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Modifications of PFC^{3D} for rock mass fall modeling

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ABSTRACT: Rockfalls are modeled as the movements of single rock blocks over a surface or as the movement of a viscous mass over a surface (e.g. DAN). In reality a mass of discrete, interacting rock blocks is moving downslope. Thus the program PFC^{3D} (Itasca 2005) based on the Distinct Element Method was modified in order to model rock mass falls realistically in 3 dimensions based on physical relations. According to observations in nature, several kinds of movements of the rock blocks (Broilli 1974) have to be distinguished during the computation (Bozzolo 1987): free falling, bouncing, rolling and sliding. In order to achieve an appropriate simulation of these different kinds of movements by *PFC*, some modifications using the implemented programming language (FISH) were necessary. The application of this method is demonstrated with the examples Punta Thurwieser (Italy) and Frank Slide (Canada).

1 INTRODUCTION

The initial failure of a slope can consist of the failure of one or more discontinuities (slip, opening) and/or a failure of the rocks (plastic deformations, formation of new fractures). Slope movements may thus increase, leading to the formation of more new fractures and mostly to complete disintegration and loosening of the rock mass. Thus a rock slope failure leads to the detachment of a rock mass consisting of a mass of blocks (e.g. caused by block toppling) and a run out starts in the form of a rock avalanche (Voight & Pariseau 1978) where rock blocks interact during the phase from detachment to deposition.

Interpretations of observations of run out rock slope failures (e.g. Heim 1932, Scheidegger 1973, Abele 1974), as well as experiments in the field and physical models, were the basis of run out prediction methods. Bagnold (1954) reported on experiments on a gravity-free dispersion of large solid spheres in a Newtonian fluid under shear, giving initial hints regarding the mechanisms of rock avalanches. Hsü´s (1975) experiments on bentonite suspensions suggested that the flow of thixotropic liquids is kinematically similar to the run out of rock slope failures. The results of the experiments showed that there is a positive semilogarithmic correlation between travel distance and the volume of the run out mass. Hungr & Morgenstern (1984) investigated the flow behavior of dry sand at high velocities by laboratory flume experiments. Hutter & Savage (1988) performed experiments with a granular mass in a chute, with a bed made up of two plane portions joined smoothly by a curved transition. They found positive agreement between the model test results and a numerical model using a Lagrangian finite difference scheme. Thus many ideas on run out prediction methods came from granular model tests.

Discontinuum (granular) mechanics methods model the run out mass as an assembly of particles moving down a surface. Each particle is followed exactly as it moves and interacts with the non moved bedrock and with its neighbor particles. Campbell & Brennen (1985) studied granular flows in a 2D numerical model using a code for molecular-dynamics calculations. Cao et al. (1996) studied the gravity driven granular flow of frictional particles down an inclined, bumpy chute by a numerical model that ensured the balance of momentum and energy.

Straub (1996) pointed out that a granular flow is a dissipative non-equilibrium system. It cannot be described without a fundamental modification to the classic thermodynamic framework. Such a modification is the assumption of a local equilibrium. He developed a model for rigid spheres with smooth or rough surfaces and for inelastic collisions. A function of restitution for the elastic properties and a Coulomb-type coefficient of friction for the surface roughness are the input parameters to model instantaneous dissipative interparticle collisions. Between the collisions, particles move along their ballistic trajectories.

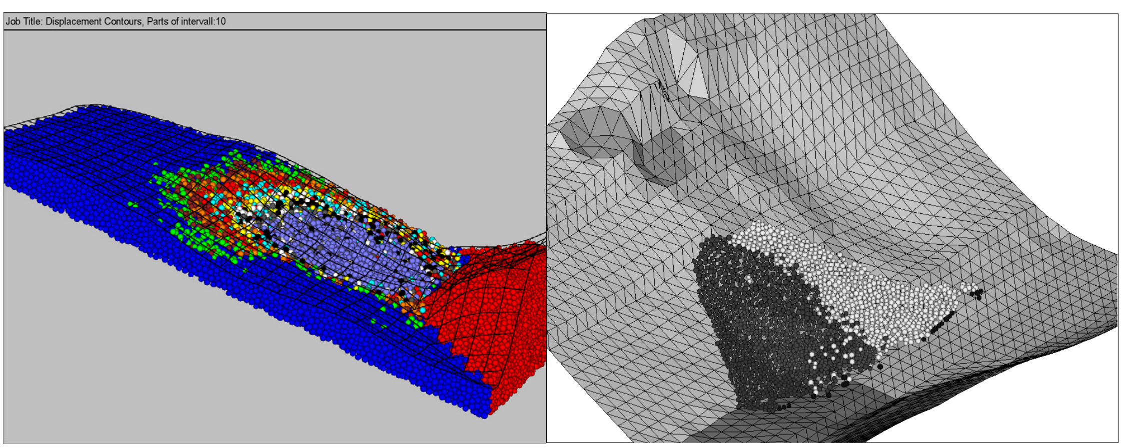
Will & Konietzky (1998) used the Particle Flow Code, *PFC*^{2D}, by Itasca in order to analyze rock fall and rock avalanche problems. *PFC* models the movements and interactions of stressed assemblies of spherical particles being in or getting into contact with wall elements. Every particle is checked on its contacts with every other particle in every time step. Roth (2003) adapted the contact management in *PFC*^{3D} in simulating rock avalanches in three dimensions.

