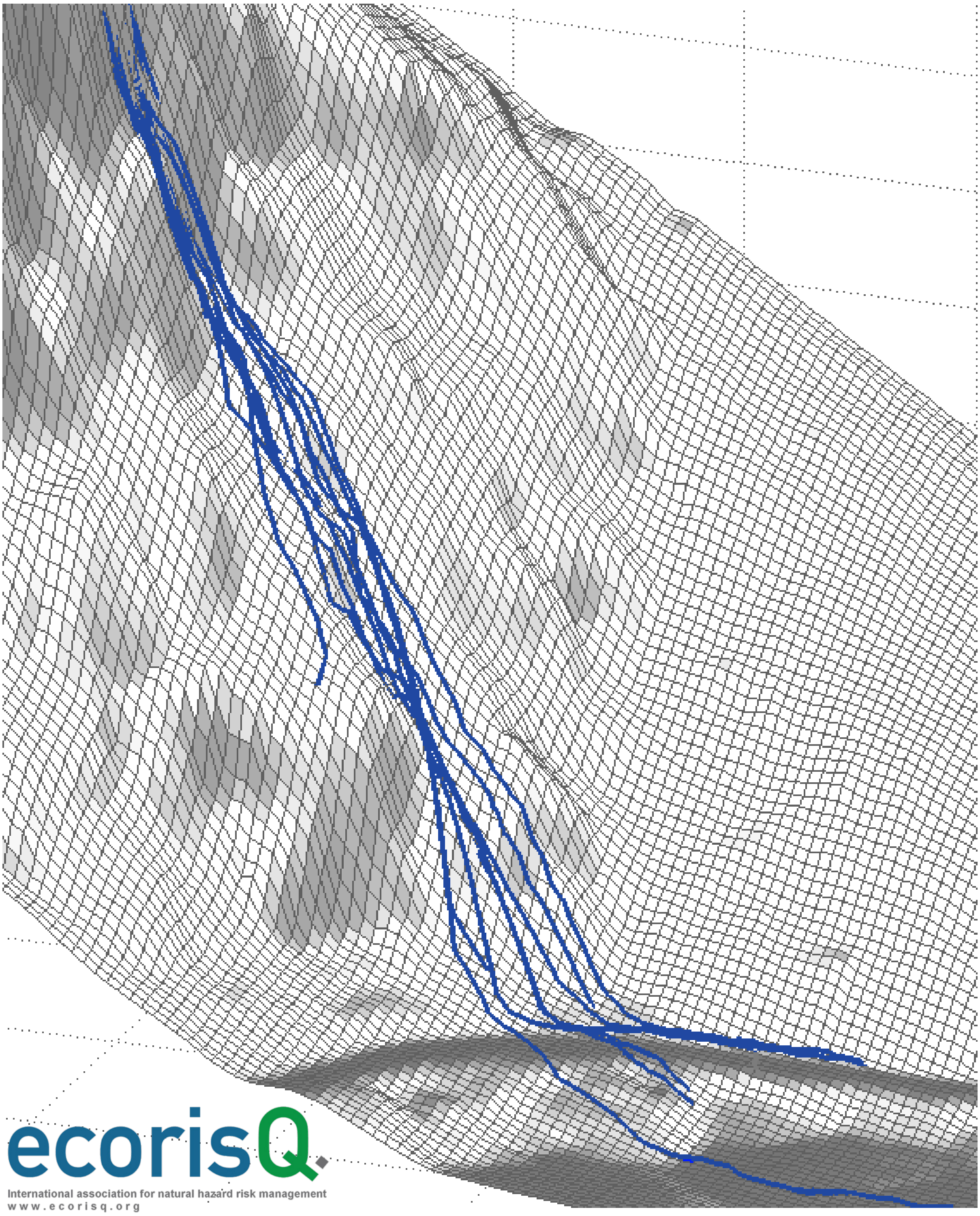
Rockyfor3D (v5.2) revealed

Transparent description of the complete 3D rockfall model



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Content

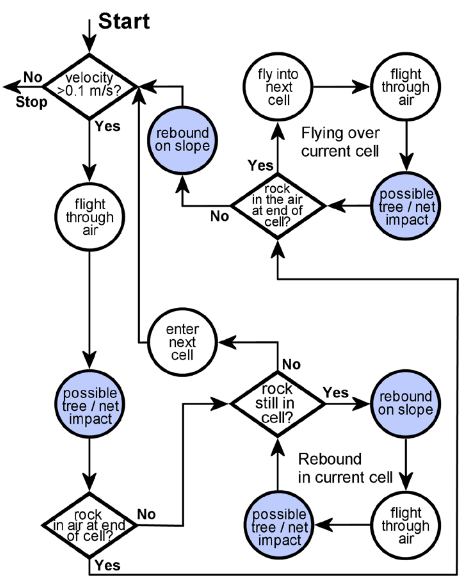
1 Introduction

Rockyfor3D is a simulation model that calculates trajectories of single, individually falling rocks, in three dimensions (3D). The model combines physically-based, deterministic algorithms with stochastic approaches, which makes Rockyfor3D a so-called 'probabilistic process-based rockfall trajectory model'. Rockyfor3D can be used for regional, local and slope scale rockfall simulations.

Rockyfor3D has been developed since 1998, initially on the basis of earlier published rockfall research work (e.g., Habib 1977; Azimi et al. 1982; Falcetta 1985; Wu 1985; Bozzolo and Pamini 1986; Spang 1988; Pfeiffer and Bowen 1989; Van Dijke and Van Westen 1990; Zinggeler 1990; Descoeudres 1997; Meissl 1998; for a detailed overview see Guzetti et al. 2002 or Dorren 2003) and later on the basis of personal field observations, experiments with the team of Frédéric Berger (Irstea Grenoble) and tests with many self-developed or other published model algorithms. From version 5.0 onwards, the program code is written in C.

The evolution of Rockyfor3D is recorded under different names (Rocky3, RockyFor) in a series of scientific articles (Dorren and Maier 2001; Dorren and Seijmonsbergen 2003; Dorren and Heuvelink 2004; Dorren et al. 2004; Dorren et al. 2006; Stoffel et al. 2006). The objective of this paper is firstly to explain how the program works and secondly to provide a transparent and consistent overview of the algorithms that are used by the current version of the model (Rockyfor3D v5.2), which is made available by the author to the international association ecorisQ (see www.ecorisq.org) and its members.

