fig. 1 Base friction modelling machine.

Bild 1 *Base Friction Maschine.*

the base of the model. Due to the movement of the base a force, the base friction force, develops in the plane of the model (Figure 1).

Development

The development of the base friction concept began 1969 when Goodman and later Hoek realized the similarity between sliding forces of a model on a surface and the gravity force. Several base friction machines with a continuous motor driven belt were built and ridged block models were investigated by different authors. Erguvanli and Goodman (1) introduced in 1972 a flour and oil based material that permitted cracking within the model. In 1979, Egger (2) presented an advanced base friction machine where a uniform pressure could be applied over the entire model surface. Two years later Bray and Goodman (3) examined the mathematical basis for the base friction concept and its limitations.

Since its invention in the early seventies numerous successful applications of base friction models can be found in literature. Due to the development of numerical modelling techniques the base friction concept became more important as a tool to study mechanisms and to verify calculated results qualitatively.

Material and model

For all base friction models shown in this paper a mixture of sand, flour, and oil with a weight ratio of about 1 : 1: 0.2 has been used. The material has an internal friction angle of approximately 42°. The models were built with a thickness of about 1.5 cm. After putting the material into the model frame it has to be compacted slightly. Before modelling the geometry, the cohesion between the belt and the model has to be broken by moving the belt a few centimetres. Then surfaces and discontinuities can be cut into the 2D-model. The models are loaded by a motor driven endless friction belt with a speed of about 1 cm/s.

Besides the limitation of two dimensional modelling the base friction model may give misleading results under general dynamic conditions. In conditions of static equilibrium and in systems with

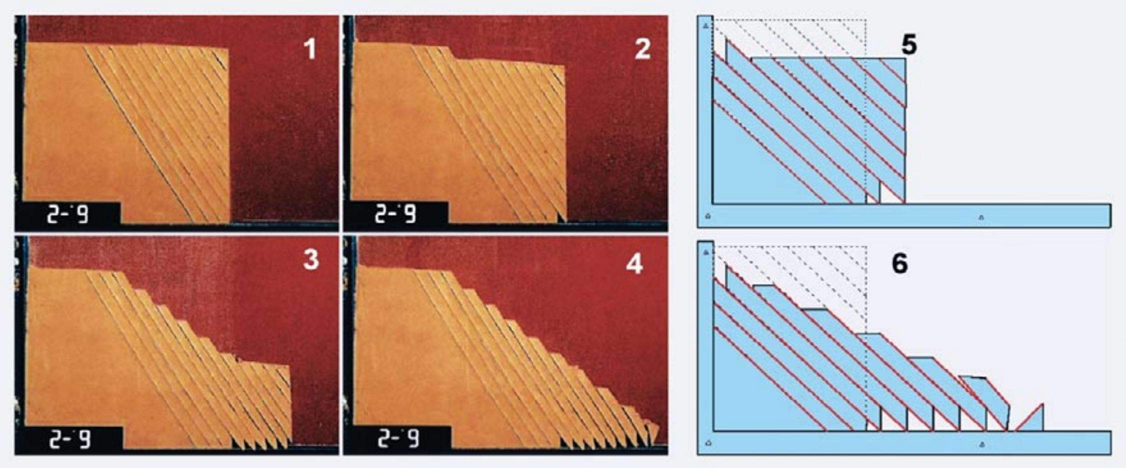

Fig. 2 Sliding on parallel discontinuities modelled in base friction and DDA.

Bild 2 *Schichtparalleles Gleiten im Base Friction und DDA Modell.*

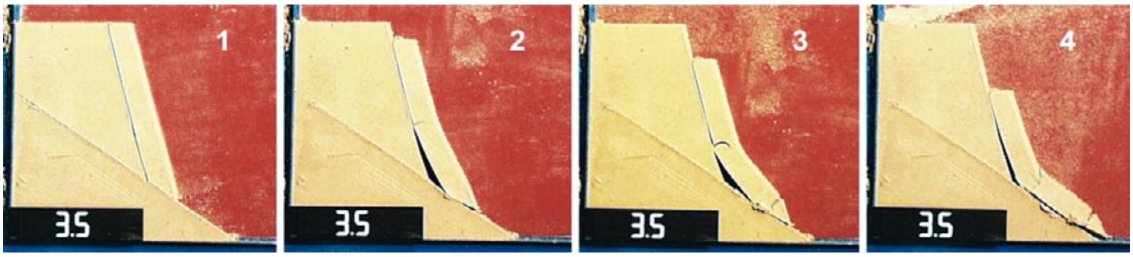

Fig. 3 Slumping of a single block.