Punta Thurwieser rock avalanche had a volume of some 2.2 Mio m^3 and reached a "Fahrböschung" of some 25°. Frank slide had a volume of some 36 Mio m^3 and reached a "Fahrböschung" of some 13°. Both run outs therefore fit well into the data of other mass movements showing that smaller volumes reach steeper "Fahrböschungen" and vice versa. It has to be assumed that this is due to the kinematics of run outs. Hungr (2007) reported that different parameters are necessary to model the run outs of smaller and larger volumes correctly using DAN (Hungr 1995). Therefore, Punta Thurwieser rock avalanche and Frank Slide were simulated using *PFC*^{3D} in order to find out whether *PFC*^{3D} can be used to simulate both steep and shallow "Fahrböschungen", and which parameters are needed to model them.

2 ADAPTATIONS NECESSARY FOR RUN OUT MODELING

PFC can simulate not only failure mechanisms of rock slopes but also the run out of a detached and fractured rock mass (Poisel & Roth 2004). Rock mass falls can be modeled as an "All Ball model" and a "Ball Wall model". An "All Ball model" (Fig. 1) simulates the slope as an assembly of balls bonded together. The simulation shows the failure mechanism of the slope due to gravity (Poisel & Preh 2004). After detachment of the moving mass, the run out is modeled automatically.

In the "Ball Wall model" (Fig. 1b) the underlying bedrock is simulated by linear (2D) and planar (3D) wall elements (Roth 2003). Therefore, an estimate or a model of the failure mechanism of the slope and of the detachment mechanism is needed as an input parameter. However, in the "Ball Wall model" the detached mass can be modeled using more and smaller balls with the same computational effort in order to approach reality better. The "Ball Wall model" offers the possibility to make use of the know-how related to run out relevant factors (coefficients of restitution, absorption, friction, etc.) applied in rock fall programs (Hoek 1987, Spang & Rautenstrauch 1988).



a) b)

Figure 1. a) All Ball model (Preh 2004), b) Ball Wall model (Frühwirth 2004).

According to observations in nature, several kinds of movements of the rock fall process (Broilli 1974) have to be distinguished during computation (Bozzolo 1987): free falling, bouncing, rolling and sliding. In order to achieve an appropriate simulation of these different kinds of movements by *PFC*, some modifications have been necessary using the implemented programming language (FISH).

In order to model the free falling of blocks, neither the acceleration nor the velocity (ignoring the air resistance) is to be reduced during fall as a consequence of mechanical damping. *PFC* applies a local, non- viscous damping proportional to acceleration, to the movement of every single particle as a default. The local damping used in *PFC* is similar to that described in Cundall (1987). This damping model is the best suited for a quick calculation of equilibrium. There arises, however, the disadvantage of the movements of the particles being damped as well. Therefore, the local damping has been deactivated for all kinds of particle movements.

Elastic and plastic deformations occur in the contact zone during the impact of a block. Both the kinetic energy of the bouncing block and the rebound height are reduced by the deformation work. The reduction of the velocity caused by the impact is modeled with the help of a viscous damping model integrated in *PFC*. The viscous damping model used in *PFC* introduces normal and shear dashpots at each contact (Fig. 2). The relation between the damping coefficient and the rebound height was/has been estimated by simulating drop tests (Fig. 3).

