Back-Calculation of Medium-Scale Rockfalls Using an Empirical GIS Model

C. Fey alpS GmbH, Innsbruck, Austria
C. Zangerl alpS GmbH, Innsbruck, Austria
V. Wichmann alpS GmbH & Laserdata GmbH, Innsbruck, Austria
C. Prager alpS GmbH & ILF Engineering Consultants ZT GmbH, Innsbruck, Austria

Abstract

Rockfall events with volumes of 1,000 to some 100,000 m³ occur frequently in fractured rock masses. Generally, the runout behaviour of such medium-scale events is controlled by complex mechanical processes and therefore difficult to describe by physical models. As opposed to single rockfalls which are characterised by falling, sliding, rolling and bouncing of one or only a few isolated blocks with minor mechanical interaction, medium-scale events are characterised by considerable rock fragmentation and block interaction. Hence a relationship between failure volume and runout length can be observed.

So far hazard mitigation focuses primarily on runout prediction with models developed for single rockfall. These models are not designed to consider the non-linear relationship between volume and runout length. Within this study a simply empirical GIS-based model was developed which is able to estimate medium-scale rock fall process areas. This rockfall assessment is based on the runout travel angle and equivalent friction angle principles. The model was tested on several case studies in metamorphic rock masses and applied to back-calculate GIS model parameters. Limitations of the model approach were studied by means of sensitivity analyses. Generally, it was found that the model was able to reproduce the process area satisfactorily and may serve as a simple and fast tool for rockfall hazard assessment.

1 Introduction

The term “rockfall” is used for a wide range of failure volumes spanning from single blocks of less than 1 m³ to large-scale rock avalanches of several million m³ (Sturzstrom, Heim 1932, Hsü 1975). Whereas single block/rockfalls are characterised by falling, sliding, rolling and bouncing of one or only a few isolated blocks with minor mechanical interaction, large rock-avalanches move as coherent flow masses which are dominated by complex block interactions. Processes like dynamic fragmentation, undrained loading and acoustic fluidisation are discussed to considerably influence the dynamics and runout behavior of large-scale rock avalanches (Hutchinson & Bandhari 1971, Melosh 1979, Davies & McSaveney 2009). Whereas such large-scale sturzstroms are rather rare events, medium-scale rockfalls comprising failure volumes of 1,000 to some 100,000 m³ are relatively frequent. Therefore hazard assessment methods which focus on potential runout and process areas are required.

Concerning this only a few software codes are able to model block interaction and fragmentation. For example the Particle Flow Code (PFC3D) considers such phenomena and thus has the capacity to model a single rockfall as well as large-scale rock avalanches. Modelling of block interactions is very complex, time consuming, assumes simplified block surfaces and geometries (sphere) and requires also empirical parameters (Poisel & Preh, 2008). Other process-based algorithms describe either rockfall as single block movement (e.g. Bozzolo et al. 1986, Azzoni et al. 1995, Meißl 1998, Guzzetti et al. 2002, Krummacher et al. 2009, Dorren 2009) or rock avalanches (Sturzstrom) as a continuum (Hungr 1995, McDougall & Hungr, 2004).
The limitations for single block/rockfall models are their sensitivity towards empirical and physical parameters. Block shape properties have to be simplified (e.g. blocks represented as spheres or mass points) and slope properties have to be implemented based on empirical parameters (e.g. friction or restitution coefficients). Several studies conducted field and laboratory experiments to investigate kinematic, dynamic and material properties of falling blocks (Ritchie 1963, Broilli 1974, Erismann 1986, Bozzolo et al. 1986, Evans & Hungr 1993, Azzoni et al. 1995).

