Models for Landslide Behaviour with Large Displacements by the Particle Flow Code

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Numerical methods are essential tools for analyses of mass movements. As it is one have to distinguish between failure or detachment mechanism and the run-out. An ideal model should, therefore, simulate both the failure mechanism and the run-out, which so far has not yet been developed.

The Particle Flow Code (PFC) of the ITASCA Consulting Group is a new procedure on the basis of the Distinct Element Method and models the movement and the interaction of stressed assemblies of circular (2D) or spherical (3D) particles. The particles can be bonded at their contact points to form a solid body that may "fracture" due to progressive bond breaking. One major advantage of the new system is the possibility to model micro- and macroscopical processes at the same time.

Calibration of a PFC-material

Although it is relatively easy to assign chosen properties to a PFC model, it is often difficult to define such properties by corresponding the behaviour of the resulting synthetic material to that of an intended physical material (so that the behaviour of the resulting synthetic material resembles that of an intended physical material). For codes that model continua, the input properties (such as stiffness and strength) can be derived directly from measurements performed on laboratory specimens. For codes such as PFC that synthesize macro-scale material behaviour from the interactions of microscale components, the input properties of the microscopic constituents are usually not known. In this case, the rel-

Modellierung des Verhaltens von Massenbewegungen bei großen Verschiebungen mithilfe des Particle Flow Codes

Numerische Rechenverfahren sind ein wichtiges Hilfsmittel bei der Analyse von Massenbewegungen. Derzeit muss noch zwischen mechanischen Modellen des Versagensmechanismus und des möglicherweise dadurch ausgelösten Felsmassensturzes unterschieden werden, weil es noch kein Universalmodell gibt, das eine durchgehende Berechnung (mit Berücksichtigung oft außerordentlich großer Verschiebungen) ermöglicht. Ein neuartiges Verfahren zur Berechnung von Massenbewegungen stellt der Particle Flow Code (PFC) der ITASCA Consulting Group dar. PFC modelliert die Bewegungen und Wechselwirkungen von belasteten Elementensembles, bestehend aus kugel- oder scheibenförmigen Einzelpartikeln. Die Partikel können durch Verbindung an ihren Berührungspunkten zu einem Festkörper verbunden werden, indem durch eine progressive Schädigung der Bindungen die Entstehung und Ausbreitung von Trenn- und Scherbrüchen modelliert werden können. Das makroskopische Materialverhalten wird dabei durch die Kalibrierung der Mikroparameter (Partikelsteifigkeiten, Bindungsfestigkeiten) des Ensembles festgelegt. Dadurch ist es möglich, die progressive Schädigung des Materials (Desintegration) bei fortschreitendem Versagen zu berücksichtigen und damit Veränderungen im Versagensmechanismus mit fortschreitender Berechnungsdauer im Modell zu verfolgen. Durch die Anwendung des Particle Flow Codes auf die Versagensmechanismen Hangkriechen, Hart auf Weich und Knicken/Beulen wurden die Eignung von PFC verifiziert und vorhandene Modellvorstellungen überprüft. Dabei wurden sowohl einfache schematische Modelle zur Überprüfung der Fähigkeiten und Möglichkeiten des vorgestellten Verfahrens als auch konkrete Modelle für die Analysen von Massenbewegungen erstellt. Die vorgestellten Modellrechnungen haben die Eignung und das Potenzial des Particle Flow Codes zur numerischen Modellierung von Massenbewegungen – vor allem bei großen Verschiebungen – unter Beweis gestellt. Der große Vorteil von PFC liegt in der Möglichkeit, nicht nur den initialen Versagensmechanismus, sondern auch die Veränderungen des Mechanismus bei großen Verschiebungen zu modellieren.

Numerical methods are essential tools for analyses of mass movements. It must be distinguished between failure or detachment mechanism and run-out. An ideal model should, therefore, simulate both the failure mechanism and the run-out, which, however, has not yet been developed. The Particle Flow Code (PFC) of the ITASCA Consulting Group is a new procedure on the basis of the Distinct Element Method and models the movement and the interaction of assemblies of circular (2D) or spherical (3D) particles. The particles can be bonded at their contact points to form a solid body that may "fracture" due to progressive bond breaking. One major advantage of this method is the possibility to model micro- and macroscopical processes at the same time. The suitability of the Particle Flow Code has been verified by the application of PFC on the failure mechanisms "Slope creep", "Hard rock lying on a soft base" and "Buckling". Therefore some simple schematic models for the verification of the features and possibilities of the presented method as well as actual models for the analyses of real cases have been developed. The application of the Particle Flow Code has shown that PFC is extremely suitable for the numerical analysis of mass movements, especially if large displacements occur. The great advantage of PFC is that it is possible to model both the failure mechanism as well as the change of mechanisms at large displacements.

