Chapter 5

Methods for Predicting Rockfall Trajectories and Run-out Zones

5.1. Introduction

Rockfall is a rapid and rather spontaneous natural hazard. It is a natural process that poses problems in many areas downslope from rocky outcrops throughout the world. To predict the potential rockfall threat, it is not only required to estimate the stopping point or the runout of falling rocks, but also to quantify their kinetic energies, passing (or jump) heights, for each point along their fall paths as well as reach probabilities of the rocks. Therefore, a rockfall trajectory study requires the use of a rockfall simulation model to produce a susceptibility map or a hazard map.

However, simply applying a rockfall trajectory simulation model does not suffice. A serious rockfall study, requires different phases that have to be prepared and executed thoroughly. For example, during a preparation phase, all existing information has to be gathered, a field study has to be carried out and the simulation data has to be prepared. Only then, a rockfall trajectory study can be started. In this chapter, we will go systematically through all the phases required for completing a consistent rockfall trajectory study.

Rockfall has a lot of different meanings. A widely used definition refers to quantities of rock falling freely from a cliff face. More specifically, we define rockfall as one or several fragments of rock (blocks) detached by sliding, toppling, or falling, that fall along a vertical or sub-vertical cliff and proceed down the slope by bouncing and flying along ballistic trajectories (Figure 5.1) or by rolling and sliding (cf. [VAR 78], [WHI 84]). This chapter deals with this type of rockfall, it

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Citation:

Dorren, L.K.A., Domaas, U., Kronholm, K., Labiouse, V. 2011. Methods for predicting rockfall trajectories and run-out zones. In: S. Lambert & F. Nicot (eds.). Rockfall engineering. ISTE Ltd. / John Wiley & Sons Inc.: pp. 143 - 173.

does not treat rockslides or rock avalanches (Figure 5.2). These terms refer to rock failures where material collapses en masse and moves down the slope in a flowing mode ([WHI 84], [HEI 32]).

Figure 5.1. *Video sequence of a single rebound from the full scale experiments carried out in France (cf. [DOR 05], image from Cemagref, France)*

Figure 5.2. *Deposit of a large rock slide at Ramberg, Flakstad, Lofoten, Norway, where the failed rock mass moved down the slope in a flowing mode of motion. This type of process is not treated in this chapter (Photo U. Domaas)*

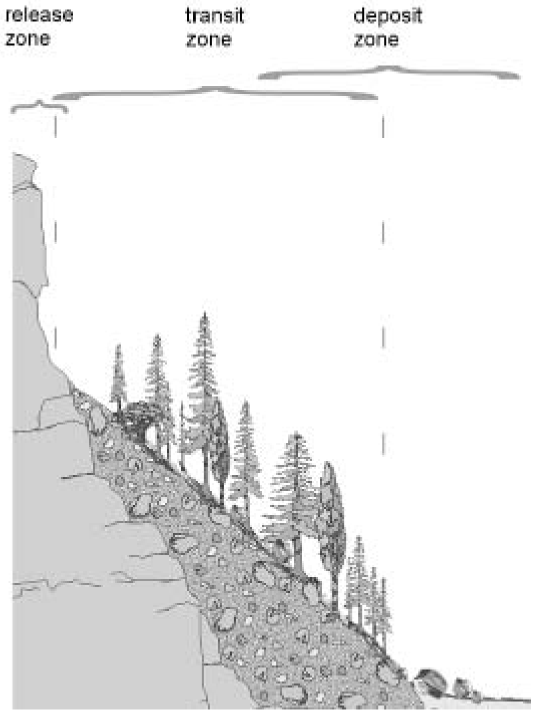

Figure 5.3. *The three typical zones on a slope where rockfall is active*

When dealing with rockfall trajectography, it is common to define three important zones on each slope where rockfall is active (cf. Figure 5.3). The uppermost is the release area (also called release zone, source zone or starting zone), which is the area where rockfalls initiate and move down the slope. In most cases this corresponds to a rocky outcrop forming a cliff or rock face (Figure 5.4), or even small rock ledges, but in some cases it might be loose rocks deposited on large mountain slopes that are remobilized. The second one is the transit zone, which is the area that is traversed by the falling rocks. In many cases this zone corresponds to the area where rocks are free falling along the cliffs and bouncing on the steep talus slopes below the release zone. The last one is the deposit zone, which is the area where rocks stop moving. Logically, the deposit zone and the transit zone are overlapping and boundaries between them are therefore not strict for different rocks at the same site. In areas where a scree or talus has formed, most of the rocks come to rest. Some of the larger rocks may travel further. The terms scree and talus are often used interchangeably, although a Google search will confirm that scree mostly refers to accumulations of gravel like material and talus to rock accumulations with particles larger than those in scree.

Figure 5.4. *A rockfall release area close to Vemork, Rjukan, Norway showing previous rockfalls and rock slides, as well as remaining potential rock fall volume of 28 000 m3.Very often a rockslide and rockfall occur similarly and it is therefore not always easy to make a distinction (Photo U. Domaas)*

Research on rockfall has been carried out since the 19th century ([BAL 75], [LAN 86], [LEH 33]) and the first modelling approaches that could be used for predicting runout zones were already developed by [HEI 32]. The first mathematical treatment of rockfall trajectories, however, dates from the sixties ([RIT 63]). From that time onwards, computer models have been developed for numerical simulation of rockfall trajectories. In parallel to model development, experimental studies, although less, have been carried out to improve the understanding on rockfall energies and rebound model parameters, as well as the role of forests. Examples are full scale ([BRO 74], [BOZ 86], [HES 87], [JAH 88], DOR 05]) and laboratory (half-scale and small-scale) experiments ([KIR 75], [CHA 02], [UEH 03], [HEI 04], [PIC 05]).