Bild 3 *Slumping eines einzelnen Blocks.*

Fig. 4 Multiple block slumping.

Bild 4 *Versagen eines Mehrblocksystems durch Slumping.*

slow movement, the base friction apparatus is a convenient method for gravity modelling. It is inexpensive, demonstrative and by stopping the belt the "gravity" (base friction force) can be switched off to observe the post peak behaviour directly.

DDA

To compare the results from the base friction models with the results from numerical calculations, discontinuous deformation analysis (DDA) was used. DDA is a displacement-based discrete numerical method developed during the 1980's (4, 5). The code is intended for modelling the behaviour of a system consisting of a large number of individually deformable blocks. DDA for windows is easy to use and has been applied successfully for slope stability analysis of discontinuous rock masses (6).

Failure modes

The three basic failure modes sliding, slumping, and toppling are shown first. Then models involving cracking, incomplete blocks, curved surfaces, and combined failure modes are shown. The focus of all models is set on the demonstration of various failure modes. Therefore the geometry of the models will be described briefly and the primary failure mechanisms and the behaviour will be discussed. The parameters used for the numerical analyses are similar to those of the base friction material to produce comparable results.

Sliding

A single block on a slope slides when it is kinematically free to move and the limit equilibrium is exceeded. These two basic conditions always have to be fulfilled to have sliding occur in any blocky system. Figure 2 shows the sequence of a sliding failure of a vertical slope in layered rock. The daylighting layers dip steeper than the friction angle of the discontinuity. The failure of the entire slope starts at the lowest kinematically free surface (Figure 2-2). If this sliding layer is kinematically blocked, the failure progresses to the next higher discontinuity (Figure 2-3). The layered blocks slide one by one until the slope has failed completely and flattened to a new equilibrium. This behaviour, caused by the cohesion of the discontinuities, can also be seen in the numerical DDA model (Figures 2-5 and 2-6).

Slumping

In the following models the failure mode of slumping is shown for single and multiple block systems. The mechanism can be described as block sliding with simultaneous backward rotation. Kinematically it is necessary to have at least two joints or joint sets. Figure 3-1 shows a situation for single block slumping. One joint dips less than the friction angle and daylights in the slope, the other joint dips steeper than the friction angle and is non-daylighting to the slope. The separated block slides along both joints and rotates at the same time. Due to the bending moment it cracks and moves toward the behaviour of a two block system (Figures 3-2 to 3-4).

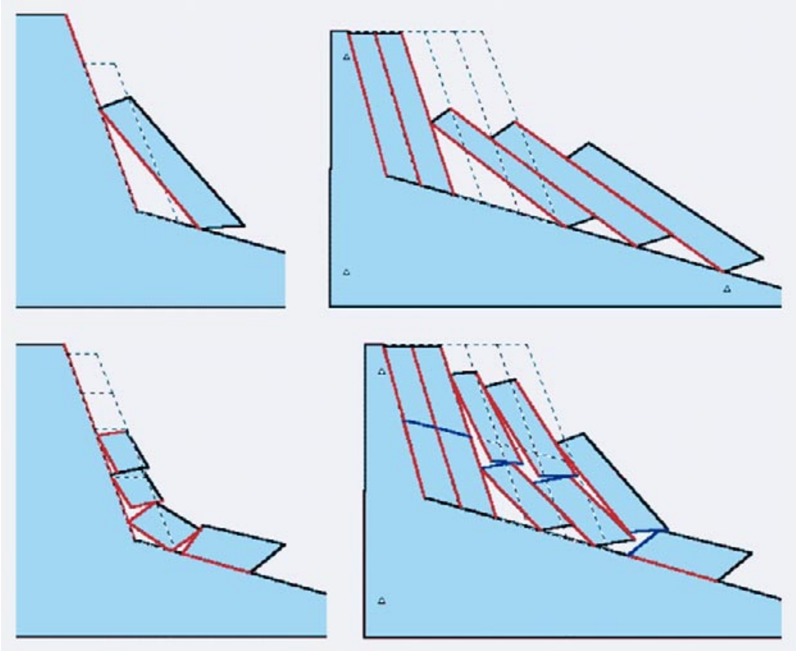

Fig. 5 DDA-models of basic slumping modes.