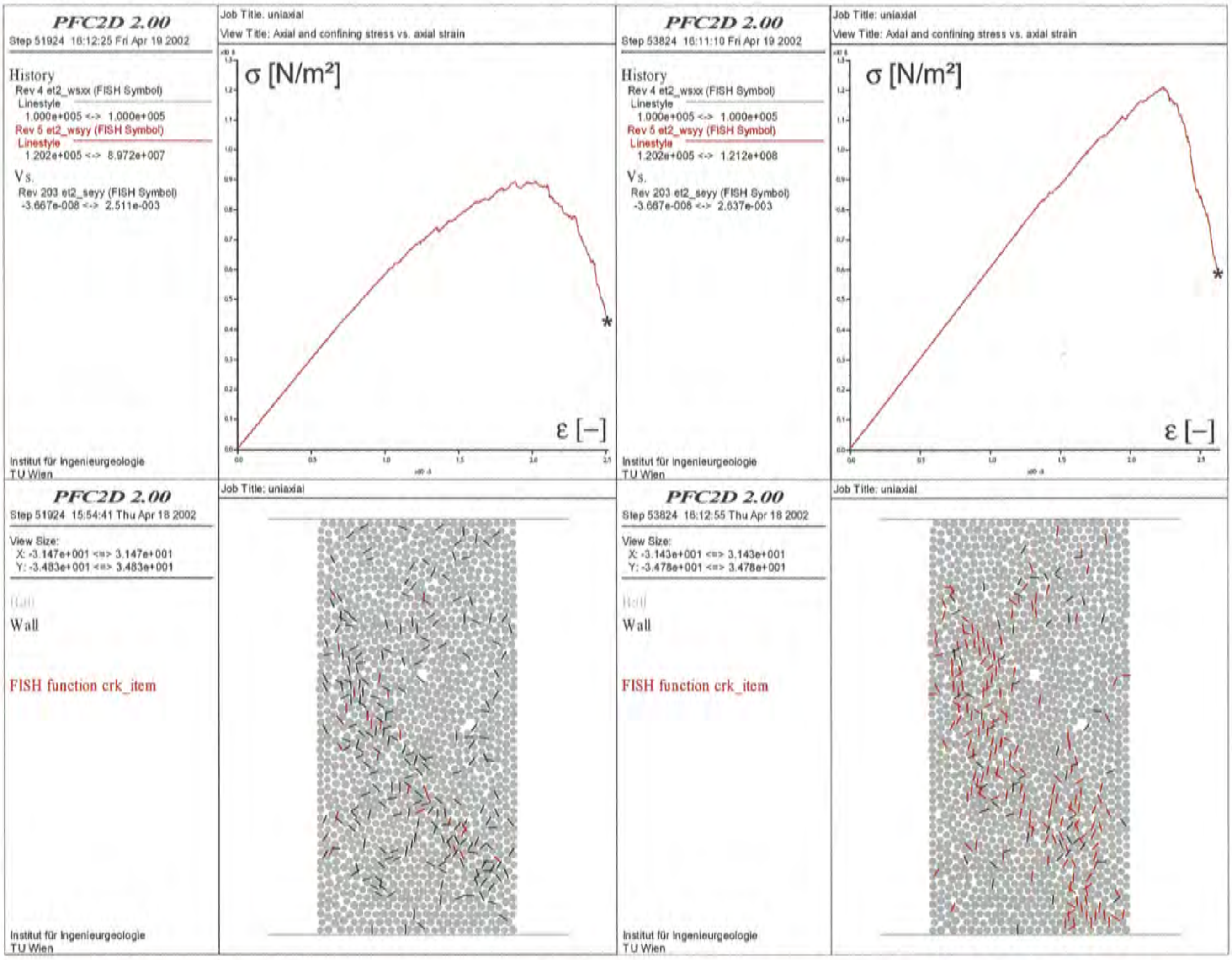

Fig. 1 Simulated uniaxial test: stress-strain curve and distribution of cracks (red: tension cracks, black: shear cracks) at final state (*); left figure – ductile material behaviour, right figure – brittle material behaviour.

***Bild 1** Simulierter einaxialer Druckversuch: Spannungs-Dehnungsdiagramm und Rissverteilung (rot: Zugrisse, schwarz: Scherbrüche) beim Endzustand (*); linke Abbildung – duktiles Materialverhalten, rechte Abbildung – sprödes Materialverhalten.*

evant behaviour (and response set that best characterizes these behaviour) of the intended physical material must be determined first, and then the appropriate microproperties are chosen by means of a calibration process in which the responses of the synthetic material are compared directly with the relevant measured responses of the intended physical material. This comparison can be made at both laboratory scale (e.g. triaxial and static-fatigue response) and field scale (e.g. back analysis of slope failures) depending upon the intended application of the PFC model.