Before we will describe currently existing models, we will firstly introduce a typical workflow of a rockfall trajectory study that should be completed to ensure consistent and relevant results. It can be divided into 6 phases (Figure 5.5). These six phases are:

A. preparation phase

B. definition of the release scenarios

C. rockfall simulation

D. plausibility check / validation of the simulation results

E. fixation of the model results

F. transformation into rockfall process maps

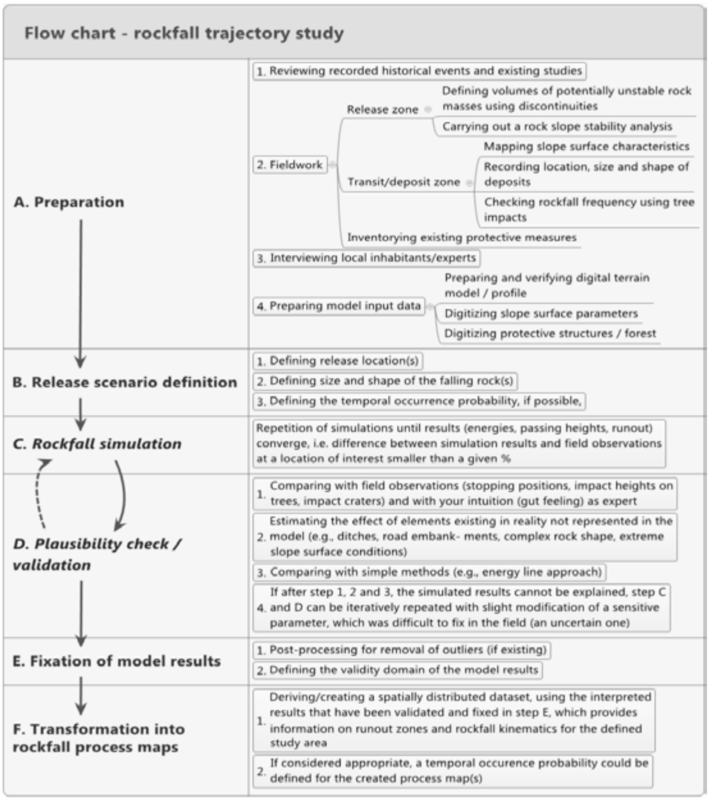

Figure 5.5. *An example of a workflow diagram for a consistent rockfall trajectory study*

Whether all six phases are actually carried out depends on the level of detail of the rockfall trajectory study. In general, three different levels, which are in a sense levels of aggregation, can be defined ([BAF 11]. The first level (L1) provides an overview, which is mostly, but not necessarily, used at the regional scale with the objective to obtain a rapid, first indication of rockfall runout zones for large areas. In Switzerland, these maps are literally called hazard indication maps. In other countries, these are often referred to as susceptibility maps. The second level (L2) is a local view, which is mostly, but not necessarily, applied at the scale of a community. This accounts often for hazard maps. The third level (L3) zooms in on a (part of a) single slope. This highly detailed level can be required for very precise questions regarding, for example, the stability of a bridge pillar threatened by a falling rock.

In cartography, the L1 would roughly represent map scales of 1:50’000 - 1:10’000, L2 would correspond to 1:10’000 – 1:5’000 and L3 to 1:5’000 – 1:1’000. For a trajectography study at the level L1, phase D, E and F of the workflow are mostly left out. This is firstly because a plausibility check for a complete region is rarely possible. Secondly because in hazard indication or susceptibility maps the raw model outcomes are displayed rather than post-processed model results.

By using the indicated workflow, we will go systematically through all the phases required for completing a rockfall trajectory study. The chapter will be closed with an outlook towards possible future improvements in methods for predicting rockfall trajectories and runout zones.

5.2. Preparation of a rockfall trajectory study

A serious rockfall trajectory study requires a comprehensive preparation phase. During this phase, firstly records on historical rockfall events that occurred at the given study site must be collected and evaluated. Here, local historical books and maps provide important information as well. These records should at least contain information on when, where and what rockfall event occurred. This means that the date of the rockfall event, the precise location of the event (if possible start and deposit point) and the size of the fallen rocks should be known. All these records should be reviewed and checked on their plausibility and uncertainty. This overview of historical events gives a first overview on the magnitude and frequency of rockfall events at the study site. Unfortunately, comprehensive records hardly exist. When data is lacking on the site of interest, records on slopes with similar features (e.g, geology, topography, roughness and surface material) may help in getting some information. In parallel, existing rockfall hazard studies provide useful information.