Rockyfor3D is continuously being used in research projects for testing, potentially leading to improvement of model algorithms (cf. Bourrier et al. 2009). **Nevertheless, for good results, Rockyfor3D requires consistent input data that represents well the reality in the terrain and that corresponds to the scale of analysis adapted to the objective of your rockfall trajectory study** (1 - a regional hazard analysis, 2 - a communal hazard analysis, or 3 - a detailed hazard analysis for a single slope)**.**



Rockyfor3D simulates the rockfall trajectory as 3D vector data by calculating sequences of classical parabolic free fall through the air and rebounds on the slope surface, as well as impacts against trees, if required (Fig.1). Rolling is represented by a sequence of short-distance rebounds and sliding of the rocks is not modelled.

Fig. 1. Flow diagram of Rockyfor3D. The blue coloured circles indicate modelling steps where changes in the fall direction of the simulated block may occur.

The required input data consists of a set of ASCII rasters (ESRI format, explanation see chapter 2), which define the topography and the slope surface characteristics, as well as a set of parameters, which define the release conditions. These input data, as well as short instructions for running Rockyfor-3D, will be described in detail in the following chapter. The main components of the Rockyfor3D model are described in detail in chapter 3. The output of Rockyfor3D is described in detail in chapter 4.

2 Model input and quick start

2.1 Raster input data

The minimum input data required by Rockyfor3D consists of a set of 10 raster maps. **All these raster maps need to have to same map extent and the same cellsize**. With increasing cellsize, both the spatial precision of the simulated maps and the accuracy of the simulated kinematics decrease. However, experience also showed that a 1 m × 1 m resolution does not necessarily improve the quality and it increases the amount of data substantially. The preferred resolution lies between 2 m × 2 m and 10 m × 10 m (cf. Dorren and Heuvelink 2004).

All rasters should be in ESRI ASCII Grid format, which is readable by all text editors. Below, an example of a small raster in such format is presented. The header provides information on the number of rows and columns in the raster (nrows and ncols), the cellsize or resolution of the raster (in m), the x- and y-coordinates of the centre (or lower left corner) of the lower left cell (xllcenter/xllcorner and yllcenter/yllcorner) and the value that represents nodata values (NODATA_value; default = -9999). Decimals should be preceded by a point (.) and not by a comma (,).

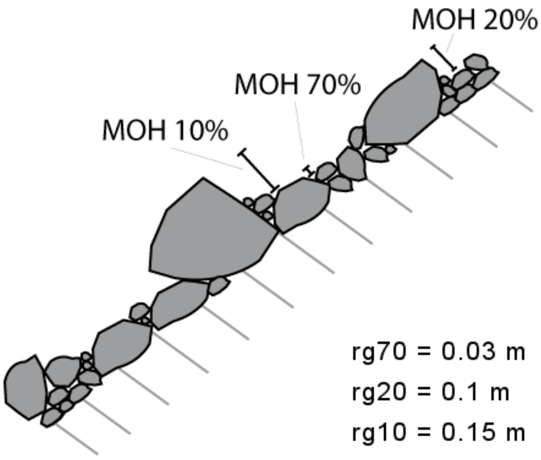
The following **ten** rasters are minimally required for using Rockyfor3D:

Nr.	Raster name	Description

1	*dem.asc*	a rasterised Digital Elevation Model (DEM), which describes the topography (double type raster; [values 0 – 8850.00 m or NODATA_value]). Laserscanning (LiDAR) generally provides accurate DEMs. From the DEM, Rockyfor3D calculates a slope map and an exposition (also called aspect) map following Zevenbergen and Thorne (1987; see also Burrough and McDonnell 1998, p. 191). A small example *dem.asc* is given below:
		`ncols 5`
		`nrows 3`
		`xllcorner 123456.123`
		`yllcorner 1234567.123`
		`cellsize 2.5`
		`NODATA_value -9999.00`
		`1115.81 1114.28 1109.25 1107.74 1105.01`
		`1110.31 1109.35 1107.33 1103.57 -9999.00`
		`1006.55 1005.00 999.62 -9999.00 -9999.00`

2	*rockdensity.asc*	a raster map with the rock density in each source or start cell (integer type raster, 2 or 4 byte; [values 0 or 2000 – 3300

		kg.m^{-3}]). The rock density map defines the cells that correspond to the release points (value > 0). In addition, this raster defines the density (in kg.m^{-3}) of the block that will be simulated from each source cell. Thus, raster cells with a value 0 will not be considered as source cells. From those cells with a value of for example 2500 or 3000, a block with a density of 2500 kg.m^{-3} resp. 3000 kg.m^{-3} will be simulated. **To avoid edge effects, source cells should not be in the two outer rows or columns of the raster. Those who are will not be taken into account !**
3 4 5	*d1.asc* *d2.asc* *d3.asc*	three raster maps defining the size of the block height, width and length in each source cell (double type raster; [values 0 – 20.00 m]). These raster maps must contain values in meters. If a dimension value defined in one of the three rasters equals to 0, that raster cell will not be considered as source cell. The three block dimensions defined in each source cell are varied uniform randomly with a predefined % (based on the defined volume variation between ±0% and ±50%) before each simulation. This random variation is always identical for all three block dimension values for one single simulation. This means that if the volume variation is set to 5%, then all 3 block dimensions are randomly decreased or increased with a value between 0 and 1.639%.
6	*blshape.asc*	a raster map defining the shape of the falling block for each source cell (integer type raster; [values 0 – 4]). The block shape raster can contain the following values: 0 No block form / no source cell defined 1 Rectangular block (all three dimensions can be completely different) 2 Ellipsoidal block (all three dimensions can be completely different) 3 Spherical block (all three dimensions are identical) 4 Disc shaped block (smallest dimensions is max. 1/3 of the other two block dimensions, which are rather comparable in size) If no block form is defined in a source cell (value 0), Rockyfor3D will simulate an Ellipsoidal or spherical block, depending on the block dimensions (given that d1, d2, d3, and rock density > 0 in that raster cell).
7 8 9	*rg70.asc* *rg20.asc* *rg10.asc*	three raster maps defining the slope surface roughness (double type raster; [values 0 – 100.00 m). The slope surface roughness is not representing the micro topography (e.g., steps in the terrain), but represents rocks, which form obstacles for the falling block, that are lying on the slope. This roughness has to be determined in the field by identifying homogenous zones in the study area, which are represented as polygons on a map. Each polygon defines the surface roughness, expressed in the size of the material covering the slope's surface, **looking in the downward**