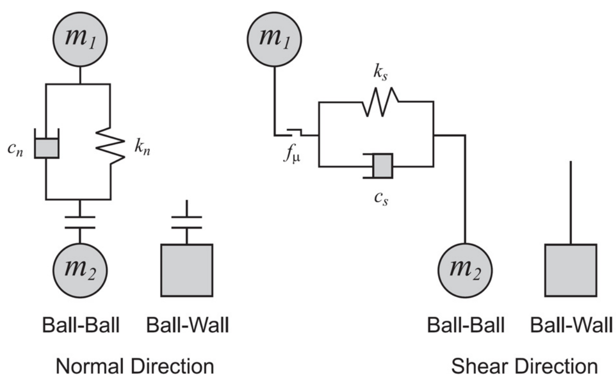


Figure 2. Viscous damping activated at a contact with the linear contact model (Itasca 1999).

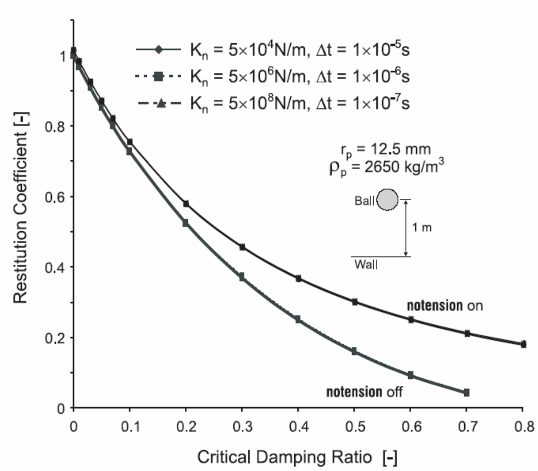


Figure 3. Relation between restitution coefficient and critical damping ratio (Itasca 1999).

The most important run out relevant effect is rolling resistance, because it is known that pure rolling of blocks in the model leads to more extensive run outs than observed in nature. The rolling resistance is caused by the deformation of the rolling body and/or the deformation of the ground and depends strongly on the ground and the block material (Preh & Poisel 2007).

Due to these deformations, the distribution of contact stresses between the ground and the block is asymmetric. Replacing the contact stresses by equivalent static contact forces results in a normal force N, which is shifted forward by the distance of c_{rr} , and a friction force F_{rr} , opposing the direction of the movement (Fig. 4).

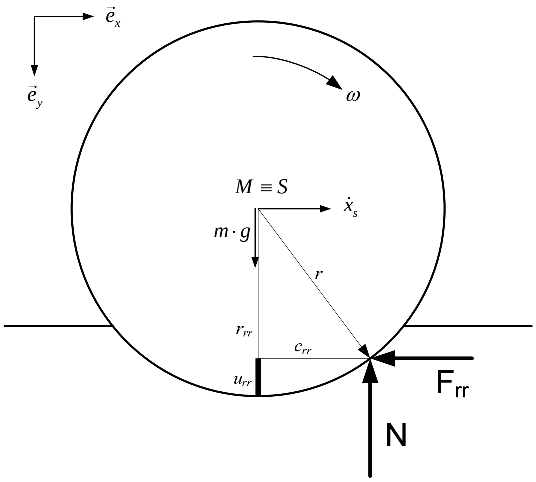


Figure 4. Calculation of the rolling resistance.

The deceleration of the angular velocity caused by the rolling resistance is calculated using conservation of translational momentum (Equation 1) and angular momentum (Equation 2).

$$m \cdot \ddot{x}_s = -F_{rr} \tag{1}$$

$$-I \cdot \dot{\omega}_{rr} = M_{rr} \text{, } I_{sphere} = \frac{2}{5} \cdot m \cdot r^2 \tag{2}$$

where M_{rr} is the resulting moment caused by the rolling resistance, I is the principal moment of inertia and ω_{rr} is the angular deceleration. The kinematic link is established by the condition of pure rolling (Equation 3).

$$\ddot{x}_s = \dot{\omega} \cdot r \tag{3}$$

The angular acceleration is defined by a finite difference relation in order to express the increment of the angular velocity per time increment. Therefore, the angular deceleration is calculated as

$$\Delta\omega_{rr} = \frac{-g \cdot c_{rr}}{r \cdot (r_{rr} - \frac{2}{5} \cdot r)} \cdot \Delta t \tag{4}$$

The rolling resistance is implemented by adding the calculated increment of the angular velocity to the angular velocity calculated automatically by *PFC* at every time step (Equation 5).