This study focuses on recent rockfall events in crystalline rock masses (Tyrolean Alps, Austria) with an occurrence frequency of decades or even less and failure volumes between 1,000 and 200,000 m³. In order to determine the accumulation path and runout length, a simple empirical model was implemented in a GIS. This model is based on a non-linear empirical relationship between volume and runout length. Advantages of this approach are: i) only a few input parameters are required, ii) simulation results can be obtained quickly, and iii) calculations can be performed using open source software (SAGA-GIS). The GIS model was applied on several rockfalls in Northern Tyrol (Austria) in order to back-calculate and determine input parameters for other case studies. Based on process areas thus obtained further 2D simulations (focussing on block energies, jump heights, protection measures) can be effectively planned.

2 Theoretical background

The basic principles of this study are based on the well-known empirical approach between failure volume and runout distance. The most common empirical runout models rely on the runout travel angle (Fahrböschung), equivalent friction angle and the minimum shadow angle (Heim 1932, Evans & Hungr 1993). These geometrical principles describe the simple relationship between travel distance and vertical fall height. The horizontal travel distance for the runout travel angle method is measured along the travel path from the top of the scarp to the furthermost accumulated runout block. For the equivalent friction angle method, the travel distance is measured along the beeline between the top of the scarp and furthermost block. For both methods the height difference is measured between the top of the scarp and furthermost block. The runout travel angle and equivalent friction angle is the arc tangent of the ratio between the travel distance and beeline, respectively and the height difference.

Compilations of numerous case studies show a semi-logarithmic correlation between rockfall runout distance and failure volume (e.g. Heim 1932, Scheidegger 1973, Abele 1974, Hsü 1975, Domaas 1985, Gerber 1994, Meißl 1998, Prager 2010), Figure 1 shows volumes and runout travel angles of rockfalls and rock avalanches compiled from several field studies. According to the lower bound envelope the runout travel angle for rockfalls with volumes of up to 1,000 m³ falls only in two cases below 38°. Runout angles for rockfalls with volumes up to 10,000 m³ do not fall below 33° and for volume of up to 100,000 m³ not below 26°. The spread in runout travel angles results from i) slope morphology, ii) terrain surface roughness and attenuation, iii) block/failure mass geometry, iv) material properties and fragmentation of the rock mass, v) water and ice content and vi) measuring errors due to localising the top of the scarp and furthermost block.
Figure 1. Semi-logarithmic correlation between runout travel angle and volume (compilation of literature and field data, Prager 2010).

3 Model

The model Rock Runout is a GIS based analyses tool. It is written in C++ and can be used as a module library in SAGA GIS, an open source GIS software. Based on user-defined scarp areas and a digital elevation model (DEM) this model enables the simulation of rockfall process areas. The critical threshold values of the runout and equivalent friction angles are the key parameter of the model and are obtained from well investigated case studies.

The GIS model requires i) a disposition model which defines the source/failure area as starting cells, ii) a digital elevation model (DEM) for the trajectory model which calculates the process path and iii) a runout model which determines the stopping criterion for the algorithm.

3.1 Disposition model

The disposition model is a user-defined grid (raster data) which represents the source area (cells) of the rock fall. It can be determined from geological field observations and/or from GIS based slope topography analyses (e.g. slopes steeper than a threshold value are prone to rockfall).

3.2 Trajectory model

A trajectory model based on four empirical parameters is applied to simulate the travel path (process path) of the rockfall. Therefore a grid-based random walk algorithm (dfwalk from Gamma 2000) in combination with a Monte Carlo approach is applied (Wichmann 2005). Each disposition grid cell represents a starting cell for the trajectory calculation on the DEM. All neighbour cells surrounding the starting cell are part of a 3 by 3 matrix (window). The elevation of the starting cell is compared to the elevation of the surrounding neighbour cells. All cells implying a lower elevation are chosen as potential flow path cells. The probability for each lower neighbour cell being part of the process path depends on two parameters: the slope threshold ($\gamma_{\text{thres}}$) and the divergent flow control ($a$). Thus the set of potential flow path cells can be restricted with these two parameters.
In order to consider the impact of the slope inclination on the lateral rockfall dispersion the slope threshold ($\gamma_{\text{thres}}$) parameter was defined. It reduces the number of potential flow path cells by a threshold angle, for example $65^\circ$. Above this angle no lateral dispersion is possible and the rockfall path follows the direction of the steepest slope gradient.

