Rock Slope Initial Failure Mechanisms and their Mechanical Models

By Rainer Poisel and Alexander Preh

A catalogue of possible rock slope initial failure mechanisms (Figure 1) is presented giving geologists as well as engineers the possibility to compare phenomena in the field and phenomena belonging to particular mechanisms in order to identify the current mechanism in a special case and to apply the adequate mechanical model. This catalogue takes into account the geological setting and the geometry of the slope, the joint structure, the habitus of the rock blocks, as well as the mechanical behaviour of the rocks and of the rock mass (deformation and strength parameters).

The possible initial failure mechanism of a rock slope must be the basis for

- Monitoring (Which quantity has to be measured where?) and interpretation of monitoring results (19),
- Modelling and analyses (Only a mechanism embedded in a model can be the result of an analysis. There is no model at present comprising all possible mechanisms),
- Risk assessment,
- Design of measures for decreasing instability and for warning.

Versagensmechanismen von Talflanken und Felsböschungen und ihre mechanischen Modelle

Ein Katalog möglicher Versagensmechanismen von Talflanken und Felsböschungen, der den geologischen Aufbau und die Hanggeometrie, das Trennflächengefüge, den Habitus der Kluftkörper sowie das mechanische Verhalten der Gesteine und des Gebirges (Formänderungs- und Festigkeitsverhalten) berücksichtigt, wird zur Diskussion gestellt. Er soll Geologen und Ingenieuren ermöglichen, Strukturen im Gelände und Strukturen, die zu bestimmten Mechanismen gehören, zu vergleichen und so den Mechanismus zu finden, der in einem Hang abläuft. In den vorliegenden Katalog von Versagensmechanismen von Talflanken und Felsböschungen wurden nur Mechanismen aufgenommen, für die es ein klares mechanisches Modell gibt.

A catalogue of possible rock slope initial failure mechanisms, taking into account the geological setting and the geometry of the slope, the joint structure, the habitus of the rock blocks, as well as the mechanical behaviour of the rocks and of the rock mass (deformation and strength parameters), is presented. Its aim is to give geologists as well as engineers the opportunity to compare phenomena in the field and phenomena belonging to particular mechanisms and to find the mechanism occurring. The presented catalogue of initial rock slope failure mechanisms only comprises mechanisms having a clearly defined mechanical model.

Many classifications of rock slope failure mechanisms do not distinguish between failure or detachment mechanism and the possible run out (e.g. rockfall, rock slide, rock avalanche) (14). As the failure mechanism influences the stability, the run out affects the danger for settlements etc. initiated by a failure. An ideal model should therefore simulate both the failure mechanism and the run out. At the moment there is no such a model.

Rock slope initial failure mechanisms

Falling of rock blocks

"Falling" is a frequently used term in many rockslide classifications. However, the examples shown in these classifications have very little to do with a real fall. They are mostly slides turning into a fall in later phases. The block theory by Goodman & Shi (8) shows that "falling" as an initial failure mechanism of a rock slope can be the result of an overhang only. Therefore it only occurs in massive rocks with clearly defined joints (see Figure 1a).

Sliding of a rock block on a single or on two discontinuities

Most probably translational sliding of a rock block on an inclined discontinuity is the initial failure mechanism of a rock slope investigated first. It is not common knowledge, however, that commercial programs analysing sliding of rock blocks on a single or on two discontinuities give false results when investigating cases with large forces pulling out of the slope (e.g. anchorage of tautline cableway). Only block theory by Goodman & Shi (8) can analyse such cases in a correct way (see Figure 1b).

Sliding of several rock blocks on a polygonal sliding plane

Sliding of a rock mass on a polygonal sliding plane is possible only when antithetic fractures (21) exist or develop during movements of the slope, making shear displacements between the blocks possible (see Figure 1c). The model best suited for analysing this mechanism is the kinematical element method (10). UDEC is also able to simulate such mechanisms (34).