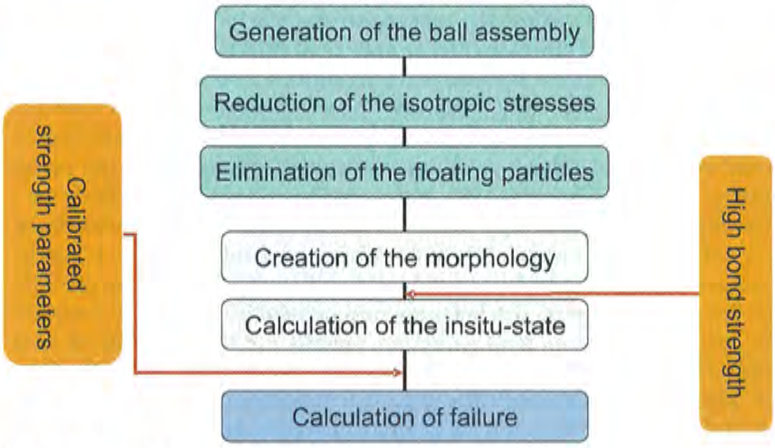

Fig. 2 Schematic diagram of model built up.

***Bild 2** Schematische Darstellung des Modellaufbaus.*

The ratio of contact-bond normal to shear strength affects the failure mode by controlling the relative numbers of shear- and tensile-failures. A PFC material with a small ratio will fail in a brittle fashion (failing predominantly in tension) while a material with a large ratio will fail in a ductile fashion (failing predominantly in shear). Figure 1 shows the stress-strain curves for a ductile (left part of the figure) and a brittle material (right part of the figure) and the distributions of microcracks.

Modelling procedure

The building up of a PFC-model takes place in six steps (Figure 2). In the first step, an irregular assembly is created by filling some given space with particles of given radii at a given porosity. The particle assembly is created using the method of radius expansion. In this approach, a population of particles with artificially small radii is created within the specified volume. A new particle will not be placed, if it would overlap another particle or a wall. The particles are then expanded until the desired porosity is obtained.

A correct in-situ stress state is of critical significance when calculating failure. The use of the radius expansion method creates an isotropic stress state. Depending on porosity, the particles can either be arranged without touching or there can be an overlap between them. The overlap induces stresses between the particles. If the stresses which are created by the radius expansion are too large, gravitation alone does not create correct initial stresses. For this reason, in a second step, the state of stress created by radius expansion is reduced by further manipulating the diameter of the particles.

When a numerical assembly of particles is compacted, even under the condition of zero friction, typically 10 to 15% of particles are found to have no or less than three contacts. These particles are termed "floaters" because they are detached from the material matrix and appear to be floating in space.

In physical specimens of an unbonded, granular material, such as sand, floaters are believed to exist, and it is therefore reasonable to accept their presence in a numerical specimen. If a particle model is used to represent a solid material, such as rock, each floater is equivalent to a void in the material. The effect of this inhomogeneity is unknown and may be small. To be on the safe side, an algorithm is used to eliminate the floating particles.

Having reduced the stresses which are resulting from expansion, and after taking away the floating particles, morphology of the slope is created by eliminating the particles above the edge of the slope (Figure 3). The initial stresses (Figure 4) are then calculated by activating gravity. High strengths of the bonds are set in order to avoid failure. Finally, the failure of the slope is induced by setting the calibrated bond strength (strength reduction).

Example applications

Slope creep

Slope creep is caused by the creep of rock masses, which is a material property and occurs in slopes as well as foundations and around tunnels in rock. According to decrease of the stress deviator with increasing depth in areas influenced by slope movements, creep of the rock mass and therefore displacements downslope decrease continuously with increasing depth (1).

When cohesion makes up a small part of the rock mass strength, the distribution of the dis-