The second user-defined parameter, the divergent flow ($a$) affects the random walk algorithm and thus also influences the lateral dispersion. The persistence factor ($p$) increases the probability that a neighbour cell is chosen as a potential path cell if the flow direction does not change considerably. This parameter reduces sharp bends (kinks) in the travel path.

The calculated probabilities are used to randomly select one of the neighbouring cells as pathway and the procedure is repeated until a stopping criterion is met (see section 3.3). For each starting cell, several random walks are calculated (Monte Carlo simulation). Each run results in a slightly different process path. The number of iterations can be defined by the user, whereas at least a value of 1,000 is useful. The number of transits through a cell (transit frequency) provides a relative measure of process intensity (Wichmann 2005, Wichmann & Becht 2006).

Generally the algorithm stops when no lower neighbour cells are available. In some cases this may lead to a too early termination of the trajectory simulation and thus to an underestimation of the process area. This may occur when i) the DEM features small-scale depressions or obstacles even at ranges of a few decimetres (so that no deeper lying neighbour cell is available) and/or ii) when larger rockfalls (up to 100,000 m³) fill up small-scale topographic depressions that are subsequently overrun by further debris reaching larger travel distances. Hence in order to avoid a too early and unrealistic algorithm stop a fourth user-defined parameter, the flow height ($f_h$), was newly introduced.

3.3 Runout model

The criterion when the calculation of the trajectory path terminates is implemented in the runout model. This model requires only one single key-parameter, either the user-defined runout travel ($\alpha_{\text{input}}$) or the equivalent friction angle ($\beta_{\text{input}}$).

Runout travel angle model:

The model computes the travel length along the process path between the starting cell and every newly selected descendant cell. For each calculation step the arc tangent of the ratio between the travel length ($d_{\text{tr}}$) and the vertical height difference ($\Delta h$) is determined and compared with the user-defined input value for the runout travel angle. If the calculation gains values equal or below $\alpha_{\text{input}}$ the algorithm stops and the maximum runout length along this path is obtained.

$$\arctan\left(\frac{\Delta h}{d_{\text{tr}}}\right) \leq \alpha_{\text{input}}$$

[1]

Equivalent friction angle model:

This model calculates the Euclidean distance (beeline) between the starting cell and every newly selected descendant cell. Again, for each calculation step the arc tangent of the ratio between the Euclidean distance ($d_{\text{ed}}$) and the vertical height difference ($\Delta h$) is determined and compared with the equivalent friction angle. The trajectory models stops when the calculated value is equal or below the user-defined $\beta_{\text{input}}$.

$$\arctan\left(\frac{\Delta h}{d_{\text{ed}}}\right) \leq \beta_{\text{input}}$$

[2]
4 Selected case studies

4.1 Geological setting

The study sites are located in the Tyrolean Alps (Austria) in the poly-metamorphic Ötztal-Stubai complex of the Austroalpine nappe units. This complex consists mainly of folded and faulted metamorphic rocks like paragneisses, micaschists, orthogneisses and amphibolites. The majority of the rock fall events originated from competent augenpeissic or amphibolitic rock masses, but also from some steeply inclined paragneissic rock slopes. Given that in all cases presented herein pre-failure monitoring was not performed the rock fall triggers are unknown so far. Nevertheless it is assumed that precipitation and/or temperature fluctuations influenced the failure process of these events. Beside this, it was found that the structural predisposition i.e. meso-scale fractures and brittle fault planes control the location and geometry of the rock slope failures.

One of the largest rockfall events of this study, the Luibiskogel rockfall (13.Nov.1999) originated from a steeply inclined amphibolitic rock face and mobilised a failure volume of more than 200,000 m³ (Fig. 2). Along the runout and proximal accumulation path the failing masses were canalised and then dispersed up on pre-existing talus deposits. The accumulated boulders show block-sizes of more than 5 m edge lengths (Fig. 2). The primary failure surface i.e. the 75 m high and 70 m wide head scarp, was clearly structurally predisposed by a pre-existing brittle fault zone.