		direction of the slope, by three size probability classes called rg70, rg20, and rg10. Each of these classes is represented by one raster map and corresponds to the height of a representative obstacle (MOH) in m that a falling block encounters in resp. 70%, 20%, and 10% of the cases during a rebound in the defined polygon (Fig. 2). **Roughness values range from 0 to 100 m (see annexe II)**. If the slope surface is smooth, a roughness value of 0 m has to be used. The value of 100 m can be used to force the simulated blocks to stop, for example in a river. The choice of the MOH values needs a lot of attention, because Rockyfor3D is sensitive to these parameters. The surface roughness is used to calculate the tangential coefficient of restitution. It is therefore just a parameter determining energy loss during a rebound on the surface; it is not a roughness which is added to the topography as represented by the DEM. Therefore, it has no effect on the terrain height or the local slope angle in a raster cell.  Fig. 2. A visualisation of the obstacle heights (MOH) representative for 70%, 20% and 10% of the surface within a homogeneous zone on the slope. **The MOH should be measured looking in down-slope direction**. During each rebound calculation, the size of the material encountered by the impacting block is randomly chosen from the three size-probability classes given their accompanying probabilities. Each size probability class is represented by one raster. For example, the cell values in the raster map *rg70.asc* represent the size of the material covering 70% of the surface of those cells. The surface roughness is an important parameter in the field recording sheet (Table 1) for preparing rockfall simulations using Rockyfor3D. Figure 3 may help to estimate size-probability classes in the field. Annexe I presents examples of roughness values from the field and annexe II explains the precision of the roughness values to be used.
10	*soiltype.asc*	a raster map defining the type of underground (integer type raster; [values 0 – 7]). This raster represents the elasticity of the underground and needs to be mapped per polygon in the

		field as well. it needs to be converted into a raster map called *soiltype.asc* using a Geographical Information System (GIS). Rockyfor3D can deal with 8 soil types (underground types), which are listed in Table 2. In the model, these soil types are directly linked to R_n values (= normal coefficient of restitution). To describe the underground, it is advised to dig a small pit with a geological hammer, i.e., look under the moss or ground vegetation cover. **A remark regarding soiltype 7 (asphalt road)**: Until now, we did not find any experimental data on the energy absorption of asphalt roads during a dynamic impact. Our R_n value, which varies between 0.32 and 0.39, is slightly lower than the 0.4 assumed by Hoek (1987) and others. Still the model can underestimate the energy loss during impacts on such roads. If the user feels that rocks travel too far, a soiltype of 3, 2 or 1 could be used for asphalt roads that absorb more energy. Feedback from users that gained experience in adapting the soiltype for asphalt roads is appreciated for further improvement of the model.

Table 2: The soiltypes used by Rockyfor3D and the related R_n values

Soiltype	General description of the underground	mean R_n value	R_n value range
0	River, or swamp, or material in which a rock could penetrate completely	0	0
1	Fine soil material (depth > ~100 cm)	0.23	0.21 - 0.25
2	Fine soil material (depth < ~100 cm), or sand/gravel mix in the valley	0.28	0.25 - 0.31
3	Scree (Ø < ~10 cm), or medium compact soil with small rock fragments, or forest road	0.33	0.30 - 0.36
4	Talus slope (Ø > ~10 cm), or compact soil with large rock fragments	0.38	0.34 - 0.42
5	Bedrock with thin weathered material or soil cover	0.43	0.39 - 0.47
6	Bedrock	0.53	0.48 - 0.58
7	Asphalt road	0.35	0.32 – 0.39

Hint for preparing rasters nr. 2 - 10:

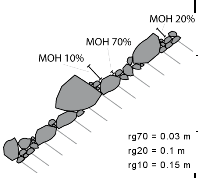
*Create a polygon vector file with 9 attributes equally named as the raster names or download shapefile and automatic data preparation scripts here. Digitise homogeneous terrain units on the basis of an orthophoto, or a hillshade of the DEM, a slope map, or eventually an accurate topographic map and of course field observations. Then rasterise the created vector file 9 times using the different attributes of the polygon map. (see this document for more details on data preparation). Once more, a**ll the raster maps need to have to same map extent and the same cellsize!** A test raster dataset can be downloaded here.*

Table 1: Field recording sheet for rockfall simulation with Rockyfor3D

General					
Date*		Nr. Polygon#		# each polygon represents a homogeneous unit; size depends on the mapping scale	
Location*		Slope angle*	(° / %)		
Name*		Zone*	☐ start / source	☐ transit	☐ deposit

Polygon characteristics				
1. Dominating rock (deposited in the polygon or potentially falling from release area)				
Block shape	☐ 1. rectangle	☐ 2. ellipsoid	☐ 3. Sphere	☐ 4. Disc
Block dimensions (d1, d2, d3):	……… (m)	x ……… (m)	x ……… (m)	
Rock density (kg.m^{-3}):				

2. Soil / underground type in the polygon								
Material constituting the under-ground	☐ river / swamp / other mate-rial in which a rock could penetrate completely	☐ fine soil material (depth > ~100 cm)	☐ fine soil material (depth < ~100 cm) / sand/gravel mix in the valley	☐ scree (Ø < ~10 cm) / medium compact soil with small rock fragments / forest road	☐ talus slope (Ø > ~10 cm) / compact soil with large rock fragments	☐ bedrock with thin weathered material or soil cover	☐ bedrock	☐ asphalt road
(soiltype) values needed for Rockyfor3D	0	1	2	3	4	5	6	7