$$\omega_i^{(t)} = \omega_i^{(t)} + \Delta\omega_{rr,i} \tag{5}$$

According to these considerations, the rolling resistance is an eccentricity c_{rr} or sag function u_{rr}. The deeper the block sags, the greater the rolling resistance $\Delta\omega_{rr}$. In classical mechanics, the rolling resistance is a function of the ratio of the eccentricity c_{rr} to the radius r.

$$\mu_r = \frac{c_{rr}}{r} [-] \tag{6}$$

This means that spherical blocks of different sizes have the same run out for the same rolling resistance coefficient. In nature, however, it can be observed that large blocks generally have a longer run out than smaller ones. Therefore, according to the damping model described, the run out is calibrated by the sag u_{rr}.

The run outs of Punta Thurwieser as well as of Frank Slide were simulated using the modified *PFC* routine described above. The input material was provided by the Organising Committee of "The 2007 International Forum on Landslide Disaster Management, Hong Kong - Landslide Runout Analysis Benchmarking Exercise" (2007). The digital terrain models (DTMs) of the terrain before (detached block of expanded rock) and after the mass movement were converted into triangulated meshes. These meshes were used to generate wall elements simulating the detachment and the terrain surface. The detached rock volume was modeled by particles (balls). The run out process was started by deleting the wall elements above the detached rock volume.

3 PUNTA THURWIESER ROCK AVALANCHE

The triangulated meshes converted from the digital terrain models were used to generate 3348 wall elements, simulating the detachment and the terrain surface. The detached, mostly dolomite rock was modeled by 2632 particles (balls) with r_{min} = 6 m and r_{max} = 11 m (Fig. 5). After starting the run out process by deleting the wall elements above the detached rock volume, 250,000 time steps were calculated.

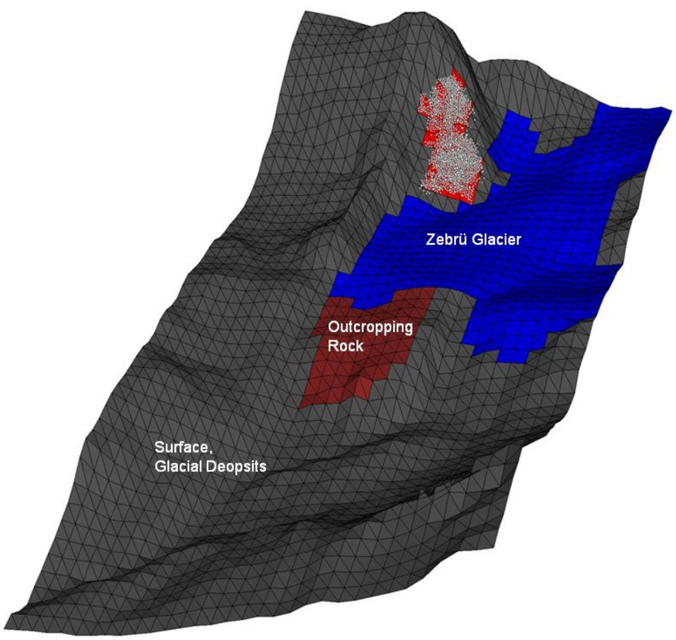


Figure 5. Punta Thurwieser terrain surface modeled by 3348 wall elements and detached rock volume modeled by 2632 particles.

According to the figures provided by the Organising Committee of "The 2007 International Forum on Landslide Disaster Management, Hong Kong - Landslide Runout Analysis Benchmarking Exercise" (2007) the terrain surface was divided into "glacier", outcropping rock" and "glacial deposits" (Fig. 5). Table 1 shows the parameters necessary to get results coinciding with observations at Punta Thurwieser Rock Avalanche. The positions of the particles after 25,000 computation steps (Fig. 6), after 50,000 computation steps and their final positions (Fig. 7) show agreement with the documented rock avalanche spreading. Coinciding with reality, the numerical model showed that a small rock portion fell in E-direction. The run out distance of this portion in the model is much too large (long arrow in Fig. 6). Presumably the roughness of the glacier in this area due to crevasses caused the blocks to stop at 3,100 m above s.l.

Table 1. Best fit parameters for simulating Punta Thurwieser Rock Avalanche.