Bild 5 *DDA-Modelle von einfachem Slumping-Versagen.*

Figure 4 shows the slumping failure of a multiple block system. The geometrical conditions are

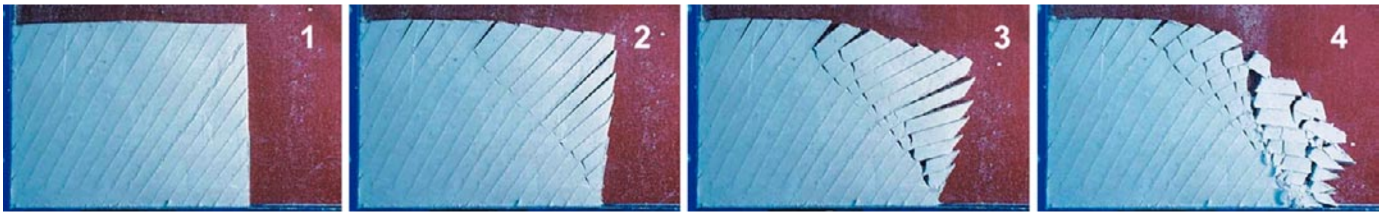

Fig. 6 Toppling of a layered rock mass.

Bild 6 *Kippen von Felssäulen.*

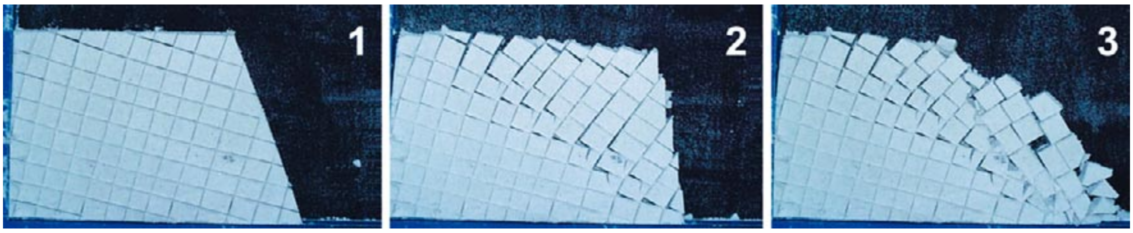

Fig. 7 Toppling of a blocky rock mass.

Bild 7 *Kippen eines Felsblocksystems.*

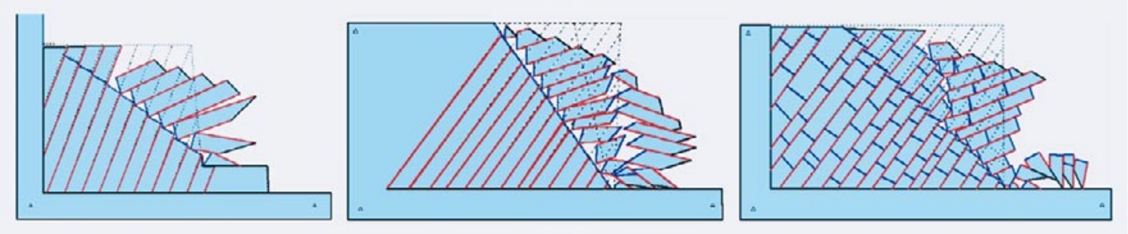

Fig. 8 DDA models with toppling failure.