3. Surface roughness in the polygon			
MOH: typical obstacle height normal to the slope surface (m) that block encounters in 70%, 20% and 10% of the cases during a rebound on the slope surface. **Should be measured looking down the slope!**		MOH for 70% of the sample area (rg70)	0 - 100 (m)
		MOH for 20% of the sample area (rg20)	0 - 100 (m)
		MOH for 10% of the sample area (rg10)	0 - 100 (m)
Lying tree stems*	Mean height = m	Area covered = %	

4. Forest*			
Representative plot size: …… m × …… m			
DBH# (cm)	# DBH: Tree diameter at breast height (usually measured 1.3 m above ground upslope from the stem) Record all the DBH ≥ 5 cm measured in the plot: e.g., 8, 31, 17, 13, …		
Stems / ha			
Mean DBH (cm)		Coniferous (%)	
Stddev DBH (cm)			
Species*			

5. Rockfall activity indicators / silent witnesses*			
Mean nr. of rockfall impacts on trees*		Height(s) of rockfall impacts on trees (m)*	
Depth impact craters (m)*		Fresh, deposited rocks in Polygon*	Yes / No

6. Remarks / sketch*
* optional fields; these are not required for Rockyfor3D

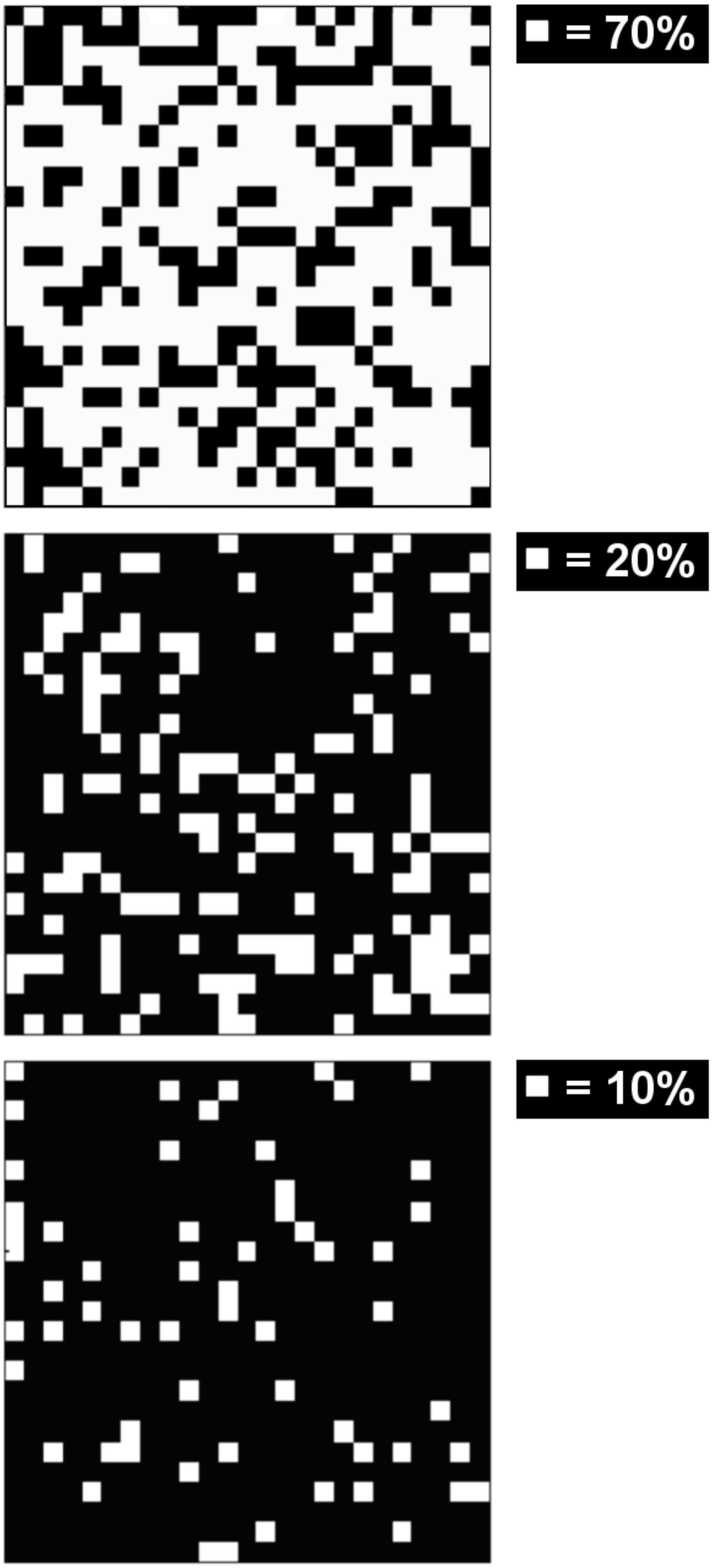


Fig. 3. Images for helping estimating the three size-probability classes in the field

2.2 Simulation with forest

If a simulation "with forest" is to be carried out, Rockyfor3D has two options for integrating forest data:

1. The first option is using a tree file, which contains x- and y-coordinates of each and every single tree, as well as their stem diameter at breast height (DBH, given in cm). Apart from exhaustive field measurements, these data can also be obtained automatically using an analysis of a normalised surface model derived from airborne laserscanning data following methods described by a.o. Popescu et al. (2002), Dorren et al. (2007), Monnet et al. (2010) (the program FINT can be used for doing this). This tree file needs to be called *treefile.txt* and should be available in the working directory. This file needs to have the following format (**without a header !**):

```
136578.55  2236789.45  43
136554.89  2236793.22  27
136531.39  2236801.37  34
...
```

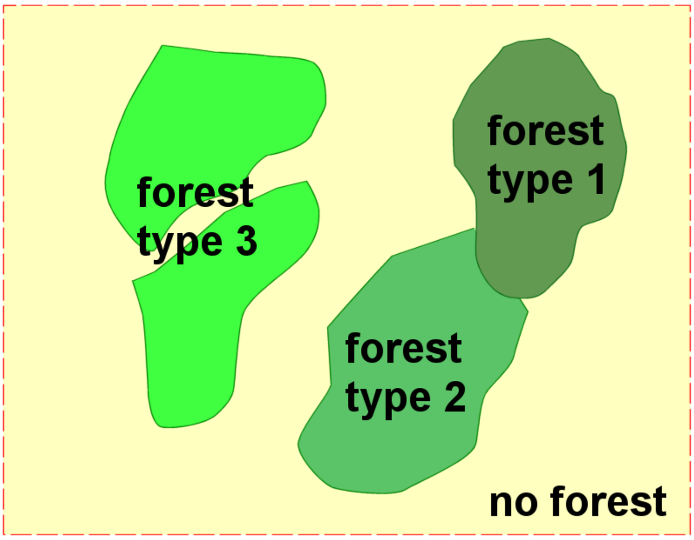
   In addition to the file *treefile.txt*, a raster called *conif_percent.asc* needs to be available in the working directory (integer type raster; [values 0 – 100 %]). In this raster map, the cell values represent the mean percentage of coniferous trees (%) within each cell (cf. Fig. 4). This raster needs to have to same map extent and same cellsize as the raster *dem.asc*.