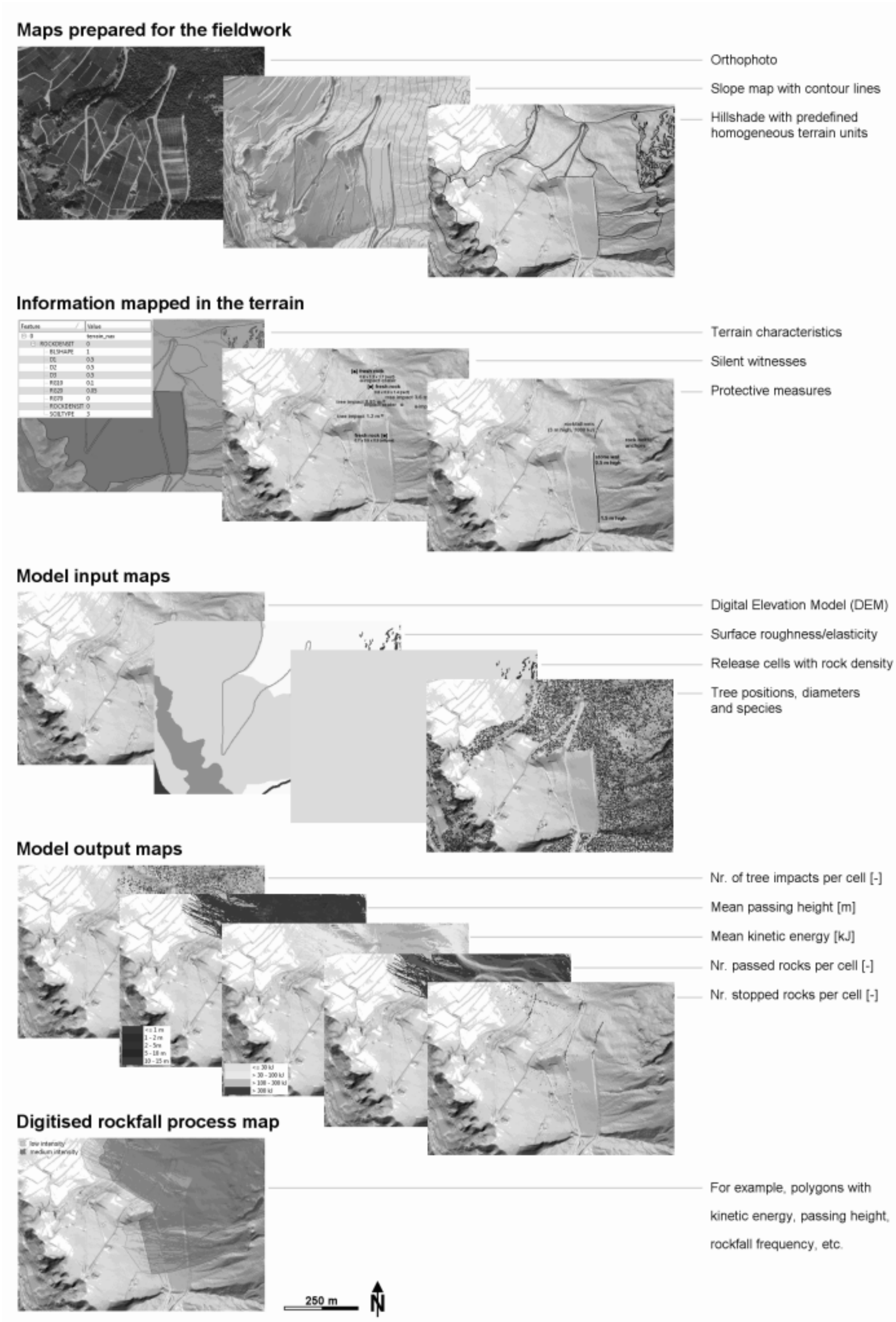

Figure 5.6. *Maps involved in a trajectory study using Rockyfor3D ([DOR 11])*

During the preparation phase it is crucial to carry out a field study to characterize and map the release zone, the transit and the deposit zone, as well as the existing protective measures. Therefore, prior to the actual fieldwork, a set of maps, which can be used in the field, has to be prepared and printed (see Figure 5.6). In the release zone, the structural properties (discontinuities, etc.) and the stability of the rock mass have to be analyzed (cf. Chapter 1 and 2 of this book). In the transit and deposit zones, the slope surface characteristics have to be mapped and recorded (see Figure 5.6). In general, these slope characteristics can be represented by the strength, stiffness, roughness and inclination of the surface material ([LAB 99]). These characteristics are very important, since they determine the energy loss and transfer between translational and rotational components during the rebound. As such they also determine the trajectory of the block (Figure 5.7). Here surface refers also includes the first meters in the underground of the slope (Figure 5.8).

Figure 5.7. *Video scene showing the variability of trajectories of different rocks originating from the same release area, which are not only due to different rock sizes but also small irregularities in the underground. (Photo Betongrenovering Drift AS, Norway)*

In addition, if the barrier effect of an existing forest is taken into account, which cannot be neglected in many cases (cf. [DOR 05]), the forest characteristics need to be inventoried and mapped. This includes the species composition, the stem density and the diameter distribution, as well as the spatial distribution of the different forest stands and couloirs or slits in the forest. Simply defined, a stand is a forest area with homogeneous characteristics. Laserscanning data allows us nowadays to map the forest automatically using difference between the digital surface model (DSM) and the digital terrain model (DTM) (cf. [PER 02], [DOR 06], [MON 10]).

Figure 5.8. *Not the moss cover, but the underground hidden under the moss cover is relevant when characterizing the slope surface for a rockfall trajectory study*

Moreover, all silent witnesses of rockfall activity have to be mapped and recorded, including size, shape and position of deposited rocks originating from the release area, rockfall traces in the release area, distance between rockfall impact craters as well as their depth, spatial distribution and heights of rockfall impact wounds on tree stems (cf. [MIK 06], [SCH 08]) and damaged branches (Figure 5.9). Finally, all technical protective measures (nets, dams, rock bolts and anchorages, wooden barriers, galleries, guard rails along roads) have to be recorded as well (see Figure 5.6). Their position, type and estimated energy absorption capacity, as well as their size or height must be noted. Important additional sources of information are local inhabitants and experts working in the area, as they mostly know about recent and/or frequent rockfall events. It might be good to carry out the fieldwork before interviewing locals, so as to carry out the fieldwork as unconditioned as possible. This means in other words, not having prefixed ideas about potentially unstable volumes and runout distances, which increases the chance of capturing unexpected phenomena. Then again, leading questions during the interview with locals in the areas of interest must be avoided to improve the quality of the obtained information.

Figure 5.9. *Silent witnesses resulting from large rocks cutting through a pole wood type forest (Photo F. Berger)*

The final phase of the preparation is to make ready the data needed for the rockfall simulation. This includes the creation of a slope profile or a DTM and thorough checking of the obtained DTM. Further, it includes the attribution of all required simulation parameters to input polygons maps or slope segments and exporting the data in the right format (see Figure 5.6). Both for 2D and 3D models, the resolution of the input maps or the level of detail of the slope profile is of great influence on the modelling results ([AZZ 95], [CRO 03]; [DOR 04]). For the DTM it can generally be said that a resolution up to 5 m is ideal, whereas larger resolutions tend to decrease the accuracy of the model results. Input data with large resolution lacks too much detail. At the same time, a very small resolution could introduce artefacts in the DTM. Moreover, it leads to huge datasets, which decreases the computing speed. In any case, before using the DTM for trajectory simulations, at least a visual check using a derived hillshade and a slope map should be carried out.

5.3. Definition of the release scenarios

The phase concerning the definition of the release scenarios, deals with determining which rock size might fall from which release area and, which is the most difficult, how often (see also chapter 1 and 2). The first information, the rock size, is defined on the basis of the discontinuity analysis in the release areas and the deposited rocks originating from the release area. The discontinuity analysis can reveal information on the distribution of rock sizes that might fall out of the cliff face as well as on their stability in the rock mass (cf., [HOE 81], [JAB 02]). However, for larger areas, such methods are hardly feasible, because it is impossible to analyze extensively the geomechanical patterns of several kilometres of cliffs ([DUS 02]). This might be a problem if a trajectography study is needed for a hazard map of a larger commune.