Parameter	Description	Detachment Area	Glacial deposits	Glacier	Outcropping Rock	Particle interaction
φ [°]	friction angle	40	60	15	45	60
urr [m]	rolling resistance	0.5	0.4	0.6	0.4	-
βn[-]	critical damping ratio, normal direction	0.8	0.8	0.8	0.8	0.5
βs[-]	critical damping ratio, shear direction	0.8	0.8	0.8	0.8	0.5

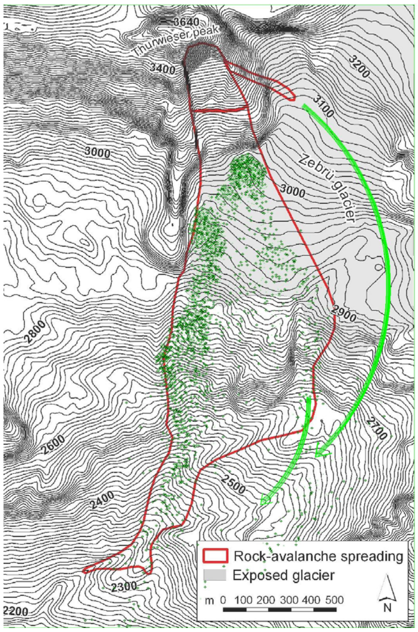


Figure 6. Particle positions after 63 seconds (25,000 steps).

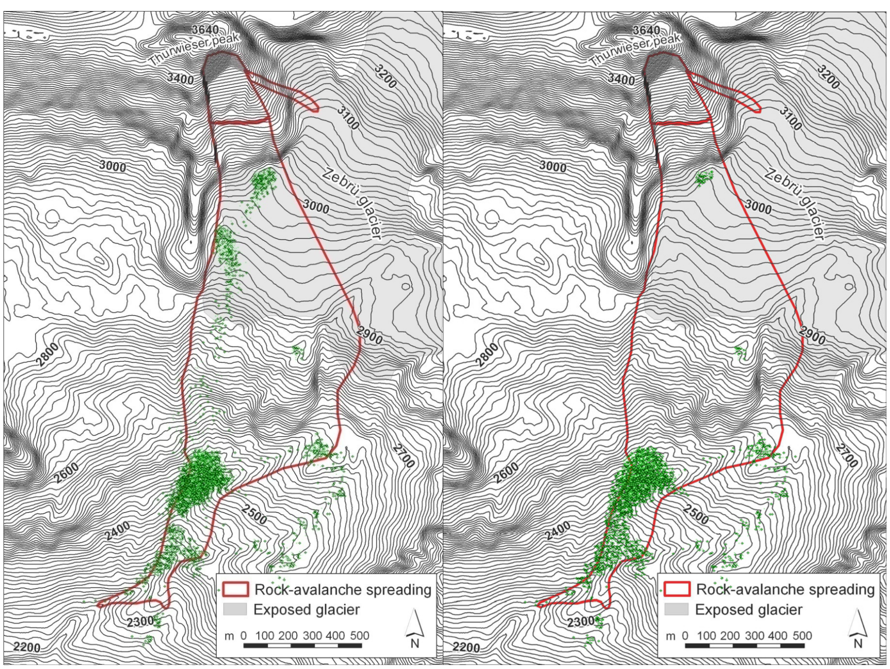


Figure 7. Particle positions after 124 seconds (50,000 steps; left) and after complete stoppage at 555 seconds (225,000 steps; right).

The final position of the particles and the deposition thicknesses in reality and in the model agrees fairly well. An even better coincidence between observed rock avalanche spreading and pathway of the particles in the numerical model could be achieved by a more exact terrain surface model (finer grid of the wall elements) and a more differentiated distribution of the glacial deposits and their parameters. This applies especially to the particles running out of the chute in the south-east of the outcropping rock (short arrow in Fig. 6). After 100 to 120 seconds the maximum travel distance of the rock avalanche is reached and after that only internal movements occur before the mass comes to final rest (Fig. 8).

4 FRANK SLIDE

The triangulated meshes converted from the digital terrain models were used to generate 3372 wall elements simulating the detachment and the terrain surface. The detached limestone rock was modeled by 19,691 particles (balls) with r_{min} = 10 m and r_{max} = 15 m (Fig. 9). After starting the run out process by deleting the wall elements above the detached rock volume, 30,000 time steps were calculated.