Bild 8 *DDA-Modelle mit Kippversagen.*

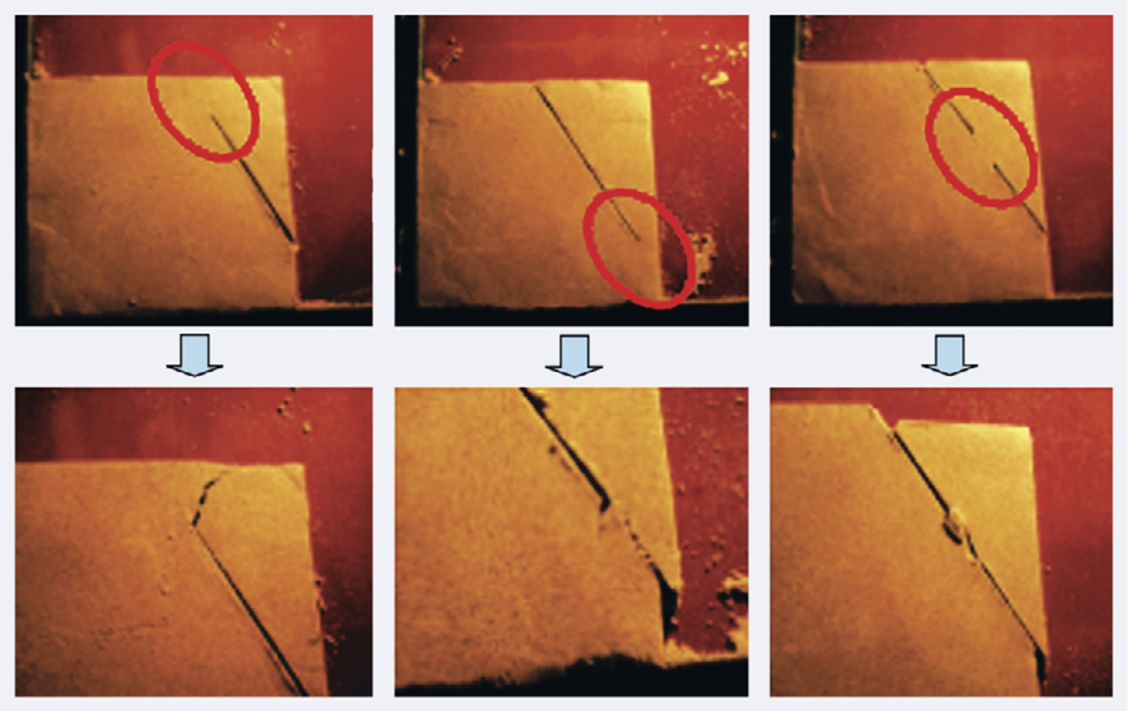

Fig. 9 Sliding of one incomplete separated block in different geometrical conditions.

Bild 9 *Gleiten eines nicht vollständig getrennten Blocks unter verschiedenen geometrischen Bedingungen.*

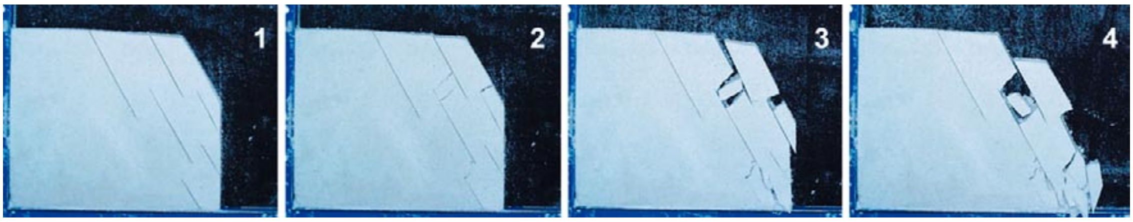

Fig. 10 Sliding failure of an incomplete fractured rock mass.

Bild 10 *Versagen durch Gleiten von nicht vollständig durchtrenntem Gebirge.*

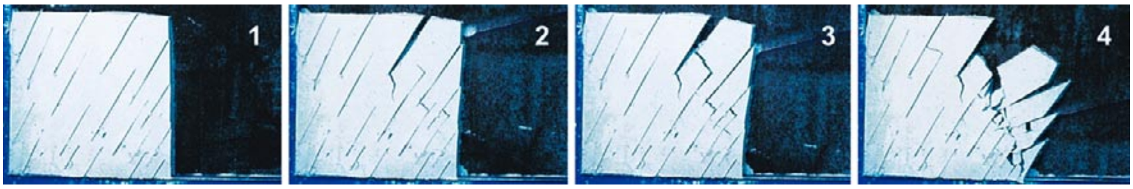

Fig. 11 Toppling failure of an incomplete fractured rock mass.

Bild 11 *Versagen durch Kippen von nicht vollständig durchtrenntem Gebirge.*

almost the same as described above for single block sliding but the rock mass is divided into rock columns by a joint set. Due to the failure of the slope along the single discontinuity at the base, the surface shape of the slope changed significantly. Figure 4-4 shows the stabilised slope with the initial slope shape.

The development of cracks is one of the big advantages of the base friction model. The numerical DDA models give good results for block systems. In principle, DDA can also be used to simulate cracking using modified joint properties but this requires that the crack location is predetermined. Figure 5 shows results of basic slumping models.