In that case, a slope threshold value is often applied to a slope map derived from a DTM for determining the potential rockfall release areas (e.g., [DOR 03] and [FRA 08]). The problem with that is fixing the slope threshold value, which is not only dependent on the geology of the study area, but also on the resolution of the used DTM. [TRO 08] propose the following relationship between the required slope angle threshold for rockfall release areas (SAT_{RA} in degrees) and the DTM resolution (RES_{DTM} in meters):

$$SAT_{RA} = 55 * RES_{DTM}^{-0.075} \qquad [5.1]$$

This relationship has been derived from a comparison between field mapped release areas and multiple DTMs with resolutions varying from 1 to 50 m of more than 20 different study areas in the Austrian, French and Swiss Alps.

An alternative promising approach, which is more accounting for the specific regional conditions is the combination of a slope angle distribution (SAD) analysis ([LOY 09]) and a COLTOP-3D ([JAB 09]) analysis might be useful. The SAD analysis allows determining the slope threshold value required for the identification of potential rockfall source areas at a local and regional scale and the software COLTOP-3D allows identifying different rock slope instabilities using a structural analysis on the basis of Matterrocking ([JAB 02], see also Chapter 2). Condition for the SAD is the availability of a high resolution DTM (1m resolution). At a slope scale, it is fairly easy to map the location of potential release zones in the field on the basis of a hillshade map.

As addressed above, the question how often a given rock size or volume falls out of a given cliff face is extremely difficult to answer. If a comprehensive record of historical rockfall events is available for a given study site, a first reliable indication of the magnitude-frequency relationship for the given outcrop can be obtained.

However, since most of these records are incomplete and not very old, little information exists on the magnitude of rare rockfall events. To deal with this weakest point of rockfall hazard studies, several authors came up with a power-law distribution for the prediction of recurrence rates for future events of a given volume (e.g., [HUN 99], [DUS 02]). Problems remain the possible biases induced by the poor quality of rockfall inventories and the sensibility of the extrapolated predictions to variations in the parameters of the power-law.

Therefore, for daily practical work, especially where rock slopes are high and inaccessible, the rockfall activity has to be estimated on the basis of the number of unstable cliff sections as observed from an opposite slope or downslope. For each unstable section, it has to be predicted how many rocks and which volumes will fall down yearly. For such a situation, it is important to try to quantify and to communicate the uncertainties related to your prediction in a transparent manner. On the basis of the predicted activity in the unstable areas and related uncertainties, a conservative assumption of the rockfall magnitude and frequency can be made.

5.4 Rockfall models

In the field of rockfall modelling, models are often split in two groups: two-dimensional (2-D) models and 3-D models. Most commonly, 2-D model are those that use a slope profile (horizontal distance and altitude axis). Whereas, a 3-D rockfall model, according to its definition, can represent completely different things. For some, it refers to models that calculate the rockfall trajectory in a real 3-D space (x, y, z), for others it refers to all models that use a 3-D Digital Terrain Model (DTM). There is no real consensus on these definitions, also not between the authors of this chapter. Then again, what is most important is transparency on how and in which spatial dimensions a model operates. Therefore, in this section we rather define the spatial domain than classifying the models into 2D or 3D.

5.4.1. Different model types

There is a very wide range of rockfall models. To present the difference between all these existing models in a simple manner we distinguish between three groups of models:

1) Geometrical models, which generally describe relationships between the total or a partial fall height and the length of the runout zone based on one or more rockfall events ([TIA 83], [KEY 99]). These are the easiest type of rockfall models. These models are actually all related to the energy line principle developed by [HEI 32]. This principle can be used to model the runout distance of many types of

moving masses, by joining the top of the collapse to the toe of the deposited mass by a straight line with a given angle (Figure 5.10), mostly between 28° and 34° ([HEI 32], [ONO 79], [TOP 87]). An alternative to this principle is the shadow angle method (cf. [EVA 93]), which joins the top of a talus slope beneath a cliff with the toe of the deposited mass by a straight line with an angle between 22° and 28° ([RAP 60], [LIE 77], [EVA 93], [JAB 11]). By using the energy line method, the rockfall velocity v at a given horizontal coordinate x, and consequently the rockfall energy, given that the rock mass is known, can easily be calculated following:

$$v(x) = f_v \sqrt{2\, g\, \Delta h(x)} \qquad [5.2]$$

Here, f_v is a velocity correction factor, g is gravity acceleration and Δh is the height difference between the energy line and the topography at a given horizontal coordinate x. Assuming that rotational energies represent around 20% percent of the total kinetic energy of a falling block ([JAB 11]), fv is set to $\sqrt{0.8}$ (= 0.9). Nowadays, these energy line principles are still commonly used in rockfall modeling, albeit often in a (two-dimensional) spatially distributed form. This is mostly being done by producing an energy cone from each potential mass movement source in a rasterized terrain model (DTM). To do this, a raster based program basically rotates the energy line 360° (or less depending on the program settings) about a vertical axis at the source. Then it detects if a DTM cell is located below the energy line level, i.e. within the cone, meaning in the runout zone (see [JAB 11]). Variations of the geometrical models are relationships between the falling volume and the ratio of the maximum vertical drop to the maximum horizontal distance travelled (e.g., [SCH 73], [TIA 83]).

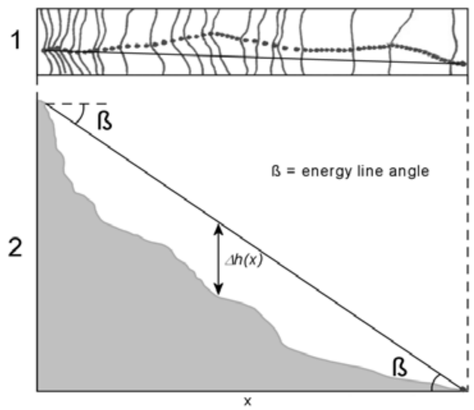

Figure 5.10. *Explanation of the energy line principle. The upper scheme (1) gives a helicopter view of a slope with the rebound positions of a rockfall event; The lower scheme (2) shows a cross section of the slope with the energy line of the rockfall event*

2) Models based on an apparent friction angle. These models are also based on the principle of [HEI 32] in the sense that an analogy is made between the energy line and a constant frictional force that is exerted on a sliding mass ([SCH 73]). However, these models converted the friction in a sliding coefficient which is dependent on the surface type. As such, the coefficient is not constant anymore between the release zone and the deposit zone, but it changes along the rockfall path. These models operate either along a slope profile, which is defined by a horizontal distance axis (x or y) and an altitude axis (z) or in a spatial domain defined by two horizontal distance axes x and y, for example a raster with elevation values or a map with contour lines (cf. [VAN 90]). In the latter case, the fall path is calculated starting from source cells and moving to the next one by choosing the nearest neighbouring cell with the lowest elevation (cf. Figure 5.11). Another possibility for calculating the fall direction is to use a flow type algorithm as shown by [DOR 03].