2. The second option is to represent the forest by using **four** raster maps, being:

    - *nrtrees.asc* – the cell values represent the number of stems per hectare within each cell (integer type raster; [values 0 – 10000 ha^{-1}])
    - *dbhmean.asc* – the cell values represent the mean DBH within each cell (integer type raster; [values 0 – 250 cm])
    - *dbhstd.asc* – the cell values represent the standard deviation of the DBH within each cell (integer type raster; [values 0 – 250 cm])
    - *conif_percent*.asc (integer type raster; [values 0 – 100 %]) – the cell values represent the mean percentage of coniferous trees (%) within each cell

   On the basis of these four rasters (see also Fig.4), the model randomly places a given number of trees within each pixel with given diameters. Then, it constructs a tree file containing the x- and y-coordinates of all trees, as well as their DBH. This tree file will be saved in your working directory under *treefile.txt* and can be used for a next simulation. The attribution of the DBH is based on a gamma distribution defined by a shape and scale parameter derived from the mean value and the standard deviation of the DBH in each cell. All forest rasters need to have to same map extent and same cellsize as the raster *dem.asc*.

Step 1: Digitise a polygon vector forest map



Step 2: Enter forest attribute data

stand	nrtrees	dbhmean	dhbstd	conif_percent
1	290	32	11	56
2	400	27	9	26
3	800	20	5	0

Step 3: Convert the vector map into rasters using the different attribute fields

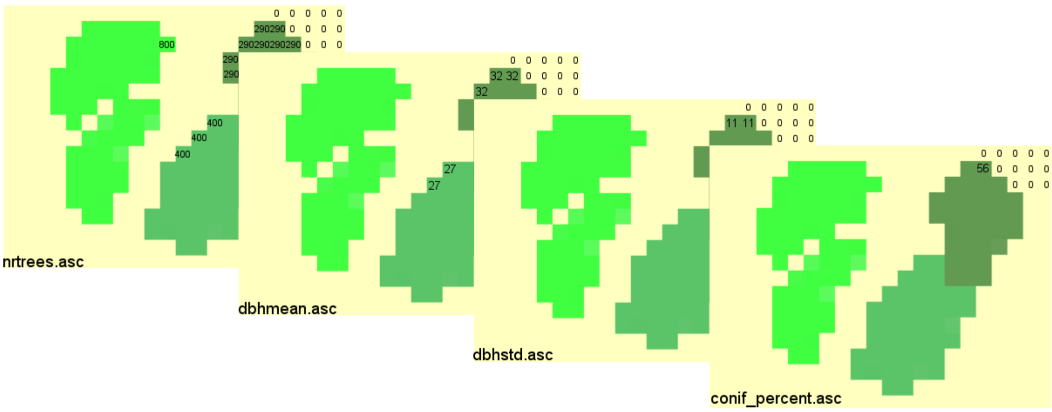


Fig. 4. A workflow for creating the forest raster maps required for option B.

The advantage of option A is that the overall so-called horizontal forest structure is well represented. This means that important rockfall couloirs are well represented. If using option B, very accurate and time-extensive digitising work is required to achieve the same structural precision. The advantage of option B is that the forest strata that are covered by the dominant trees (e.g., understory vegetation) are better represented than be the laserscanning data. Since these forest strata are constituted of rather small but many trees, they can have a significant protective function in addition to the large dominant trees.

2.3 Simulation with rockfall nets

If a simulation "with rockfall nets" is to be carried out, the following 3 rasters should be available in the working directory:

1. *net_number.asc* (integer type raster; [values 0 – 999])
2. *net_energy.asc* (integer type raster; [values 0 – 20000 kJ])
3. *net_height.asc* (integer or double type raster; [values 0 – 10 m])

These rasters can be created using vector to raster conversion of one or multiple lines, which have the attributes net_number (-), net_energy (the energy absorption capacity of the net in kJ) and net_height (in m, **measured normal to the slope surface !**). Again, all rockfall net rasters need to have to same map extent and same cellsize as the raster *dem.asc*. Each individual line representing a net requires a unique net_number. There is no limitation for the number of nets, however, they should not cross each other.

2.4 Calculation screens

If a simulation "with rockfall nets" is carried out, detailed data on the rockfall kinematics are collected "in the nets", which act as calculation or control screens. These data are saved in a text file called "*Rockyfor3D_vx_x_CalC_SCR_ dd-mm-yy_HHhMM.txt*", which can be easily opened in a spreadsheet program.

Using a net_energy of 0 and a net_height of 0 allows efficiently collecting data at the position of a given net line, without accounting for the barrier effect of a net in the simulation. Even if the net_height is 0, data will be collected each time a rock enters or passes over one of the cells where a "net" is virtually located. There is no limitation for the number of nets/calculation screens.

The following data are recorded for each block arriving in the net (calculation screen):
1. kinetic energy (*E* = translational and rotational in kJ)
2. vertical passing height (*Ph_vert* in m)
3. velocity (*V* in $m.s^{-1}$)
4. rotational velocity (V_{rot} in $rad.s^{-1}$)
5. impact angle (*Imp_a* in degrees = angle between a horizontal plane and the trajectory of the block the moment the block arrives in the net; negative value means a descending block, positive value means an ascending block).
6. passing height, normal to the slope surface (*Ph_norm* in m)

In addition, the total number of blocks (*n*) arriving in the net (or calculation screen) is recorded. The output text file contains both post-processed data and the raw simulated data per calculation screen. The post-processed data contains for example the median, as well as the 90%, 95% and 98% value (resp. x50, x90, x95 or x98) of the probability density function of the variables 1 to 5 described above for each calculation screen number (*scr_nr*). Here, the scr_nr is equal to the rockfall net number described in section 2.3.