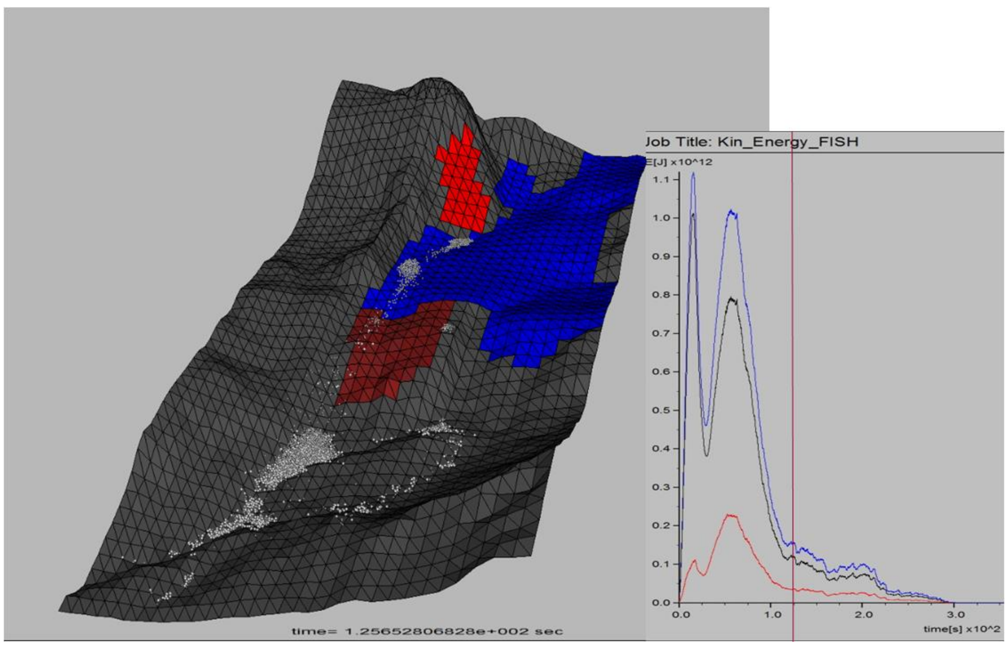


Figure 8. Positions of particles after 125 seconds and development of kinetic energy [J] over time (Rotational kinetic energy (red line), translational kinetic energy (black line), total kinetic energy (blue line)).

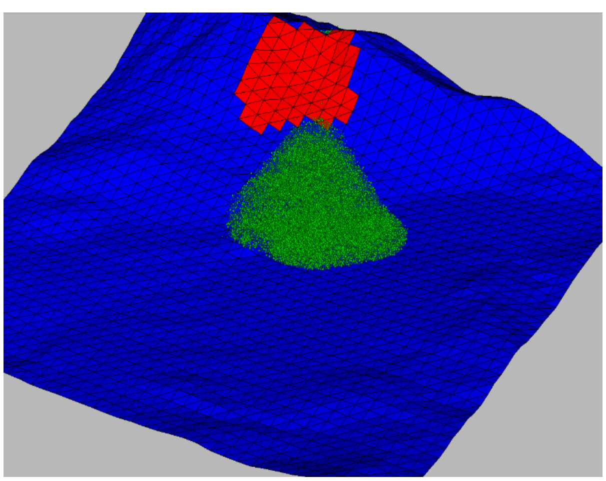


Figure 9. Frank Slide terrain surface modeled by 3200 wall elements and detached rock volume modeled by 19,691 particles.

Table 2 shows the parameters necessary to get results coinciding with observations at Frank Slide (comp. Cruden & Krahn 1978). The development of kinetic energy over time (Fig. 10) reveals a maximum after 25 seconds. At this point of time the center of gravity of the mass is passing the river. The small amount of rotational energy reveals that a coherent mass is sliding down slope (Fig. 10).

After 70 to 80 seconds the mass comes more or less to rest. Afterwards only minimal velocities and kinetic energies and therefore displacements (mostly backward movements) can be observed in the system. This corresponds well to observations in reality. The final positions of the particles in the *PFC* model (Fig. 11) show no particles at rest in the floodplain. This corresponds well to the observation in reality that only minor damming of the Crowsnest River (indicating that the landslide eroded some material from the floodplain) was observed after the landslide.

Table 2. Best fit parameters for simulating Frank Slide.