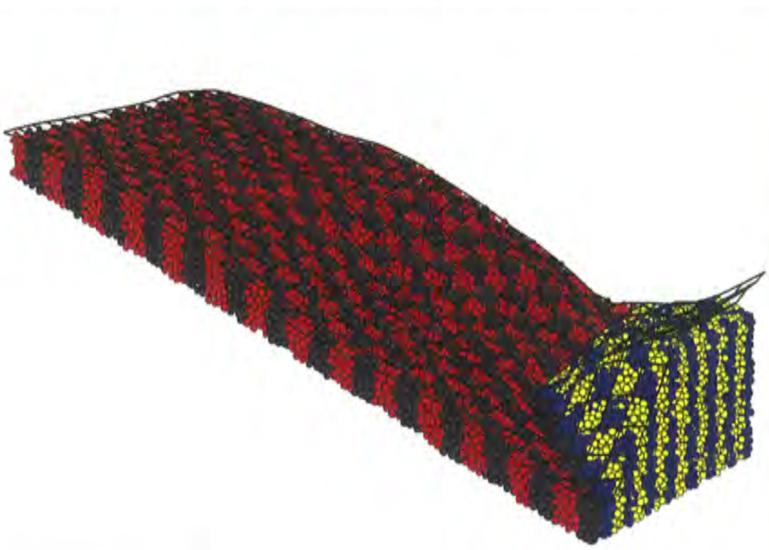

Fig. 3 PFC^{3D}-model.
Bild 3 *PFC^{3D} -Modell.*

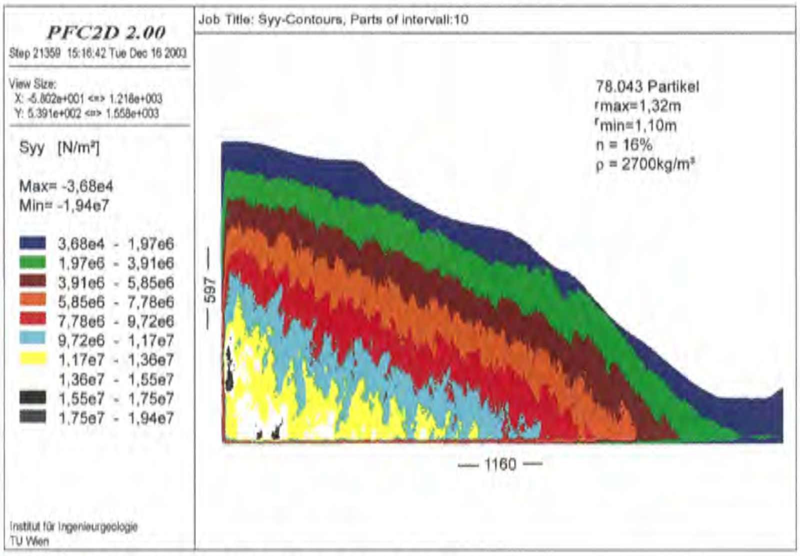

Fig. 4 Initial stress state, Vertical stresses contours.
Bild 4 *Initialspannungszustand, Konturplot der Vertikalspannungen.*

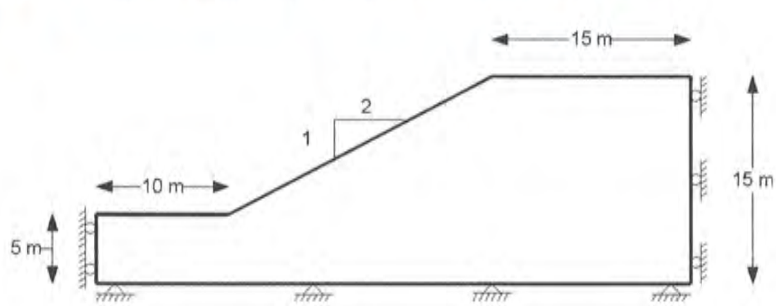

Fig. 5 Slope geometry.
Bild 5 *Böschungsgeometrie.*

Table 1 Material properties (macroparameters).
Tabelle 1 *Materialparameter (Makroparameter).*

ρ [kg/m³]	E [GPa]	ν [–]	c [kN/m²]	φ [°]
2.000	0.2	0.25	3	20

Table 2 Microparameters.
Tabelle 2 *Mikroparameter.*

Parameter		Description	Value
ρ_P	[kg/m³]	Particle density	2381
k_n	[N/m]	Particle normal stiffness	$4 \cdot 10^8$
k_s	[N/m]	Particle shear stiffness	$1.6 \cdot 10^8$
μ	[–]	Particle friction coefficient	0.1317

placement rates is progressive (outcrop bending), whereas if cohesion is larger, the distribution of the displacement rates indicates a zone of maximum shear strain rate at a certain depth (block slope creep).

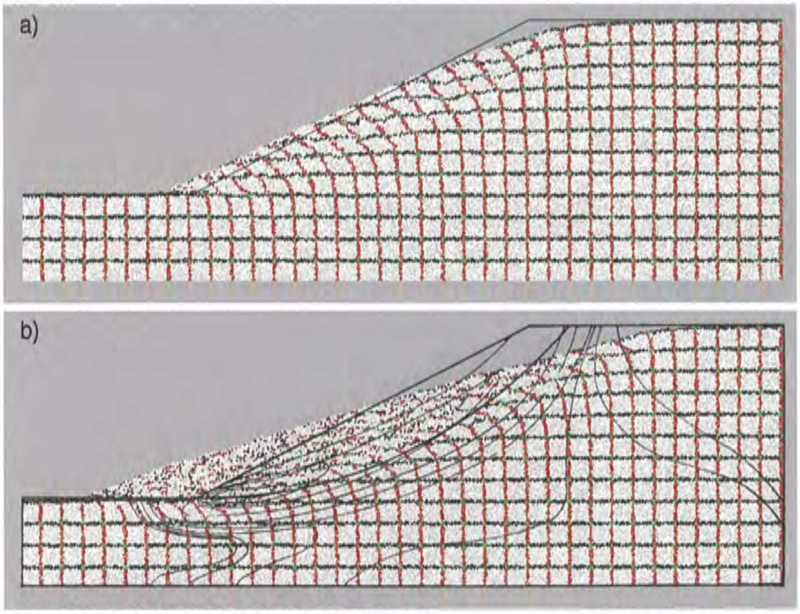

Fig. 6 Failure sequence; a) 200 000 calculation steps; b) 1 300 000 calculation steps.
Bild 6 *Phasen des Versagens; a) 200 000 Rechenschritte; b) 1 300 000 Rechenschritte.*