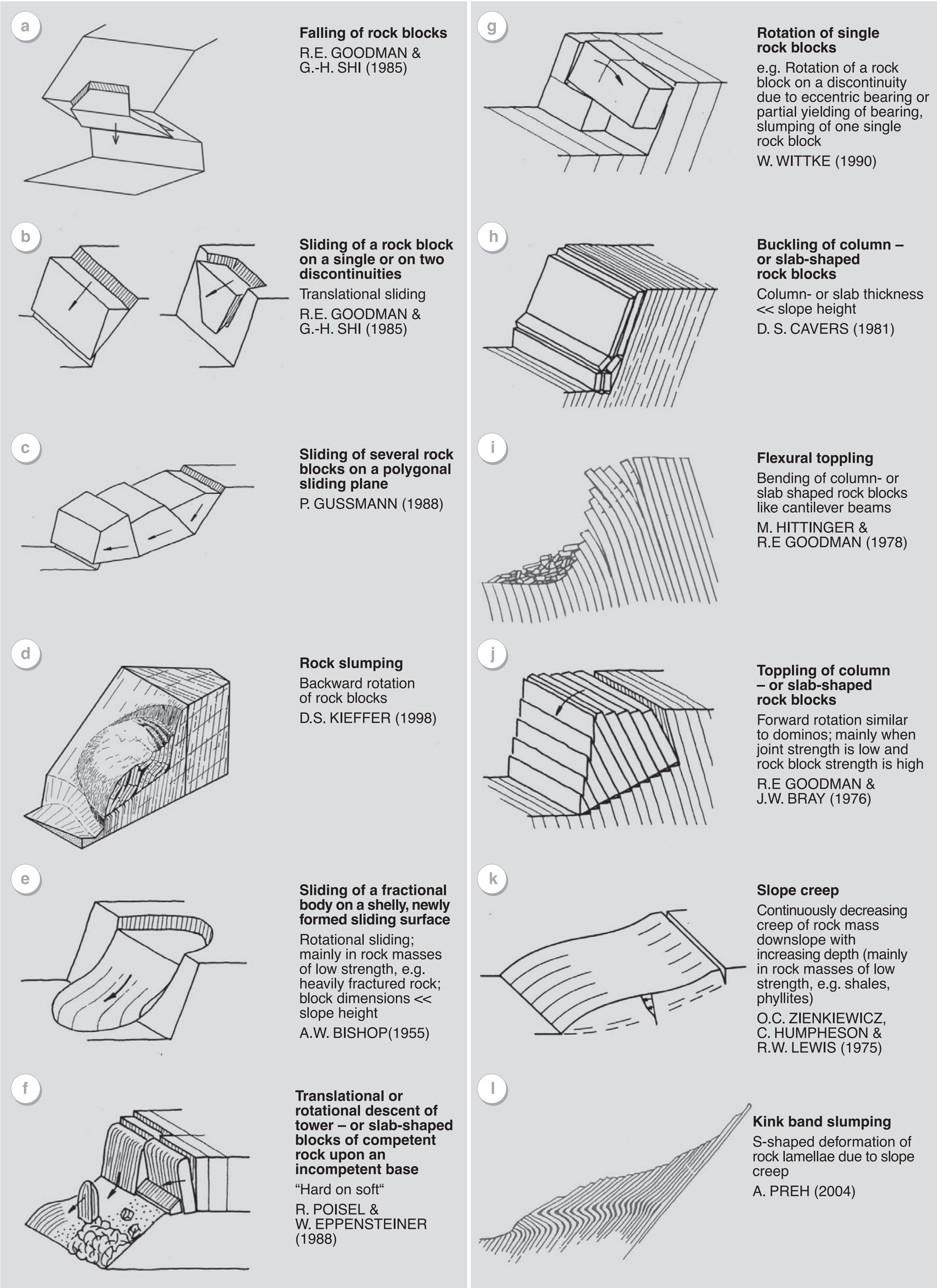

Fig. 1 Rock slope initial failure mechanisms and their mechanical models.