2.5 Settings in the GUI

The following settings can be defined in the graphical user interface (GUI) of Rockyfor3D:

Simulation settings

- Number of simulations: this defines the number of individual rockfall trajectories that will be simulated from each source cell.
- Variation of rock volume in %: this means the percentage with which the three defined block dimensions will be randomly varied during each single trajectory simulation. The default value is 0%.
- Additional initial fallheight: this is the height (in m) above the DEM surface from which the block will be released initially. This allows the user to increase the initial vertical velocity of the simulated block. This value can also be helpful when using low resolution DEMs, in which small cliffs are badly represented. The default value is 0 m.
- Save NetCDF file: this file is normally quite a large file and can only be used in Trajectoval3D.
- Using input rasters: the simulation will be based on the input rasters *rg70.asc*, *rg20.asc*, *rg10.asc* and *soiltype.asc*
- Rapid automatic simulation: Rockyfor3d will create the input rasters *rg70.asc*, *rg20.asc*, *rg10.asc* and *soiltype.asc* with pessimistic values on the basis of the slope gradient. Sources areas are all cells steeper than a given slope threshold α, which is calculated following Eq. 1. The roughness and soil type values are attributed on the basis of the following rules:
  I. Sources areas: soil type 6; roughness 0, 0, 0 (rg70, rg20, rg10)
  II. Slope > 35°, soil type 4; roughness 0.05, 0.05, 0.1 (rg70, rg20, rg10)
  III. Slope 25° - 35°, soil type 3; roughness 0.05, 0.05, 0.05 (rg70, rg20, rg10)
  IV. Slope 15° - 25°, soil type 2; roughness 0.01, 0.01, 0.01 (rg70, rg20, rg10)
  V. Slope <15°, soil type 1; roughness 0.01, 0.01, 0.01 (rg70, rg20, rg10)

Block definition

- Rock density (kg/m3): the rock density can be defined either by the user input raster *rockdensity.asc* (by doing so, the user also defined the start locations) or by choosing a value (in kg/m3) in the graphical user interface. In the latter case the start positions will be defined automatically using a slope gradient threshold. All cells with a slope gradient steeper than this threshold will be considered as startcell. This threshold (α, expressed in °) is only dependent on the resolution (or cellsize) of the *dem.asc* and is calculated following (after Arpa et al. 2008, p. 314):

  $$\alpha = 55 * \text{cellsize}^{-0.075} \tag{1}$$

- Block dimensions (m): the block dimensions can be defined either by the user input rasters *d1.asc*, *d2.asc* and *d3.asc*, or by the graphical user interface
- Block shape: the block shape can be defined either by the user input raster *bl_shape*.asc or by the graphical user interface

Protective measures

- Simulation using forest: this defines if forest is taken into account in the simulation or not. In case of a simulation with forest it should be defined which input data will be used (forest rasters or treefile.txt; see Section 2.2).
- Simulation using nets: this defines if nets (or calculation screens) are taken into account in the simulation or not (see section 2.4).

Other initial parameters fixed by Rockyfor3D are the initial horizontal velocity V_{hor} = 0.5 $m.s^{-1}$ and the vertical velocity V_{vert} = -0.5 $m.s^{-1}$. The velocity component V_{vert} at the first impact on the slope surface, can be increased by rising the additional fallheight.

2.6 How to run Rockyfor3D

To run Rockyfor3D, the file ***setup.exe*** should be used to install the program. If this is done, the program can be opened as usual with other programs. The first step is to choose the working directory (cf. Fig. 5) that includes the **required input raster files** (*dem.asc*, …). Then all other simulation settings can be defined and the simulations can be started by pushing the corresponding button (Run Simulation). If known errors occur, the user will be informed in the Messages window; unknown errors might lead to a program crash. In that case, do not give up hope and start over, sometimes computers have a will of their own. After finishing the simulations, the output raster data (cf. chapter 4) are saved in a subdirectory of the defined working directory and a hillshade overlain with a map with the nr. of passages will be shown in the GUI. The created subdirectory will the simulation results is called 'Nsims- x_m3', where N = the number of simulations per start cell and x is the volume of the simulated block. If this has been defined by in the GUI. In the case the rock volumes have been defined by input rasters the value will remain x. If the simulation included forest and/or nets, the words Forest and/or Nets will be included in the subdirectory name. The output rasters can be opened in standard GIS software, such as the open source programs SAGA-GIS (www.saga-gis.org) or QGIS (www.qgis.org), or the ESRI product ArcGIS.