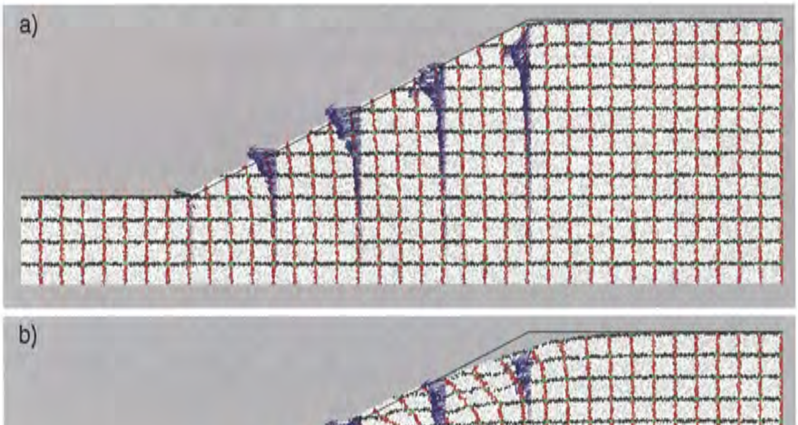

Fig. 7 Distribution of the displacement rates at five profile lines distributed over the whole slope; a) 50 000 calculation steps; b) 600 000 calculation steps.
Bild 7 *Verteilung der Verschiebungsgeschwindigkeiten in fünf über die Böschung verteilten Profilen; a) 50 000 Rechenschritte; b) 600 000 Rechenschritte.*

Zienkiewicz, Humpheson & Lewis (2) have investigated the rock slope shown in Figure 5 by means of the Finite Element Method. Table 1 shows a set of material properties for an unstable state of the slope near the limited equilibrium investigated by Zienkiewcz et al. using the shear strength reduction technique.

A PFC-model was built up for the slope investigated by Zienkiewcz et al. to compare the results calculated by PFC with the analysis done by means of the FEM-method. The microparameters for the PFC material were calibrated by the simulation of biaxial and drop tests (Table 2).

To identify the failure mechanism and the moving mass, a rectangular grid was laid on the slope by colouring particles (Figures 6 and 7). The deformation pattern of the grid-like coloured particles shows the typical features of a creeping slope (Figure 6):

- A zone of tensile stresses on top, forming "Graben"-like structures on the surface ("Bergzerreissung"),
- Continuously decreasing displacement rates with increasing depth as a result of rock creep (outcrop bending - red lines; Figure 6a),
- Loosening of the rock affected by the movements (Figure 6b).

Figure 6b shows a comparison of the detached rock volume calculated by the PFC- and the FE-model. The detached rock volume in the FE-model has been identified by the distribution of the shear strain rate (black contour lines) whereas in the case of the PFC-model the detached rock volume has been identified by deformation pattern of the grid-like coloured particles. Comparison of the results of the methods shows that the PFC-model gives approximately the same detached rock volume as the FE-analysis.

Figure 7 shows the changing of the displacement rates at progressive failure at five profile lines distributed over the whole slope as well as the transition from the failure mode slope creep to the failure mode sliding can be observed.

By means of PFC and the introduced method, it is possible to model the initial failure mechanism slope creep, the transition from slope creep to sliding and the following run-out in one model.

Hard, competent rock lying on a soft, incompetent base

Primarily, the failure mechanisms of this system are determined by the breaking and slipping of hard, competent rock and the squeezing out of the base material. The expressions "hard" or "competent" in this case relate to rock masses with rigid and brittle material properties (that is, rock blocks which fail through the formation and propagation of cracks in the uniaxial compression test, e.g. thick lime or marble). The term "soft" on the other hand is related to rock masses having a ductile or flowing behaviour in certain geological time periods.