Bild 1 *Versagensmechanismen von Talflanken und Felsböschungen und ihre mechanischen Modelle.*

ROCK SLOPES

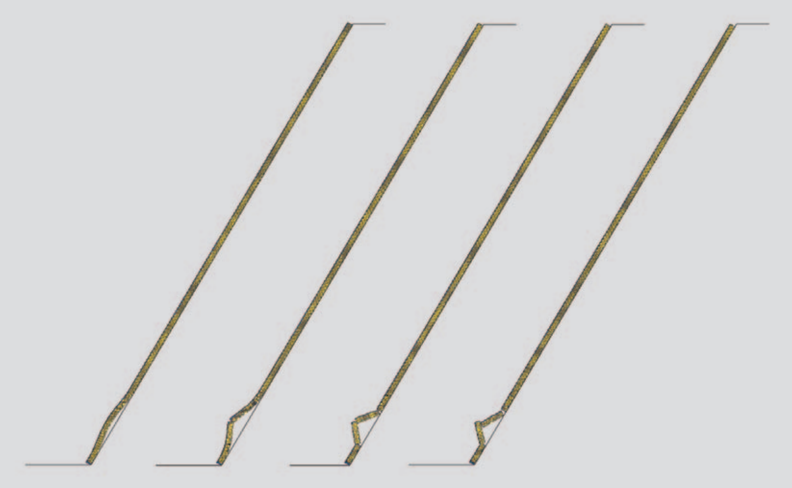

Fig. 2 Buckling failure of a slab-shaped rock block modelled by PFC.

Bild 2 *Knicken (Beulen) eines plattenförmigen Kluftkörpers modelliert mittels PFC.*

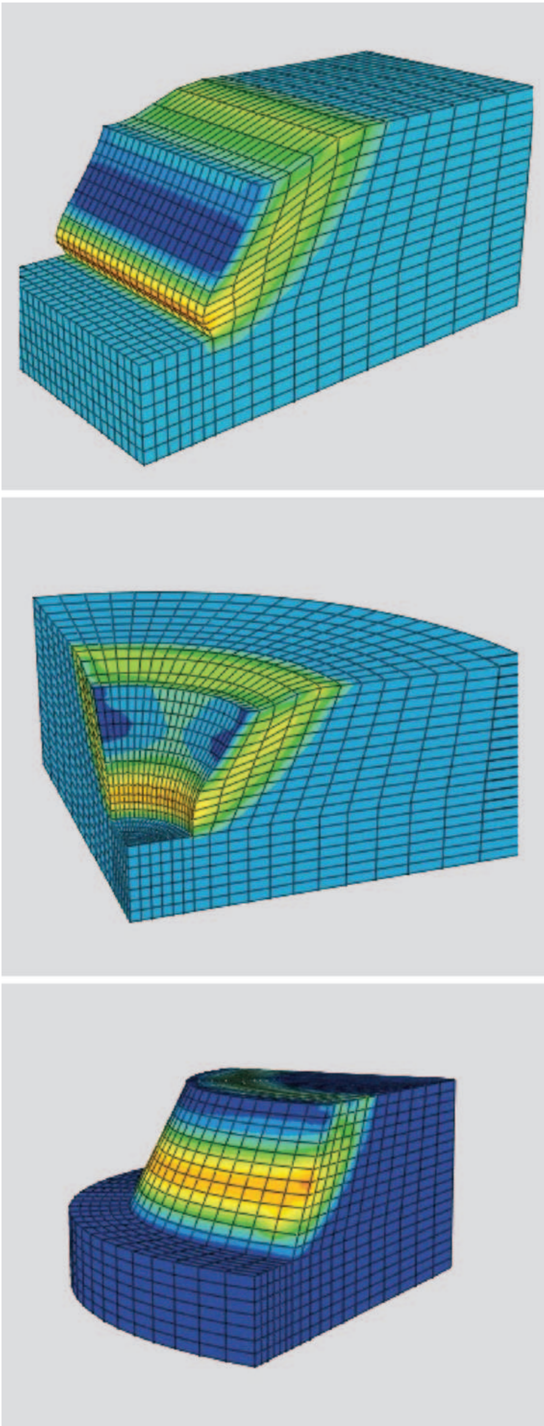

Fig. 3 Creep of a straight, concave and convex slope modelled by FLAC3D.