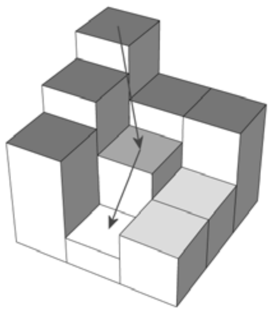

Figure 5.11. *A portion of a Digital Elevation Model (DEM) represented as cubes is shown to explain the simplest fall direction algorithm, which is "flow to the lowest neighbor"*

3) Process-based models, which simulate the flight parabolas and rebounds on a slope surface. They are detailed in the next sections.

5.4.2. Rock shapes in trajectory models

An important characteristic that allows distinguishing between different rockfall trajectory models is the representation of the simulated rock in the model. This can firstly be done by a lumped mass, which means that the rock is represented as a single, dimensionless point. The second approach is the rigid body, meaning that the rock is represented by a real geometrical form, which is often a sphere, cube, cylinder or ellipsoid. In general, this approach is used by the deterministic models mentioned above. The last approach is the hybrid approach, meaning a lumped mass approach for simulating free fall and a rigid body approach for simulating rolling, impact and rebound. More detailed descriptions can, amongst others, be found in [GUZ 02] and [AGL 03].

5.4.3. Spatial dimensions of trajectory models

The process-based, or trajectory models can firstly be grouped according to their spatial dimensions. The majority of the rockfall trajectory models belongs to the so-called 2-D models that simulate the rockfall trajectory along a slope profile, which often follows the line of the steepest descent. ([RIT 63], [BOZ 86], [PFE 89], [SPA 95]). All 2-D models, which are calculating the rock as a lumped mass, i.e., represented by a single point, could actually be defined as 1-D models. The variables that are calculated for this point are its velocity or its energy, as well as its vertical height above the surface. When knowing the absolute height of the surface along a horizontal distance axis, the model calculates in one single, vertical dimension only. Plotting of the resulting trajectories is logically in a 2D space.

The second group of trajectory models can be characterized by the fact that the direction of the rockfall trajectory in the x,y domain is independent from the kinematics of the falling rock and its trajectory in the vertical plane. In fact, in these models, the calculation of the fall direction (in the x,y domain) could be separated completely from the calculation of the rockfall kinematics and the rebound positions and heights. This means that these models actually carry out two separate calculations. The first one determines the position of a slope profile in an x,y domain and the second one is a rockfall trajectory simulation along the previously defined slope profile. Examples of such models are those that calculate rockfall kinematics along a slope profile that follows the steepest descent as defined on the basis of a digital terrain data (cf. Figure 5.11), as was done in [DOR 03]).

The last group of rockfall trajectory models calculates the rockfall trajectory in a 3-D space (x, y, z) during each calculation step. In these models, there should be an interdependence between the direction of the rockfall trajectory in the x,y domain, the kinematics of the falling rock, its rebound positions and heights (e.g., [DES 87], [GUZ 02], [DIM 02], [AGL 09]) and if included, impacts on trees ([DOR 11], [RAM 10]). The major advantage of 3D models is that diverging and converging effects of the topography, as well as exceptional or surprising trajectographies, i.e. those that are hardly expected in the field, are clearly reflected in the resulting maps. An example from Norway simulated with Rockyfor3D is presented in Figure 5.10. A disadvantage of 3-D models is the need for spatially continuous parameter maps, which require much more time in the field than parameter value determination for slope profile based trajectory simulations.

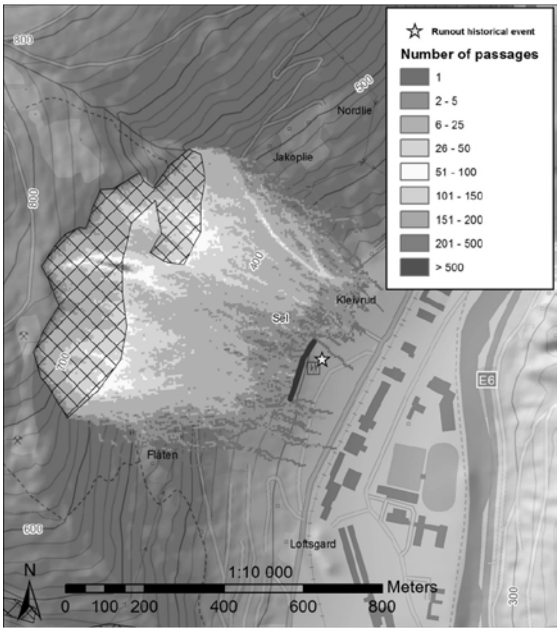

Figure 5.12. *A view of a shaded topographic map with rockfall trajectories/the number of passed rocks per cell on a slope in Otta, Norway. The trajectories were simulated by the 3D rockfall model Rockyfor3D (20 rocks per cell), taking into account the presence of single trees and a catching dam (as indicated by the thick line W from the start symbol in the map). The yellow star represents the stopping position of a historical rockfall event (1m^3 block), which fell down the slope before the dam was build*

5.4.4. Modelled rockfall kinematics

Another characteristic that can be used to describe a rockfall trajectory model is the general underlying calculation principle of the rockfall kinematics. Some models simulate the movement of a rock with detailed characterizations for bouncing, sliding and rolling ([KOB 90], [EVA 93], [AZZ 95]), while other models consider bouncing, rolling and sliding as identical movements, which are described by a succession of impacts and bounces ([PFE 89]). Models applying specific algorithms for calculating rolling and sliding velocities mainly use Coulomb's law of friction. The fall phases through the air are calculated with standard algorithms for a uniform accelerated motion, resulting in a perfect parabolic path. For calculating the rebound of the simulated rock on the slope surface, most of the models use a normal (rn) and a tangential coefficient of restitution (rt) (cf. Chapter 6 in this book) and some models an additional friction coefficient for rolling. The models that use these kind of coefficients generally apply a probabilistic approach for choosing the parameter values used for the actual rebound calculation. This is done to account for the enormous variability in the real values of these parameters, due to the terrain, the rock shape and the crushing effect of the rock during the rebound. Rather than directly accounting for this effect by predefining a rt value, the model should calculate the penetration depth in the slope surface and the effect it has on energy loss and transfer between rotational and translational components. The penetration depth is influenced by underground characteristics, the impact energy and impact angle, as well as the shape of the falling rock (Figure 5.13). An example of an algorithm allowing a realistic penetration depth calculation is described in [PIC 05]. [DOR 11] developed an algorithm that calculates the rt on the basis of the rock size and the roughness measured in the terrain, in which the penetration depth calculation following [PIC 05] is integrated.