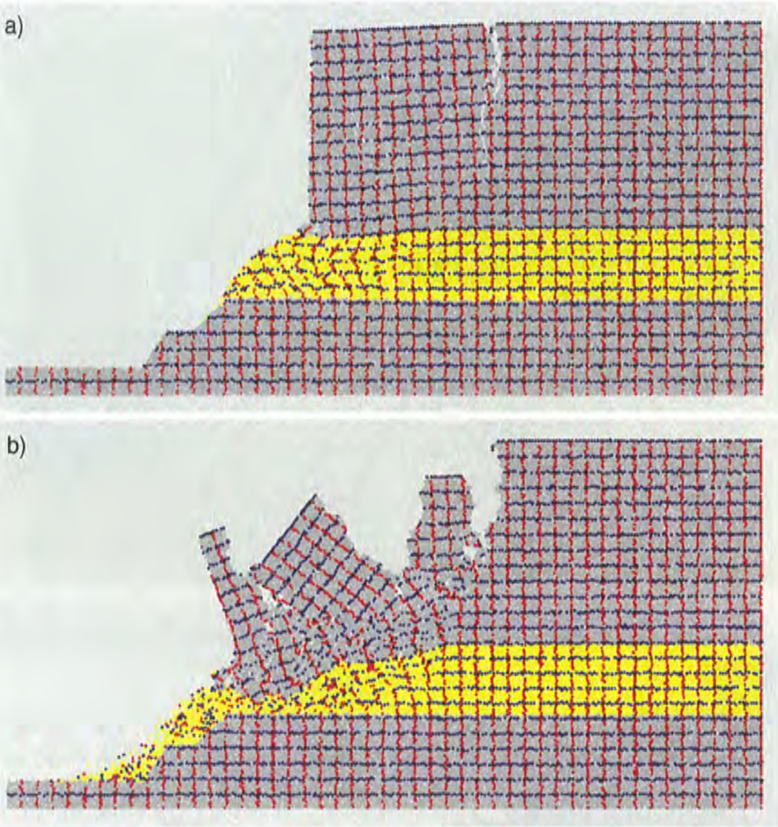

Fig. 8 Principle model of the system "hard rock lying on a soft base": a) failure of the model at 5 000 steps), b) failure of the model at 40 000 steps.

Bild 8 *Schematisches Modell des Mechanismus „Hart auf Weich": a) Versagen bei 5 000 Berechnungsschritten, b) Versagen bei 40 000 Berechnungsschritten.*

Established on model tests by Siberbauer (3) and numerical analyses using FLAC by Zettler (4), a principle model was developed (Figure 8) to check the suitability of PFC using the Contact bond model to reproduce the failure mechanism.

The application of PFC to analyse the failure mode "hard on soft" is demonstrated on the mass movement Murau in Styria/Austria. Figure 9 shows a simplified geological section through the examined slope, where hard marble layers are lying on a base of a soft and flaky phyllite.

A parameter study was carried out using FLAC to determine the material strength parameters for the case of a limit state equilibrium (5). Table 3 shows a set of material properties near the state of limit equilibrium. These macroproperties determined by FLAC were used for the calibration process of microproperties of the PFC-material. Table 4 shows the microparameters used in the PFC calculations calibrated by means of simulated material tests (Biaxial and Brazilien).

The main objective of the analysis of the mass movement Murau was to clarify whether the cracks observed in the marble could be explained with the assumed mode of failure "hard on soft". Currently, two active areas with cracks are shown in the up-to-date mapping. Figure 10 shows the state of the PFC model after 150 000 calculation steps. The areas with intense fracturing correspond to observations in nature. In the model the marble disintegrates completely with increasing movements, pushing continuously towards the valley (Figure 11).

PFC is extremely suitable for the analysis of the failure mechanism "hard on soft" as it is able to model the squeezing out of the base material, fracture processes in hard rock and run-out. Since parameter studies are, however, difficult to carry out because great effort involving in material calibration, it is useful to combine PFC with other FD or FEM codes.

Buckling

Buckling failure can occur in slopes built up by rock columns or rock slabs which are thin compared to the slope height. Failure by buckling may be initiated by forces external to the slab, by ground water pressures, by applied forces or by the weight of the slab itself, especially if the slab is curved convex.

The stability of the slope represented in Figure 12 was analysed using the PFC^{2D} for different slope angles, material stiffnesses and strength of the discontinuities. The results of the numerical

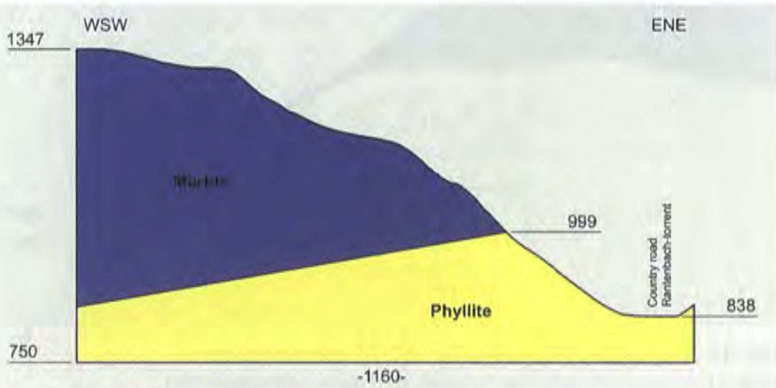

Fig. 9 Simplified geological cross section.

Bild 9 *Vereinfachter geologischer Schnitt.*

Table 3 Material properties (macroparameters).

Tabelle 3 *Materialparameter (Makroparameter).*

	ρ [kg/m³]	E [GPa]	ν [–]	c [MPa]	φ [°]	σ_t [kPa]
Marble	2 700	15	0.15	1.0	40	800
Phyllite	2 700	3	0.3	0.1	20	80

Table 4 Microparameters used in the PFC calculations.