Bild 3 *Kriechen eines geraden, eines konkaven und eines konvexen Hangs modelliert mittels FLAC3D.*

Rock slumping

Rock slumping is a characteristic mode of backward rotation of rock blocks (18) similar to a ladder leaned too gently against a wall (see Figure 1d). As with toppling failures, rock slumps involve load interaction between steeply inclined columns that are rotationally unstable, and occur when pure sliding along the discontinuities is inadmissible. Kieffer (17) gave a limit equilibrium analysis for this mechanism, Discrete Element Codes (e.g. UDEC, DDA by Shi & Goodman (31)) can also model this mechanism effectively.

Rotational sliding of a fractional body on a shelly, newly formed sliding surface (circular failure)

Though rock slope failures are controlled by geological features (mostly some few discontinuities) in general, a circular failure like in soil can occur in rock masses of low strength, e.g. heavily fractured rock, when block dimensions are much smaller compared to slope height (see Figure 1e). As the geometry of circular failures in soft or heavily fractured rock is similar to that in soil, the stability assessment methods used for soil slope failures (e.g. 1, 16) can also be applied to circular failures of rock slopes.

Translational or rotational descent of tower- or slab-shaped blocks of competent rock upon an incompetent base

The system of hard, competent rock (e.g. massive limestone) lying on a soft, incompetent, ductile base (e.g. phyllites, slate) is a case appearing more often than generally believed. Due to the squeezing out and yielding of the incompetent base material, the competent rock is subjected to tensile stresses, therefore fractured intensively and thus shows a disintegration into huge blocks (see Figure 1f) (23). Generally these blocks may

- Slide downhill translatoric and upright,
- Form a rotational slide together with the moving base material (internal, backward rotation) or
- Topple downhill (external rotation; most dangerous case leading to sudden rock avalanches).

This mechanism can reach much deeper into the slope than other mechanisms. Modelling this mechanism is possible using FLAC or PFC.

Rotation of single rock blocks

Rotation of rock blocks around an axis horizontal and parallel to the slope surface is part of many initial failure mechanism of rock slopes (e.g. rock slumping, toppling). However, rotation of single rock blocks with a rotation axis not horizontal or not parallel to the slope surface or both, such as a torsional failure according to Goodman (9) or slumping of just one rock block, are special cases, not trivial to analyse (see Figure 1g). Physical models very often help a great deal in understanding such cases. Wittke (32) gave an overview of such cases and formulae for analysing this mechanism.

Buckling of column- or slab-shaped rock blocks

Buckling failure can occur in slopes built up by rock columns or rock slabs which are thin compared to the slope height (see Figure 1h). Eulerian buckling formulae by Cavers (2) give extremly conservative results in general, because Cavers estimated the buckling length much too long. Numerical investigations using PFC by Preh (27) (Figure 2) showed that the buckling length is about one quarter of the total slope length and that the Eulerian buckling formulae by Cavers (2) overestimate the critical load for slopes which are almost vertical. Furthermore, they underestimate the critical load for lower inclinations, taking into account the correct buckling length. The almost vertical slopes are therefore less stable than the Cavers model predicts, taking into account the correct buckling length and the slopes with lower inclinations are more stable than the Cavers model predicts, taking into account the correct buckling length.

Toppling

Flexural toppling

Flexural toppling is the result of the overturning and cantilever beam-like bending of rock blocks formed by joints (schistosity, bedding) dipping into the slope (see Figure 1i). The stresses resulting from cantilever beam-like bending may cause a second set of joints normal to the first one. A typical feature of flexural toppling as well as block toppling is the sawtooth pattern of the slope surface.