In the same year (11. March 1999) another impressive rockfall occurred at Huben, gaining a similar volume than the Luibiskogel event (Fig. 3). This rapid and unexpected event reached the Ötztal valley floor, destroyed a newly built saw mill, crossed the main road and stopped close to the river (Ötzaler Ache). The main road was covered by block debris on a length of approximately 100 m and a thickness of about 4 m. Post-failure field mapping showed that the source area is located primarily in amphibolites and, to a minor extent, in granitic orthogneisses. Favourably for slope failure orientated meso-scale fractures influenced the failure behaviour.

Figure 2. Luibiskogel rockfall source (head scarp) and accumulation area (left), and large-scale amphibolitic boulders (right).
In the nearby surroundings of Huben und Luibiskogel, two smaller rock fall events were investigated at Astlehn and Auerbach (Fig. 3, 4). At Astlehn a 15,000 m$^3$ slab of amphibolitic and paragneissic rock collapsed along meso-scale fractures. Whereas the main portion of the rock fall mass was deposited after a travel distance of less than 300 m from the head scarp, a few blocks were canalised in a gully and reached the valley floor more than 700 m below. The 15,000 m$^3$ Auerbach event originated from an orthogneissic (augengneissic) rock mass and shows a runout path along a deeply incised and sharp bended gully.

Figure 3. Huben (left) and Astlehn rockfall (right) showing head scarps, transit and accumulation areas.

Figure 4. Auerbach rockfall showing the head scarp (left) and the deposition area of augengneiss blocks (right).
Further rockfall events in the Ötztal, Pitzal and Kaunertal valley (all Tyrol, Austria) were studied to obtain empirical key-parameters (travel runout angle, equivalent friction angle, volume; see Table 1) for runout backcalculation. Many of these case studies are characterized by multi-phase failure, whereby the exact failure dates are unknown. Due to this, the estimation of the volumes and source area geometries may imply some uncertainties.

Although all these events occurred in metamorphic rock masses and show clear structural predispositions, the substrate and the topographic characteristics of the rock fall path is considerably variable. The rock fall paths or at least sections thereof are localised either in narrow gullies or wide slopes, which means a variable degree of lateral constraint. Furthermore the rockfalls ran out on different types of substrate e.g. glacial till, talus deposits, pre-existing rock fall deposits and/or valley floor deposits. And finally also the density and type of vegetation cover along the flow path is highly variable.

### 4.2 Field-based runout travel and equivalent friction angle

The runout travel and friction angles were determined by field observations, and analyses of aerial views and digital elevation models. A 1 m grid DEM based on airborne laser scanning (Federal Government Tyrol) as well as a 10 m DEM based on photogrammetric analysis (Federal Office of Surveying Austria) was available. Values for equivalent friction angle and runout travel angle are shown in Table 1. At the case studies Astlehn, Auerbach and Luibiskogel (all Ötztal valley) a few boulders were canalised and deposited far below the main accumulation area. Thus Table 1 differentiates between the main accumulation area (MA) and the distalmost deposits (DD). In some cases it was not possible to identify the furthermost travelled boulder. At some multi-phase failure events it was difficult to differentiate between recently deposited boulders and older ones. And locally e.g. at the Wassertal rockfall (Pitztal valley) lower parts of the deposits have been eroded by post-kinematic debris flows.