Toppling

While the equilibrium for toppling of a single block is a very simple geometrical condition, the evaluation for a multiple block system involves complex iterative solutions. The model in Figure 6 shows a typical geometrical situation for a toppling slope failure in a layered rock mass. The joints are daylighting but dip steeply into the slope, so sliding is kinematically inadmissible. Due to the base friction force the rock columns start bending towards the slope and begin to crack. This results in slip along the discontinuities and, based on geometry and material properties, in friction forces along the joints. The toppling failure of a slope is recognized by open joints and obsequent facing scarps above the slope. Finally the separated blocks topple towards the toe of the slope and form a flatter and stable slope.

Figure 7 shows the toppling failure of blocky rock mass. In this model a second joint set creates a multiple block system. Generally the failure mode is the same as described above for a layered rock mass. Due to the higher degree of fracturing, the system has more kinematic freedoms and can topple without the propagation of new cracks. However, Figure 7-2 shows the development of some new cracks due to overstressing of individual blocks. Finally the loosened rock mass becomes stable due to the changed geometrical situation (Figure 7-3).

Due to the necessity of kinematical freedom for the rotation of the blocks it is essential to use blocky systems to allow toppling failure in a model like DDA which does not permit new cracks. Figure 8 shows some examples of toppling failure modelled with DDA.

Failure of incomplete blocks

To have a more realistic model of the rock mass, discontinuities with limited extent are used. Since blocks are not completely isolated, meaning they are connected by "rock bridges", these rock bridges have to fail to make sliding or toppling possible. The failure mode of the slope as well as the failure of the rock bridges are controlled by the local geometrical situation, which introduces local stress concentrations. Numerical models for these failures are not shown because realistic fracturing modelling is not possible with DDA. Figure 9 shows base friction models for incomplete blocks which tend to slide. Various basic failure mechanisms occur within the rock bridges.

The model in Figure 10 shows a slope consisting of a rock mass with a set of incomplete discontinuities dipping towards the slope. The sequence shows the failure of different rock bridges. These failures create a separated and kinematically free block which is then able to slide along the new developed stepped sliding plane.

A very similar situation with the incomplete joints dipping in the opposite direction can be seen in the base friction model in Figure 11. Due to the bending of the rock columns and the slip between the rotating blocks new cracks develop and make toppling kinematically possible. The series of pictures in Figure 11 shows the failure of the model due to the gravity analogue base friction force. Figure 11-4 does not represent stable slope conditions.

Sliding on curved surfaces

For sliding of rock layers on curved discontinuities basically the same conditions have to be fulfilled as for sliding on planar surfaces. The biggest difference is the change of the dip angle of the discontinuity. This leads to different factors of safety at different locations. In concave discontinuities the factor of safety is higher in the flat parts of the sliding plane near the slope surface. This results predominantly in compressive stress within the sliding block and a high stress concen-

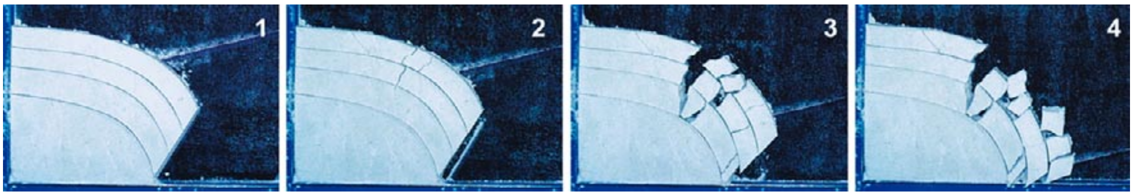

Fig. 12 Sliding on concave curved surfaces.

Bild 12 *Gleiten auf konkaven Oberflächen.*

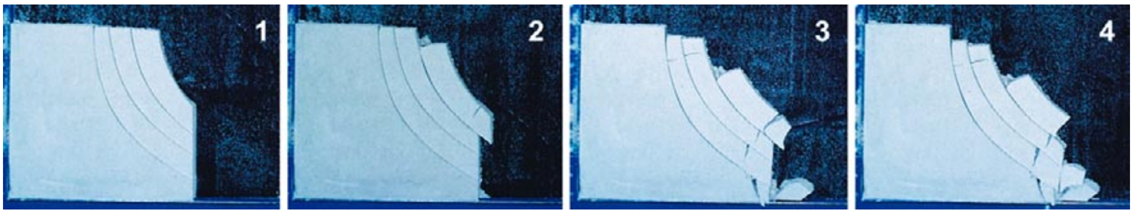

Fig. 13 Sliding on convex curved surfaces.