Toppling of column- or slab-shaped rock blocks (block toppling)

When the second set of joints is more intense, block toppling takes place, which is a forward rotation of rock blocks similar to dominos (see Figure 1j); it occurs mainly when joint strength is low and rock block strength is high.

Flexural as well as block toppling can be effectively modelled numerically by the discrete element codes UDEC and 3DEC from Itasca.

Chevron toppling

As a consequence of progressive failure in the joints dipping out of the slope, block toppling may result in a sliding failure after a certain amount of toppling. This mechanism was called chevron toppling by Cruden, Hu & Lu (3).

3D-effects

Goodman (7) pointed out that toppling can occur only if the layers strike nearly parallel to the strike of the slope within 30°. Numerical investigations using 3DEC by Wollinger (33) showed that toppling is possible if the strike difference is up to 40°.

Transition from toppling to slope creep

There is no difference between toppling and slope creep in principle (compare velocity distributions), because reducing the spacing of the joints dipping into the slope means a change from toppling to slope creep. However, toppling is ruled by the joint structure, because the strength of the joints is decisive, whereas slope creep is ruled by the strength of the rock material. Investigations by Reitner, Lang & van Husen (28) in a mountain built up by phyllonites dipping steeply to the north, have shown that slope creep dominates in the slope dipping to the north, whereas toppling dominates in the slope dipping to the south, because in the slope dipping to the south schistosity planes have an orientation optimal for toppling. In the slope dipping to the north rock strength prevails, leading to slope creep, because the orientation of the schistosity planes does not make toppling possible.

Stresses in the toe area of toppling slopes are very high (12), because the whole slope is lying on the toe. Thus the rock material fails and is very often completely crushed. Rock material strength is approaching its residual strength, which is the strength of the joints. So the complete mass is no longer discontinuous, which leads to slope creep in the toe region. This mechanism can be modelled very well by UDEC and 3DEC assuming the block material as a Bingham material (25).

Slope creep

Slope creep (see Figure 1k) is caused by the creep of rock masses, which is a material property (20) and occurs in slopes as well as in foundations and around tunnels in rock. According to the decrease of the stress deviator with increasing depth below the slope surface, creep of the rock mass and therefore displacements downslope decrease continuously with increasing depth (up to 200 m).

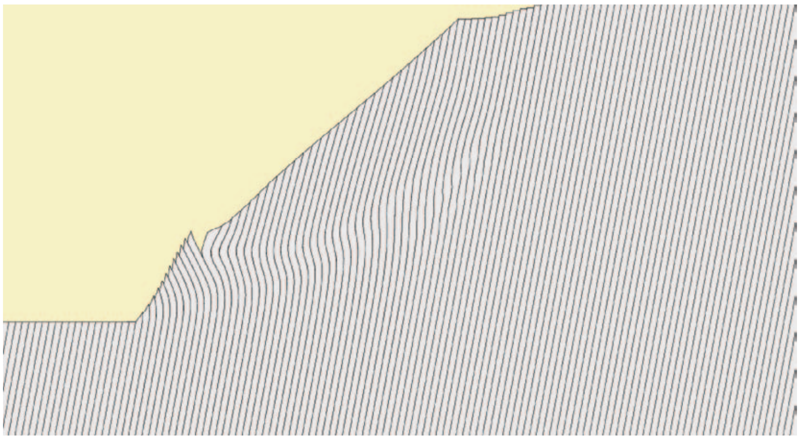

Fig. 4 Kink band slumping modelled by UDEC (27).

Bild 4 *Knickband-sackung modelliert mittels UDEC (27).*

Typical features of a sagging slope are a tension crack (in German "Bergzerreissung") in the upper slope surface and a bulging toe of the slope (24).