Figure 5.13. *Two photos illustrating that the penetration depth has to be taken into account when calculating rockfall trajectories, especially in softer underground material (Photos T. Vernang). The left photo also shows the effect of the rock shape on the trajectory*

There are models that use deterministic approaches for calculating the rockfall rebound. These models use mostly a discrete element method (cf. [CUN 71]), such as the Discontinuous Deformation Analysis ([YAN 04]) or the percussion theory ([DIM 02]). More details on different ways for calculating a rebound of a falling block are presented in Chapter 6 of this book.

Without going to much in detail, it can be said that the mode of motion of a falling rock is strongly, but not solely, governed by the slope gradient. A good generalizing figure on the relationship between mean slope gradient and the mode of motion was already published by [RIT 63]. However, the mean slope gradient values shown in his figure are rather optimistic in the sense that bouncing occurs on slopes that are much less steep than 45° and (free-)falling of rocks also occurs on slopes with a mean gradient less than 70°. Here we define (free-)falling as the initial mode of motion when rock fall down a (semi-)vertical cliff or a longer flight phase between two rebounds, e.g., a parabolic trajectory through the air between two rebounds larger than 20 m horizontal distance. Therefore, we propose to a relationship between the mode of motion in which a (relative) number of rocks passing a section of a slope and the slope gradient of the given slope section. This relationship assumes that the different modes of motion are distributed normally around specific slope gradient, without having fixed slope gradient thresholds (Figure 5.14).

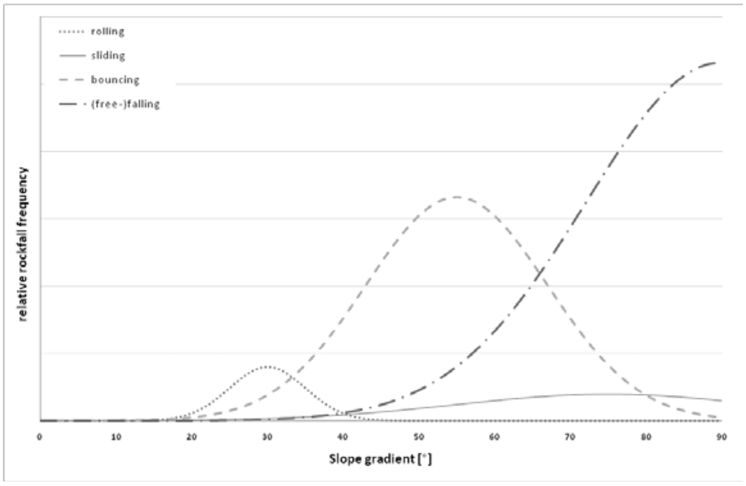

Figure 5.14. *Histogram illustrating that the main modes of motion of a falling rock are cover wide ranges of mean slope gradients*

5.4.5. Accuracy of rockfall models

Unfortunately there are few studies that really deal with the question how accurate rockfall trajectory models predict energies, passing heights and/or runout distances. Here we will present the summaries of two such studies. One study, which deals with back-analyses of rockfalls using trajectory models is published by [LAB 04]. In this study, three very different models were compared varying from 2-D to 3-D and from lumped mass to rigorous as well as from deterministic to probabilistic ones. This study concluded that, provided that the model parameters are well calibrated, all three models appear suitable for the prediction of runout zones. However, while reproducing similar runout zones, the three models may produce very different passing heights and kinetic energies along the rockfall paths. The last conclusion was that, for the 2-D models, the choice of profiles that are representative of the potential trajectories is not easy on sites with a complex topography.

Another study is published by [BER 06], in which consultancies using commercial rockfall trajectory software, as well as rockfall software developers, were invited to use their simulation tools to predict the trajectories of 100 rocks in 2D or 3D using a digital elevation model of a site in the French Alps. These data have been compared with observations gathered from real size rockfall experiments carried out at the same site. Additional data provided to the participants were: the geographic location of the experimental site, the form and volume of the rocks used during the experiments and the locations of two calculation screens on the main rockfall path. Characterization of the soil had to be done by the participants. At the calculation screens, each candidate had to calculate the mean and maximum values for the velocity, the kinetic energy and the passing height. In addition, the stopping points of each rock had to be calculated. In total 22 candidates expressed their interest in the benchmarking test and finally 12 participants from 4 different countries sent back their simulated data. Only 3 out of 12 were capable to simulate the rockfall kinematics at the two calculations screens with an error of ± 20%. Seven participants were capable to simulate the observed stopping distance with an error of ± 10%. The maximum errors observed were in the order of +400% (for the prediction of energy values). Among the commercial models used, three of them were used by multiple participants. The outcomes of the test showed that two different users can obtain completely inaccurate or, in contrast, very accurate results with the same model. This indicates that the role of the expert is crucial in hazard assessment based on rockfall simulation models, which was one of the key outcomes of this study and also indicated by [LAB 04]. Both studies also showed that it generally easier to model accurate runout zones than accurate rockfall kinematics.