Bild 13 *Gleiten auf konvexen Oberflächen.*

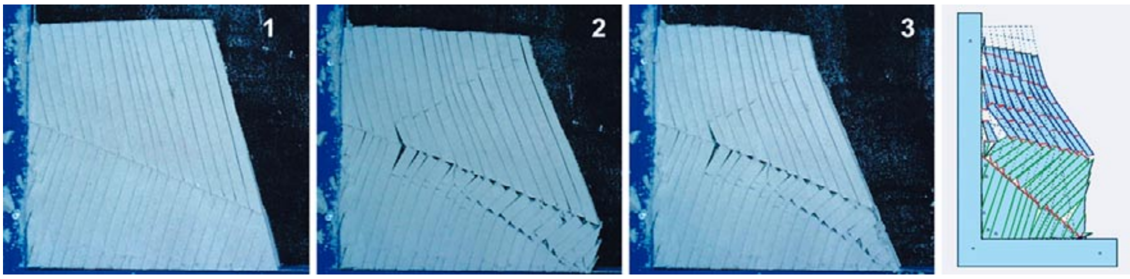

Fig. 14 Slope with slumping and toppling failure within one model.

Bild 14 *Böschungsmodell mit gleichzeitigem Slumping- und Kippenversagen.*

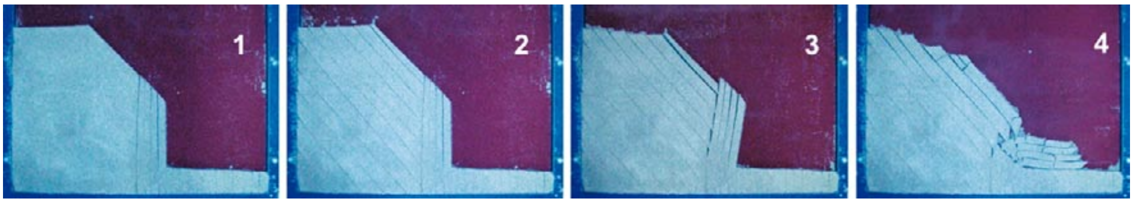

Fig. 15 Slope with sliding and toppling failure within one model.

Bild 15 *Böschungsmodell mit gleichzeitigem Gleit- und Kippenversagen.*

tration at the base of the slope. With convex layers the opposite situation is observed. The FOS in the sliding plane has its minimum near the slope surface where the sliding block is under tensile stress. The behaviour of such slopes is shown in the models in Figures 12 and 13. In general, if the curved sliding surface is not circular, the sliding block must deform internally as it moves.

Combined failure modes

In the models described previously, each failure mode was shown separately. In this series models contain an active and a passive failure mode within one slope.

The slope in Figure 14 is divided into two layers. The discontinuities of the lower layer dip steeply towards the slope. If the rock mass of the upper layer is continuous the slope will be stable. For an upper layer jointed parallel to the slope the blocks begin to slide and force the rock columns of the lower layer to topple. Due to the more or less horizontal movement of the upper parts of the toppling blocks the blocks of the upper layer continue their failure in a slumping mode. The whole process leads to the development of a kink band and finally to stable conditions (Figure 14-3).

Another passive toppling failure of a slope is shown in Figure 15. The slope is divided into a front part with vertical discontinuities and a rear part. Again, for a continuous rock mass in the rear part, the slope is stable. With a rock mass consisting of slope parallel joints the sliding blocks force the rock columns to topple.

Conclusion

To give a demonstrative overview of the generally complex processes of slope instabilities the failures mechanisms have been examined in a series of physical base friction model tests and duplicated in the non-cracking cases with a discrete numerical model (DDA). These models give a clear and qualitative overview of the different failure modes: sliding, slumping, and toppling within different boundary conditions. When the mode of failure has been identified as in these examples, it is feasible to discuss a quantitative limit equilibrium or numerical analysis that is properly constrained and meaningful.

References

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Authors

Dipl.-Ing. Andreas Goricki, Institute for Rock Mechanics and Tunnelling, Rechbauerstraße 12, A-8010 Graz, Austria, E-Mail goricki@tugraz.at; Professor Richard E. Goodman, University of California, Berkeley; Consultant: 13110 Pomo Lane, Mendocino, California, 95460, USA, E-Mail rgoodman @mcn.org