<table>
<thead>
<tr>
<th>Rockfall</th>
<th>Volume [m³]</th>
<th>Runout travel angle measured [°]</th>
<th>Equivalent friction angle measured [°]</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Äußerer Bliggkopf (Kaunertal)</td>
<td>&lt;5,000</td>
<td>MA = 39.0° to 37.0°</td>
<td>MA = 41.6°</td>
<td>unknown (multi-phase event)</td>
</tr>
<tr>
<td>Obergurgl (Ötztal)</td>
<td>5,000</td>
<td>MA = 40.3°, DD = 40.3°</td>
<td>MA = 40.3°</td>
<td>unknown (multi-phase event)</td>
</tr>
<tr>
<td>Wassertal (Pitztal)</td>
<td>5,000</td>
<td>MA = 47.8°, DD = unknown</td>
<td>MA = 46.9°</td>
<td>post 2000</td>
</tr>
<tr>
<td>Breite Lehn (Ötztal)</td>
<td>10,000</td>
<td>MA = 34.2°, DD = unknown</td>
<td>MA = 34.2°</td>
<td>unknown (multi-phase event)</td>
</tr>
<tr>
<td>Winnebach (Ötztal)</td>
<td>10,000</td>
<td>MA = 35.0°, DD = unknown</td>
<td>MA = 35.0°</td>
<td>2006</td>
</tr>
<tr>
<td>Astlehn (Ötztal)</td>
<td>15,000</td>
<td>MA = 39.8°, DD = 35.8°</td>
<td>MA = 40.0°, DD = 36.1°</td>
<td>spring 2007</td>
</tr>
<tr>
<td>Auerbach (Ötztal)</td>
<td>15,000</td>
<td>MA = 45.7°, DD = 37.0°</td>
<td>MA = 48.9°, DD = 47.0°</td>
<td>2008</td>
</tr>
<tr>
<td>Huben (Ötztal)</td>
<td>200,000</td>
<td>MA = 34.1°, DD = 34.1°</td>
<td>MA = 34.1°, DD = 34.1°</td>
<td>11.03.1999</td>
</tr>
<tr>
<td>Luibiskogel (Ötztal)</td>
<td>215,000</td>
<td>MA = 33.8°, DD = 31.9°</td>
<td>MA = 35.7°, DD = 32.3°</td>
<td>13.11.1999</td>
</tr>
</tbody>
</table>
5 Model parameter calibration and back-calculation of case studies

In order to obtain empirical parameters for the hazard assessment of new case studies, the model input parameters have been calibrated on well-known rockfall events. Therefore well-exposed case studies were investigated to determine the failure volumes and process areas (source, transit and accumulation area). Based on this, the four trajectory model parameters ($\gamma_{thres}$, $a$, $p$, $f_h$) and the two user-defined parameters (runout travel and equivalent friction angle) were varied in order to obtain a best fit of the simulated and field mapped process areas. Subsequently, for the model and parameter evaluation, the best-fitting user-defined GIS runout travel and equivalent friction angles were compared with those obtained from the case studies in Table 1.

A difficult task of the back-calculations relates to the pre-failure topography: the airborne laser scanning flights were performed 2006 i.e. after the occurrence of the majority of rockfall events presented herein; thus a reconstruction of the pre-failure topography (without the rockfall deposits) is necessary to perform the back-analyses with the original slope conditions. This reconstruction was carried out on 1 m contour lines which were generated from a DEM for the whole study area. Considering the topographic characteristics of the slope areas adjacent to the rockfall process areas, the 1 m contour lines of the scarp and accumulation areas were modified to obtain the pre-failure slope geometry. The resulting contour lines were interpolated and form a newly generated pre-failure DEM grid. This approach avoids potential boundary differences (breaklines) between the original (post-failure) and modified (pre-failure) DEM which may affect the simulation process (trajectory path). This interpolation process smoothens the terrain and causes for steep slopes (ca. >65°) considerable elevation inaccuracies in the DEM. For slopes flatter than 65° the inaccuracy is insignificant and does not decisively affect the simulation results.