A final important aspect in relation to the accuracy of rockfall trajectory models is the number of simulations per rockfall release area required for obtaining statistically valid results. For fully deterministic models, the answer is quite simple. One simulation per release area will do. The question in that case will be whether all possible events have been reproduced. For probabilistic models, convergence tests will have to be carried out to determine the required number of simulations per release area. For typical rockfall trajectory simulations this could mean that model outcomes converge if the standard deviations or the 95% confidence interval of the modeled distributions of energies, passing heights and runout distance, at the location of interest in the study area, produced by sequential simulation n and n+1, becomes smaller than a given percentage. This percentage has never been fixed by specialists working on rockfall modelling, but differences of 5% and less should be sufficient. When hazard mapping is performed with a trajectory simulation model that use probabilistic approaches, it comes out that the minimum number of runs required for achieving a similar map from one simulation to the other is very variable. On 2-D slope profiles, it can range from 1’000 to 1’000’000 runs (and sometimes more), depending on the hazard mapping methodology and on the national guidelines ([ABB 09]).

5.4.6. Accounting for protective measures

Protective measures that should be accounted for in rockfall trajectory models are technical and biological protective measures which have a relevant effect on the rockfall process (nets, dams, galleries, guard rails along roads for smaller rocks, and forests). For all these measures, it can basically be said that their position, the estimated energy absorption capacity, as well as their size or height should be integrated in the rockfall model. Unfortunately, a limited amount of models has the possibility to do so. Only a few rockfall trajectory models (e.g., [RAM 10], [DOR 11]) explicitly take into account the mitigating effect of existing forest cover, which is non-negligible (cf. Figure 5.15), even in case of rock avalanches. Its efficacy depends logically on the length of the forested slope in the transit zone and the forest characteristics, such as stem density and diameter distribution. Explicit incorporation in the models means that the spatial distribution of different stand densities, stem diameter distributions and even tree species are accounted for. Recent data describing the energy dissipative effect of trees is published in [DOR 06b] and [JON 07]. Until ten years ago, the energy dissipative capacity of trees was seriously underestimated, i.e., adult coniferous trees were thought to dissipate energies up to 10 kJ instead of more than 200 kJ. Daily practice of experts using rockfall trajectory models for rockfall hazard assessment shows that in many cases, the mitigating effect of forest is included by increasing the slope surface roughness. To account for large, non-rotten stems this would be acceptable for areas where multiple trees have been felled and deposited on the slope, because they do increase the roughness in reality. For standing trees, this approach is less suited, as in reality there is always a probability that a rock does not impact any tree at all. This cannot be reproduced when increasing the slope surface roughness.

Figure 5.15. *Photo showing the protective function of the forest above a heavy traffic pass road (Brünig Pass) in Switzerland (Photo L. Dorren)*

Technical protective measures such as rockfall nets and barriers, if accounted for in rockfall models, are generally presented as lines with a given height and a given energy absorption capacity. If the rock does not jump over, but impacts the virtual line representing the protective measure, the defined amount of energy, which can be absorbed by the barrier, is subtracted from the total amount of energy of the falling rock. A logical way of doing this would be to split this energy reduction proportionally over the two translational and the rotational velocity components on the basis of their respective values before the impact. Rockfall dams (Figure 5.16) and galleries can be integrated in the terrain model or slope profile and have therefore an unlimited energy absorption capacity, as they are represented as all other slope surface types. Their influence on the falling rock is only caused by the effects of their geometry.

Figure 5.16. *Photo showing an 8 m high rock catching dam, with a wire rope net on top protecting against ballistic rock fragments along the Gotthard highway in Switzerland (Photo V. Labiouse)*

5.5 Plausibility check / validation of model output

Step 1: Probably for most people who use rockfall models, the first plausibility check is the gut feeling, which is natural and non-negligible. In other words, we evaluate intuitively whether the model, in general, produced rockfall trajectories we expected. It is needless to say that this first check, although very important, does not suffice as an objective comparison with reality. Therefore, a validation using the silent witnesses observed in the field, the data from records on historical events, and information coming from other existing studies or local eyewitnesses has to be done. If the produced results correspond to, for example, the stopping positions of rocks and passing heights marks on trees observed in reality, it can be concluded that plausible rockfall trajectories have been simulated. Where there are no marks on three stems, representative rebound craters and angles may be measured in the field, and used to validate trajectories and corresponding velocities. In that case the next phase in the workflow (Fig. 5.5) can be carried out, meaning that the data can be fixated and transformed into readable rockfall process maps.

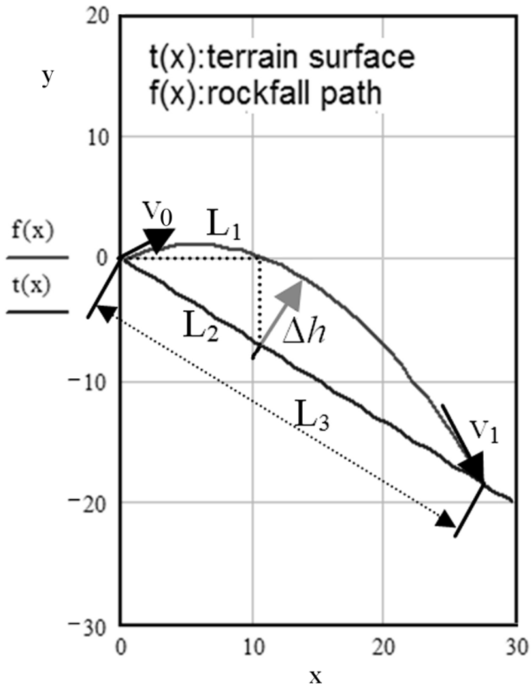

Figure 5.17. *Sketch for recalculating a single rebound*

A plausibility check on the basis of observed impact craters and broken tree branches can be additionally done with a back calculation of the velocity during a single rebound along a rockfall path on a slope with a gradient β. The terrain can be then described by the expression (cf. Fig. 5.17):

$$t(x) = -\tan\beta \cdot x \qquad [5.3]$$

The rock flying through the air follows a parabolic path f(x), where the rebound angle is α (relative to the horizontal plane) and with a corresponding starting velocity v:

$$f(x) = \left(\frac{-g}{2 \cdot v_0{}^2 \cdot \cos\alpha^2}\right) \cdot x^2 + \tan\alpha \cdot x \qquad [5.4]$$

Following through the single rebound it is of interest to know the maximum height above the ground. This can be used for choosing minimum height on a rockfall fence or catching dam. The height normal to the ground will be:

$$\Delta h = \frac{0.5 \cdot v_0^2 \cdot (\cos\alpha)^2 \cdot (\tan\alpha + \tan\beta)^2 \cdot \cos\beta}{g} \qquad [5.5]$$