Tabelle 4 *Mikroparameter.*

Parameter	Description	Marble	Phyllite
E_c [Pa]	Contact modulus	$15 \cdot 10^9$	$3 \cdot 10^9$
k_n/k_s	Particle stiffness ratio	2.3	2.6
μ	Particle friction coefficient	0.839	0.364
$\sigma_{c\,(mean)}$ [Pa]	Normal strength, mean	$24.5 \cdot 10^5$	$1 \cdot 10^5$
$\sigma_{c\,(std.\,dev.)}$ [Pa]	Normal strength, standard deviation	$12.3 \cdot 10^5$	$0.5 \cdot 10^5$
$\tau_{c\,(mean)}$ [Pa]	Shear strength, mean	$152 \cdot 10^5$	$8 \cdot 10^5$
$\tau_{c\,(std.\,dev)}$ [Pa]	Shear strength, standard deviation	$76 \cdot 10^5$	$4 \cdot 10^5$

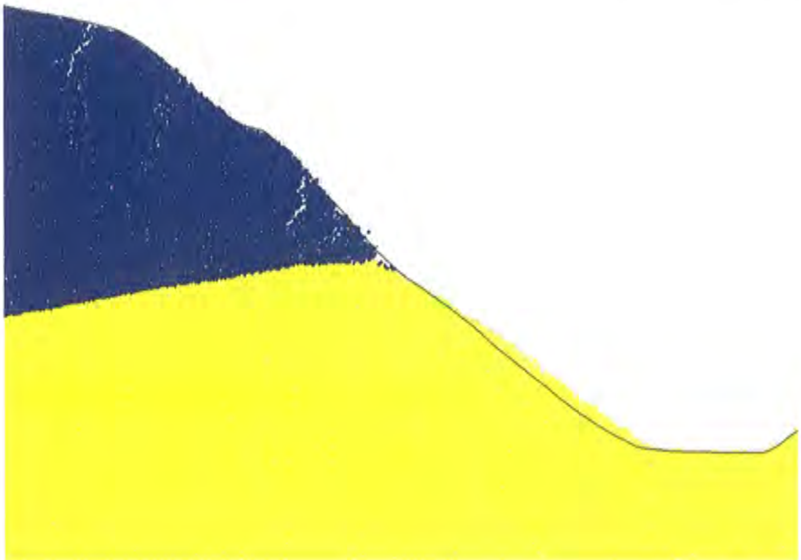

Fig. 10 Failure of the PFC model (150 000 steps).
Bild 10 *Versagen des PFC-Modells (150 000 Berechnungsschritte).*

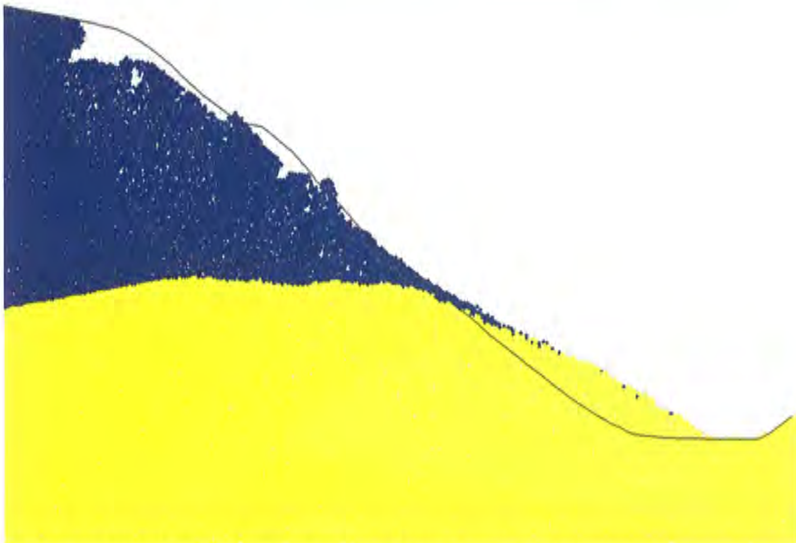

Fig. 11 State of the PFC model after 650 000 calculation steps.
Bild 11 *Zustand des Modells nach 650 000 Berechnungsschritten.*

investigations were compared with the analytical solution given by Cavers (6).

The material properties selected are listed in Tables 5 and 6. The stability of the slope was analysed for five different sets of material properties of the rock slabs and for two different parameters of the strength of the joints.

The critical slope angle α_{cr} was calculated for each possible combination of these parameters. The critical slope angle α_{cr} was determined by reducing the slope angle α starting from a slope angle of 80° in increments of 5° until a stable solution was achieved.

PFC was used to analyse the stability of only the foremost rock slab being modelled by orthogonally packed particles connected by parallel bonds. Linear wall elements simulate the bedrock (Figure 13). The particles are assumed to be disks of equal size with a diameter of 20 cm and a thickness of 1m. Thus, the rock slab of 80 m length and 80 cm thickness consists of 400 x 4= 1 600 particles.

A comparison with Cavers (6) analytical solution was made by modelling linear elastic material behaviour for the rock. Therefore, the normal and shear strengths of the parallel bonds were set at high values to avoid breaking of the bonds. By way of example, the influence of the material strength of the rock slab on the failure mechanism was investigated for one set of material properties (Table 5 – Set E; Figure 14).