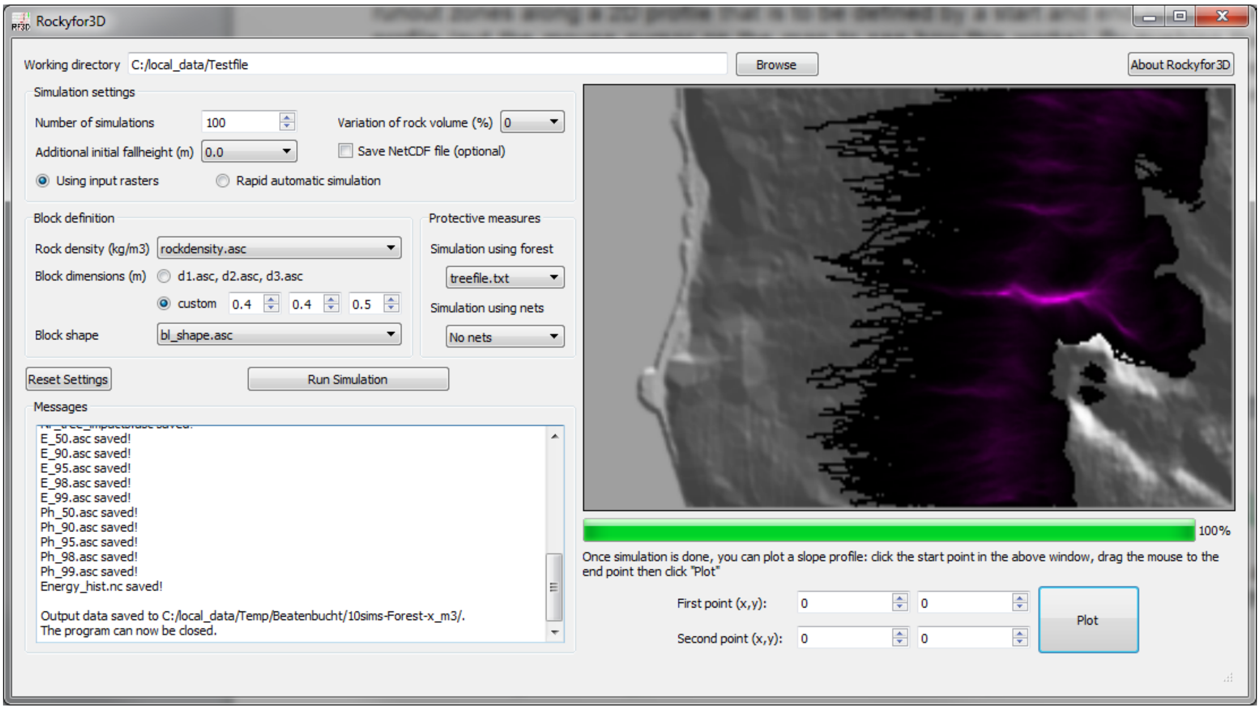


Fig. 5. The graphical user interface (GUI) of Rockyfor3D.

After finishing the simulations, a preliminary data analysis can be carried out by using the GUI. The user can visualise an envelope of simulated energies, pass heights and runout zones along a 2D profile that is to be defined by a start and end point of the profile (put the mouse cursor on the map to see how this works). By pushing the button ‘Plot’ after having defined the two profile points, the 2D analysis profile will be displayed in a second figure window. The data shown in the analysis profile will be saved in the working directory as an ASCII txt file called:
“*Rockyfor3D_vx_x_ProfileData_dd-mmm-yyyy.txt*”.

2.7 Command line version of Rockyfor3D

Rockyfor3D can also be run using its command line version (RF3D_cmd.exe) in a MS-DOS command window, which allows automatizing repeated simulations with various settings using a DOS batch file (see internet for help on these).

To run RF3D_cmd.exe go to the command window and type:

C:\Progr…\ecorisQ\RockyFor3D_5.x\bin\RF3D_cmd.exe

then the available options, as well as an example of a valid RF3D_cmd command will be shown.

3 Main components of the model

3.1 Block form

Rockyfor3D has the possibility to use rectangular, ellipsoidal, spherical and/or disc type block forms as input for the simulations. This block form determines 1) the block volume (and consequently its mass) and 2) the moment of inertia (*I). Both are calculated on the basis of three defined block dimensions d1, d2 and d3 following the code below:

D_arr = sort[d1, d2, d3]; (smallest dimension is stored in D_arr[0], largest in D_arr[2]

```
Case Blockform 1 // rectangle
  BlockVolume = d1 * d2 * d3;
  BlockMass = RockDensity * BlockVolume;
  *I = BlockMass * (D_arr [1]* D_arr [1] + D_arr [2]* D_arr [2]) /12;

Case Blockform 2 // ellipsoid
  BlockVolume = 4.0/3.0 * pi * d1/2 * d2/2 * d3/2;
  BlockMass = RockDensity * BlockVolume;
  *I = (BlockMass) * (0.5* D_arr [1]* D_arr [1] + 0.5* D_arr [2]* D_arr [2]) /5;

Case Blockform 3 // sphere
  BlockVolume = 4/3 * pi * (d1/2)* (d1/2) *(d1/2);
  BlockMass = RockDensity * BlockVolume;
  *I = 2/5 * (BlockMass) * (d1/2) *(d1/2);

Case Blockform 4 // disc
  BlockVolume = pi*((D_arr [1] + D_arr [2]) *( D_arr [1] + D_arr [2]) /16) * D_arr [0];
  BlockMass = RockDensity * BlockVolume;
  *I = 0.5 * (BlockMass) * ((D_arr [1] + D_arr [2])* D_arr [1] + D_arr [2]) /16;
```

For calculating the block position, the rebound on the slope surface and impacts against trees, Rockyfor3D always uses a spherical shape (see also Fig. 4), which can have 2 different dimensions: 1) the smallest one of the defined d1, d2 and d3, which is used to calculate whether the block impacts a tree and 2) a larger one, which is the mean of the two largest dimensions of d1, d2 and d3. The latter is for calculating the energy loss during impacts on the ground, i.e., the ratio between the surface roughness and the radius of the largest block perimeter (see also Eq. 8).

Other, more complicated block forms as well as explicit effects of the block form on the fall direction are not taken into account. This would imply an algorithm that allows calculating a statistically sound number, meaning a lot, of trajectories, while accounting for all effects of the block form on the character of the rebound that occur in reality. At present, an algorithm that satisfies both conditions does not exist. Since the algorithms used for calculating the fall direction in Rockyfor3D are based on field observations, in which multiple block forms were involved, the form is implicitly accounted for by the probabilistic fall direction algorithms used in the simulation.

3.2 Parabolic free fall

The parabolic free fall is calculated with a standard algorithm for a uniformly accelerated parabolic movement through the air. This calculation allows determining the position, and the velocity at the intersection with a 3D topography that is represented by the Digital Elevation Model (DEM). As such, Rockyfor3D simulates a 3D trajectory by calculating the evolution of its position along the x-, y- and z-axes. Here, the x-axis corresponds to the east-west direction, the y-axis to the north-south direction, and the z-axis to its vertical position. By its x and y coordinates, the 3D trajectory is linked to input and output raster maps. Knowing the position of the rebound, the slope surface characteristics defined by the input raster maps at that position, as well as the incoming velocity, the rebound calculation can be initiated.

3.3 Rebound on the slope surface

The velocity after a rebound on the slope surface, also called a bounce, is principally calculated with 10 functions. An important first step is the conversion of the incoming velocity in the horizontal plane xy (V_{hor}) and the one in the vertical plane z (V_{vert}) into an incoming normal Vn and tangential velocity Vt (with respect to the local slope) (cf. Fig. 6).