The x-coordinate for the highest point above the ground is:

$$L_1 = \frac{v_0^2 \cdot (\cos\alpha)^2 \cdot (\tan\alpha + \tan\beta)}{g} \qquad [5.6]$$

and along the ground:

$$L_2 = \frac{2 \cdot v_0^2 \cdot \cos^2\alpha}{g \cdot \cos\alpha}(\tan\alpha + \tan\beta) \qquad [5.7]$$

When the rock lands after the rebound, the rebound length along the terrain will be:

$$L_3 = \frac{v_0^2 \cdot (\sin(2 \cdot (\alpha + \beta)) + 2 \cdot \cos(\alpha + \beta)^2 \cdot \tan\beta}{g \cdot \cos\beta} \qquad [5.8]$$

When landing, the rock will logically have a higher velocity (v1) than when it started:

$$v_1 = \sqrt{v_0^2 + L_3 \cdot 2g \cdot \sin\beta} \quad [5.9]$$

Results from calculations as the ones above are useful for a first analysis of rockfall velocities and energies, but also for a more thorough validation of modelled results. From a statistical point of view, it should however be kept in mind that a single event and even a few events fitting within a computed stochastic distribution are not sufficient to assert that the model parameters are well calibrated and that the trajectory results are reliable. The more field observations are reproduced by the simulations, the higher the confidence.

Step 2: On the other hand, if the produced results do not correspond to the features or events observed in reality, it does not necessarily mean that the model produced errors. In that case, it has to be checked whether elements that exist in reality are not represented in the model (e.g., ditches, road embankments, complex rock shape, or extreme slope surface conditions). If so, the simulations can be repeated with an adapted slope profile or DTM, and/or with a different rock shape.

Step 3: In addition, it makes sense to compare the simulated results with the outcomes of other methods, such as the energy line approach. The energy line approach can give a good indication of extreme runout zones (e.g., when using an energy line angle of 27°). Because even if the simulations do not reproduce the features indicated by the silent witnesses, it might be possible that the event simulated by the model, did not yet occur, but would be possible in reality.

If after step 1, 2 and 3, the simulated results cannot be explained, workflow phase C and D (cf. Fig. 5.5) can be iteratively repeated with a slight modification of a sensitive model parameter, especially if this parameter represents a terrain characteristic, which was difficult to determine in the field, e.g., the slope elasticity. It is advisable, to only change one parameter at a time.

If the simulated rocks, after having adapted several parameters, still travel further than the extreme runout calculated with the energy line method, it may be wise to abandon the simulations. It all depends on the number of such “extreme” rocks.

5.6. Fixing model results and translation into a readable map

Fixing the model results mean that simulated outliers, if existing, have to be removed from the produced datasets. Such outliers could be rocks that travelled too far or single rocks with extreme lateral deviations in case of 3D simulations. As such, a zone can be defined that is subsequently accepted as the valid runout zone. This zone is then assumed to be the spatial validity domain. Within this valid runout zone, kinetic energy and passing height values have to be fixated. Models with probabilistic approaches produce distributions, or sometimes only quantiles, of energy and passing height values. On the basis of these outputs the user can decide which values will be considered valid and which one are not. Also here, no rules have been fixed and therefore, experts still discuss whether 5%, 2% or 1% confidence intervals should be used in this process.

The next and final step is to transform the fixated results in readable maps. To do so, the simulated results have to be post-processed, which generally means that they have to be classified into predefined or user-defined classes. Then, on the basis of the classified data, rockfall process maps can be derived from the simulated maps in order to create spatially distributed datasets showing for example the 95% confidence interval of the distribution of kinetic energies or the mean passing heights within the rockfall runout zone in the study site (Fig. 5.6). If considered appropriate, a temporal occurrence probability could be defined for each created intensity map, but this depends on the accuracy with which the temporal probability of the rockfall release scenario could be defined. The temporal occurrence probability linked to each created intensity map then includes both the release or onset probability and the probability of reach.

When finally presenting the results of the trajectory study, not only the readable maps have to be shown, also a technical report has to be delivered. In such report, daily practice shows that it is more and more common to systematically and transparently describe all the phases required for completing the study. This means including summaries of existing studies and maps, a list of the historical events, the recorded silent witnesses, the input parameter maps, the defined scenarios and underlying assumptions, the simulated results and finally the considerations during fixation and post-processing of the simulated results for creating those readable rockfall process maps. Only in such a way, the transparency and traceability of rockfall trajectory studies can be improved, and consequently their consistency and relevance.

5.7. Future improvements

The first future improvement in rockfall trajectory studies will probably be related to an increase of the objectivity with which the slope surface parameters can be determined in the field. This means that new, more representative and useful rebound algorithms should be developed. Here, useful is meant as an algorithm that allows for a repeatable and reproducible estimation of the required parameters in the field. Carrying out and observing full scale rockfall experiments has been very helpful for the development of the algorithm presented in [BOU 09]. But still, more work has to be done and probably different stochastic algorithms for different soil types based on data from real size and half-scale experiments might bring a solution.

Secondly, Light Detection And Ranging (LiDAR) technology will continue to develop, which will lead to an increasing availability of better quality high-resolution DTMs and Digital Surface Models (DSMs). With these data, it will become possible to automatically map areas with different surface roughness values within larger study areas. This will increase the efficiency of the fieldwork. In addition, high resolution models of rocky outcrops offer better possibilities for structural analyses, which facilitates a better identification of rockfall release areas. Finally, more detailed or more widely available LiDAR data will facilitate the mapping of forest structures and single trees, which can then more easily be integrated in rockfall models.

Investigations of rockfall runout distributions outside talus slopes should be carried out and analyzed for different regions, to get better relationships between runout zones, rock sizes (magnitude) and return periods (frequencies). These results can again be used to tune our rockfall models. In this context, considerations about statistical tests (e.g., a chi-square goodness-of-fit test) that could be used by modellers to check the consistency of their results with field observations would be helpful. In addition, based on the understanding gained by the above mentioned relationships, a physical mitigation can be planned to increase the safety for the road to an acceptable level with fairly simple affordable measures.

Last but not least, the unstoppable increasing computing power will allow calculating faster and more 3-D rockfall trajectories as well as for larger areas.

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