5.1 Model parameter calibration

The four model parameters were calibrated by back-calculations of selected case studies. Therefore they were systematically varied and model results were compared with mapped accumulation boundaries. For the slope threshold a fixed value of $\gamma_{thres}=65°$ was used; above a slope inclination of 65° no divergence is allowed and the algorithm chooses only one neighbour cell, i.e. the cell with the highest vertical gradient. In order to represent the lateral spread of the process area the GIS model yields good results by using a value of 1.6 for the divergent flow control parameter $a$. Furthermore a persistence factor of $p = 1.5$ has been applied to achieve a best fitting of the process area (accumulation area). The parameter flow height was varied for each case study depending on the raster resolution of the DEM and topographical situation.

5.2 Verification of the runout model

After calibration of the model parameters the runout angles were verified. Therefore a comparison between the measured runout travel angles ($\alpha_{measured}$) and equivalent friction angles ($\beta_{measured}$) and the user-defined input values were performed (see Table 1).

5.2.1 Travel angle runout model

Simulation results show that the model input value $\alpha_{input}$ required to fit the process area adequately deviates from the measured value $\alpha_{measured}$. In order to represent the mapped runout, the user-defined $\alpha_{input}$ has to be lower than the measured field value, $\alpha_{measured}$. Sensitivity analyses showed that $\alpha_{input}$ depends strongly on the setting of the parameters for dispersion, i.e. slope threshold as well as the divergent flow control, the flow height, the slope geometry and the raster resolution. Parameter settings allowing a higher degree of dispersion enable a longer travel path. For example a higher value of the divergent flow control parameter increases the number of possible selected neighbour cells and hence the trajectory does not always follow the path of the steepest descent. This in turn will cause numerous changes of the path direction and the stopping criterion i.e. the arc tangent of the ratio between vertical height difference and travel distance is met earlier. This lead to an underestimation of the real runout length. For example a too early termination of the travel path has been observed at the uniformly inclined slopes at Breite Lehn (Table 1). In this case the vertical gradient between the centre cell and all neighbour cells
is similar. Thus all neighbour cells have more or less the same probability being potential descendant cells. This will cause frequent changes in the travel direction with an increase of the trajectory length and finally a stop the algorithm. A similar effect is observed for high resolution DEM grids where small-scale surface structures may influence the travel path length (see section 3.3).

5.2.2 Equivalent friction angle runout model

The equivalent friction angle algorithm yielded reasonable results for the back-calculation, i.e. the difference between the user-defined $\beta_{\text{input}}$ and the measured field value $\beta_{\text{measured}}$ is very low. A minor trend was that $\beta_{\text{input}}$ tends to be a little higher than the real equivalent friction angle $\beta_{\text{measured}}$. As opposed to the travel runout model the equivalent friction angle model marginally overestimates the rockfall process areas. This algorithm is more stable than the travel angle runout model because it is based on the arc tangent of the ratio between the beeline and the vertical height difference. Thus the length of the simulated travel path has no influence on the result and a too early stopping of the algorithm (see section 5.2.1) is avoided.

6 Results and discussion

The process areas simulated by Rock Runout fit satisfyingly to the mapped process areas of the selected case studies. In a few cases lateral dispersion was over- or underestimated. In all case studies except Huben these variations are small and a consequence of model simplifications as well as DEM effects (e.g. Luibiskogel and Auerbach, Fig. 5). Further uncertainties were caused by the difficulty to localise exactly the failure and deposition areas and the reconstruction of the pre-failure DEM. As a constraint Rock Runout is not able to directly consider surface properties and other obstacles, i.e. dense forest. For example in Astlehn the runout length of the rockfall may be affected by the afforestation.