In order to assess the stability of the rock slab, it was necessary to model a geometrical imperfection. Thus, an initial deflection of 10 cm was mounted in the bottom sixth part of the slab to force the rock slab to buckle (see Figure 13). The course of the deflection was approximated by means of a sinus function. In the case of a regular assembly, the microparameters can be calculated directly.

The numerical investigations show that the buckling length is about one quarter of the total slope length and that the Eulerian buckling formulae by Cavers overestimate the critical load for slopes which are almost vertical. Furthermore, they underestimate the critical load for lower inclinations with regard to the correct buckling length. The almost vertical slopes are therefore less stable than the Cavers model predicts with regard to the correct buckling length, while the slopes with lower inclinations are more stable than the Cavers model predicts with regard to the correct buckling length.

Table 7 shows a comparison of the derived critical slope angle between the PFC model

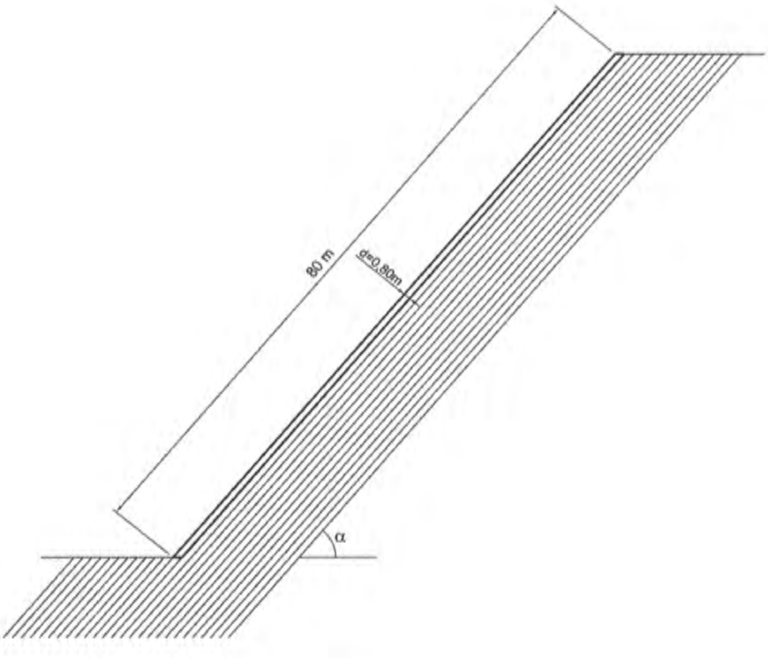

Fig. 12 Slope geometry.
Bild 12 *Böschungsgeometrie.*

Fig. 13 Buildup and bearing of the slab-shaped rock block.
Bild 13 *Aufbau und Lagerung des tafelförmigen Kluftkörpers.*

Fig. 14 Failure sequence – Transition form flexural to three-hinge buckling.
Bild 14 *Versagensablauf – Übergang vom Biegeknicken zum Dreigelenkknicken.*

and the adjusted analytical solution according to Cavers. The study shows that PFC can be used to calculate the buckling of rock slopes, but it is much more complex than analytical methods.

An advantage of PFC lies in the fracture mechanics it includes. Modelling the material failure of the rock slab plays only a minor role when determining the limit state equilibrium, as strength is not exceeded until after the loss of the stable equilibrium. A great advantage of numerical investigation is that the buckling length results from the calculation and does not need to be estimated.

Conlusions

The application of the Particle Flow Code has shown that PFC is extremely suitable for the numerical analysis of mass movements, especially if large displacements occur. The great advantage of PFC is it is possible to model both the failure mechanism as well as the change of mechanisms at large displacements.

Table 5 Material properties for the rock (macroparameter).
Tabelle 5 *Materialparameter der Kluftkörper (Makroparameter).*

Set of parameters	ρ [kg/m³]	E [GPa]	ν [–]	τ_{zul} [MPa]	σ_Z [MPa]
A	2 700	0.8	0.10	linear elastic	linear elastic
B	2 700	1.0	0.10	linear elastic	linear elastic
C	2 700	1.2	0.10	linear elastic	linear elastic
D	2 700	3.0	0.10	linear elastic	linear elastic
E	2 700	1.0	0.10	10	5

Table 6 Material properties for the joints.
Tabelle 6 *Materialparameter der Trennflächen.*

Set of parameters	c [kPa]	φ [°]
A	0	10
B	0	30

Table 7 Comparison of numerically and analytically derived critical slope angle (the comparably smaller slope angle is bold printed).
Tabelle 7 *Vergleich des numerisch und analytisch bestimmten kritischen Böschungswinkels (kleinerer Wert ist fett gedruckt).*

E [GPa]	φ = 10°		φ = 30°	
	PFC	Cavers	PFC	Cavers
0.8	55	**50**	60	**60**
1.0	60	**55**	**65**	70
1.2	**65**	70	**75**	80

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