Parameter	Description	Detachment Area	Surface	Particle Interaction
φ [°]	friction angle	15	8	30
Urr [m]	rolling resistance	0.05	0.10	-
βn[-]	critical damping ratio, normal direction	0.5	0.5	0.3
βs[-]	critical damping ratio, shear direction	0.5	0.5	0.3

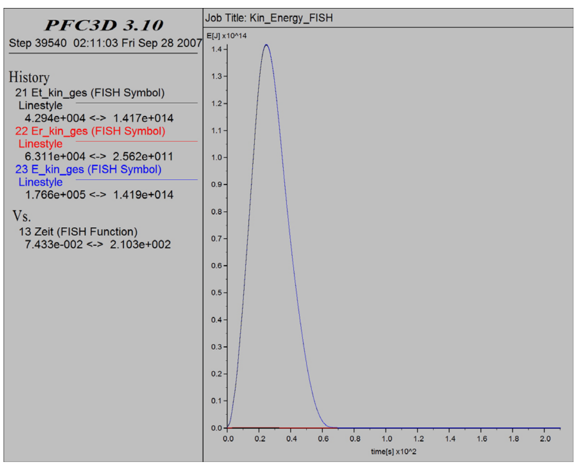


Figure 10. Rotational kinetic energy (red line), translational kinetic energy (black line), total kinetic energy (blue line) [J] over time [s].

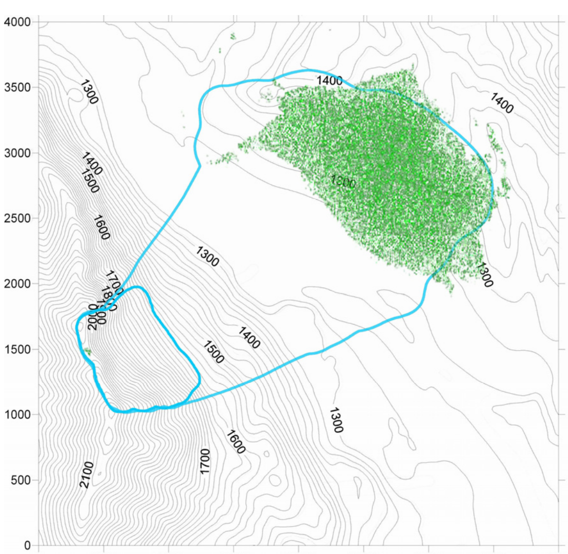


Figure 11. Final distribution of particles.

The DTM of Frank Slide shows a ridge in the northern part (orographically left) of the final pathway. This ridge greatly influences the final distribution of the *PFC* particles. However, the path plan does not show this ridge. The differences between the slide deposit and the final distribution of the *PFC* particles may be caused by this ridge.

5 COMPARISON AND CONCLUSIONS

The comparison of the *PFC*-models of Punta Thurwieser Rock Avalanche and of Frank Slide shows:

1 The parameters necessary to get results coinciding with observations in nature (Tables 1 & 2) are completely different.

2 The developments of mean particle velocities as well as of kinetic energy over time are completely different: there is much internal movement for a long time after reaching the maximum run out distance in Punta Thurwieser, but there is just some backward movement down the opposite slope after run up in Frank Slide.

3 Some 30 percent of total kinetic energy is rotational kinetic energy in Thurwieser, whereas the contribution of rotational kinetic energy in Frank Slide is zero.

Thus Frank run out is a real "slide" of a coherent mass (comp. Cruden & Krahn 1978), whilst Punta Thurwieser run out is a rock mass fall with much internal movement. The parameters for a run out simulation therefore have to be chosen in such a way that the simulation gives a rock mass fall in one particular case and a slide of a coherent mass in another corresponding to the real conditions. Hungr (2007) reported that different parameters are necessary to model the run outs of smaller and larger volumes correctly using DAN.

Punta Thurwieser rock avalanche as well as Frank slide fit well into the data of other mass movements showing that smaller volumes reach steeper "Fahrböschungen" and vice versa (Scheidegger 1973). However, it cannot be assumed that the volume is the only influencing parameter for the run out kinematics. Frank Slide and Randa Rock Fall had both approximately the same volume but very different "Fahrböschungen". The detachment mechanism (sliding, toppling, etc.; Poisel & Preh 2004), the morphology of the detachment surface (more or less undulated in case of a sliding failure mechanism etc.) have significant influence on the degree of loosening of the moving mass and on the trigger mechanism of the run out. The morphology of the pathway of the run out also has a great influence on run out kinematics.

Therefore, the prediction of the run out kinematics and the fixing of the parameters is a demanding task in each case when modeling run outs.

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