Slope creep can be effectively modelled numerically by the code FLAC and FLAC^{3D} from Itasca using a Mohr-Coulomb failure criterion, which assigns, due to the timestep algorithm routine, a behaviour like that of a Bingham material (20). Zischinsky (37) investigated several cases of slope creep and derived a velocity distribution typical of such slopes. Zienkiewicz, Humpheson and Lewis (36) showed that a slope of a Bingham material reveals continuously decreasing displacements with increasing depth.

Zischinsky (37) chose the term "sagging" (in German "Sackung") for this type of failure mechanism. However, "sagging" indicates a vertical movement (11) while phenomena described by Zischinsky are triggered by displacements parallel to the slope surface. Hutchinson (15) gave examples for "sagging" comprising extremely different mechanisms. Thus it seems better to avoid the term "Sagging" (in German "Sackung") and to use "slope creep" (in German "Hangkriechen") instead.

3D-effects

3D-effects have a strong influence on the stability of rock slopes, although they are very often neglected. Figure 3 shows FLAC^{3D} models of a straight, a concave and a convex slope built up by the same Bingham material. Stability investigations by the shear strength reduction technique based on the definition of safety by Fellenius (5) have shown that a concave slope is much more stable than the straight, as space becomes narrower when the mass is moving down. In contrast, the convex slope is slightly less stable than the straight slope (26, 30, 35).

Transition from slope creep to a circular failure

Examples in the field show that slope creep may lead to a circular failure, due to high shear strains in the transition zone from rock remaining in place and displaced rock. Those high shear strains cause fracturing of the rock and decreasing rock strength in this zone, leading to localization of the zones failing in shear. This can be modelled effectively by FLAC (4). Thus, limit equilibrium methods for a circular failure and FLAC using the shear reduction technique give the same results (35).

Kink band slumping

The term "kink band slumping" has been introduced by Kieffer (17) describing a mechanism leading to a S-shaped deformation of rock lamellae dipping steeper than the slope surface. Zischinsky (37) and Nemcok, Pasek, Rybar (22) described similar slope deformations calling them "deep-seated creep" and "Sackung". Numerical analyses (27) showed that this deformation is a consequence of rock creep and slipping of joints (Figure 4). As the upper parts of the moving rock mass slump due to the slipping of joints kink band slumping is not a special form of slope creep, which leads to tension in the upper parts of the slope and mostly to a tension crack.

Water

Water is a very important factor, and it is possible to include the effect of water on the stability of a rock slope in a coupled mechanical-hydraulic analysis by the codes mentioned above. The real problem, however, is to obtain the necessary information. In most rock slope failures, the hydraulic conditions are very complex and never known precisely enough in order to take them into account in an analysis which may be close to reality. In many cases it is better to ignore ground water and to take it into account by back calculating the angle of friction, which includes then the effect of water. However, this procedure is wrong for example when differences in a reservoir level are big.

Concluding remarks

The catalogue of initial rock slope failure mechanisms only comprises mechanisms having a clearly defined mechanical model. We often have to draw conclusions from a few vague surface structures as to what the interior structure or mechanism of a slope failure may be like. As in structural geology, it is an important criterion for the correct interpretation of structures to check if the mechanism in a certain case is possible not only in a geometrical or kinematical, but also mechanical way. Riedmüller (29) pointed out that eventually only a mechanical model can identify the true causes of a rock slope failure. Moreover, the numerical models (especially for the initial failure mechanism and for the run out) and their results can only be as good as the models they are based on (e.g. topographic, geologic).

The catalogue presented takes into account the geological setting and the geometry of the slope, the joint structure, the habitus of the rock blocks, as well as the mechanical behaviour of the rocks and of the rock mass (deformation and strength parameters). In order to classify and model a rock slope failure, close cooperation between geologist and engineer is therefore of paramount importance:

- ➪ Analysis of structures (observation and identifying of discontinuities and fractures) by the geologist, because the geologist is qualified for this work,
- ➪ Synthesis of a mechanism by both the geologist and the engineer,
- ➪ Modelling by the engineer, because the engineer is qualified for this work,
- ➪ Interpretation of results by both the geologist and the engineer,
- ➪ Back to analysis of structures?

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