The quality and resolution of the digital elevation model has a considerable influence on model results. For example it was difficult to get reasonable results for the medium-scale rockfalls Huben and Luibiskogel if the calculation were based on a 1 m DEM. The reason behind can be found in the high resolution of the laser scanning DEM which is in the range of a few decimetres and show the micro-relief at high detail. Small obstacles and depressions in the DEM lead to an abortion of the algorithm or deflection of the process path. Whereas for events between 1,000 to 10,000 m$^3$ this solution fits with field observations, this is not the case for the rockfall events Huben and Luibiskogel characterised by several 100,000 m$^3$. Rockfall deposits are able to override these minor obstacles. On the other hand modelling of small rockfalls in the range of several 1,000 m$^3$ based on a 10 m raster resolution DEM lead to an overestimation of the lateral spread of accumulation area. In addition, the coarse raster size causes difficulties in defining the detachment areas (e.g. Auerbach and Astlehn). Figure 6 shows the model results of the rockfall Astlehn on a 1 m raster and on a 10 m raster. It was found that rockfall modelling based on a 10 m DEM leads to an overestimation of the lateral extension of the process.

The parameter flow height is required to model medium-scale rockfalls like Huben and Luibiskogel. The failing masses at Huben ran out on a valley floor with a small depression parallel to the slope (Fig. 7). In the GIS simulation this small depression leads to a deflection of the process path by almost 90° and a too early abortion of the simulation because no neighbour cells at lower elevation exist. In this case the path finding algorithm is not able to model the field observed runout of the rockfall.

The applicability of the two runout models was tested. The runout travel angle model in combination with the random walk trajectory model has considerable limitations for the estimation of the process area. It was found that the runout travel angle is highly sensitive to model parameter settings, the slope geometry and the raster resolution. It contrast the equivalent friction angle runout model is less sensitive and is more appropriate to estimate rockfall runout. Results showed that the measured equivalent friction angles and input equivalent friction angles do not vary significantly.
Figure 5. Back-calculation of the process area of the Luibiskogel rockfall (top) with model parameters: $\alpha_{\text{input}}=33.8^\circ$, $a=1.6$, $p=1.5$ and the Auerbach rockfall (bottom) with model parameter: $\alpha_{\text{input}}=35.5^\circ$, $a=1.6$; $p=1.5$. Red line represents field-mapped process area.
Figure 6. Back-calculation of the process area of the Astlehn rockfall with model parameters: $\alpha_{\text{input}}=32^\circ$, $a=1.6$; $p=1.5$. Raster resolution of 1 m (top) and 10 m (bottom). Red line represents field mapped process area.
Based on the case studies and on values from literature a runout travel angle of $\alpha = 32^\circ$ was found to be most suitable to assess potential rockfalls with volumes up to 100,000 m$^2$. Given that the empirical semi-logarithmic correlation is primarily based on a volume and runout travel angle relationship, the equivalent friction angle is less dependent from the volume; but strongly relates on the topography of the runout area. Especially, bended runout paths lead to larger equivalent friction angles (e.g. Auerbach due to a deeply incised gully). The same rockfall event showing a straight runout path would yield a flatter equivalent friction angle. Hence it is less suitable using the equivalent friction angle model to estimate the runout of rockfalls characterized by intensively curved paths. For rockfalls with rather straight travel paths the equivalent friction angle and runout travel angle show similar results.

Based on these cases studies the rockfall process area can be assessed by the combination of the equivalent friction angle model with the user-defined runout travel angle value. For slopes with straight runout areas the model will yield good results. In the case that the travel path is strongly deviated by bended channels or gullies (e.g. Auerbach) the process area is rather overestimated.

### 7 Conclusions

Hazard assessment with Rock Runout provides a simple and quick approach to estimate rockfall process areas. It shows an overview of potentially affected areas and outlines main rockfall trajectories. The advantage of Rock Runout compared to complex process-based models is its simplicity. The model is fast calculating and implemented in open source GIS. It only requires a digital elevation model, a source area grid and the key parameters, the equivalent friction angle and/or runout travel angle, respectively. Due to the high calculating speed different scenarios and feasibility studies at a local or regional scale can be performed.

### 8 Acknowledgement

The authors wish to thank the Tiroler Wasserkraft AG (TIWAG), A-6020 Innsbruck, ILF Consulting Engineers Ltd., A-6063 Rum, GEO.ZT GmbH, A-6060 Hall, and FFG (COMET) for supporting this work.
9 References