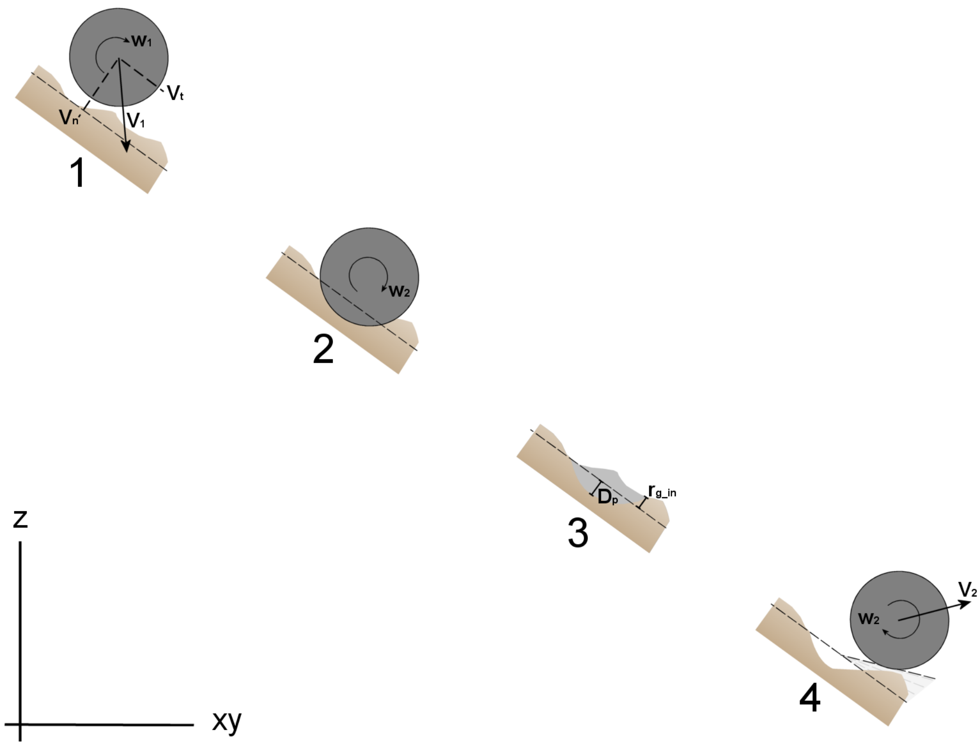


Fig. 6. The rebound as represented by the algorithms used by Rockyfor3D.

Then, the penetration depth of the block at the impact location is calculated on the basis of the work of Pichler et al. 2005:

The required input parameters for this algorithm are:

- the normal coefficient of restitution (R_n)
- the diameter of the block (d in m)

- the mass of the rock (RockMass in kg)
- the impacting velocity of the falling block (V in $m.s^{-1}$)

The used constants are:
- k = 1.207 (dimensionless constant accounting for the spherical block shape)
- B = 1.2 (dimensionless compressibility parameter of the impacted material, which varies little for different surface materials according to Pichler et al. 2005)

The main penetration depth (D_p) functions are:

$$\frac{D_p}{d} = \frac{2}{\pi} N \ln\left[\frac{1 + I_e / N}{1 + k\pi / 4N}\right] + k \quad \text{for } \frac{D_p}{d} > k \tag{2}$$

$$\frac{D_p}{d} = \sqrt{\frac{1 + k\pi / 4N}{1 + I_e / N} \frac{4k}{\pi} I_e} \quad \text{for } \frac{D_p}{d} \leq k \tag{3}$$

where,

$$I_e = \frac{RockMass * V^2}{R_i * d^3} \tag{4}$$

where R_i is the indentation resistance of impacted material (in MPa). This is calculated following,

$$Ri = 55 * 10^9 * R_n^{\ 7} \tag{5}$$

This function provides values between 1 - 5 MPa for fine soil and 200 - 250 MPa for bedrock.

$$N = \frac{RockMass}{\rho_{soil} * d^3 * B * 0.5} \tag{6}$$

where ρ_{soil} is the density of impacted material (in kg/m^3), which is calculated with,

$$\rho_{soil} = 1200 * \ln(R_n) + 3300 \tag{7}$$

This function provides values between 1500 kg/m^3 for fine soil and bedrock 2500 kg/m^3 for bedrock.

In Rockyfor3D, the maximum penetration depth D_p equals the simulated block radius. If the penetration depth is calculated, the calculation of the block velocity after rebound can be initiated.

An important parameter for calculating the velocity of the block after rebound is the tangential coefficient of restitution (R_t, cf. Chau et al. 2002). Dorren et al. (2004) showed that this R_t is determined by the composition and size of the material covering the surface and the radius of the falling block itself, since for larger rocks the effective surface roughness is lower than for smaller rocks (cf. Kirkby and Statham 1975; Dorren 2003), and analogue to the principle of the slope variation coefficient used by, e.g., Pfeiffer and Bowen (1989), Spang and Krauter (2001) and Dorren et al. (2004). Therefore, Dorren et al. (2006) proposed the following algorithm to calculate the R_t:

$$R_t = \frac{1}{1+((MOH + D_p)/R)} \tag{8}$$

where, MOH is the representative obstacle height at the slope surface (m), D_p is the penetration depth (m) and R is the radius of the falling block (m).

All practitioners know that it is not possible to measure the MOH in detail at each location on an active rockfall slope. As it is feasible to make a polygon map with mean diameters of the material covering the surface classified in different diameter classes, the R_t should be derived from such a map. We chose to map three MOH classes that are representative for the mean obstacle height a rock encounters during 70%, 20%, and 10% of the rebounds in a mapped polygon. Then, the rebound algorithm in Rockyfor3D chooses the MOH on the basis of the three cover classes in the polygon using a random number. Thus the values given by the three size probability classes Rg70, Rg20, and Rg10, represent values that are used in respectively 70%, 20% and 10% of the rebound calculations.

The obtained R_t is used for calculating the tangential velocity component of the block after the rebound (V_{t2}) following Pfeiffer and Bowen (1989):

$$V_{t2} = \sqrt{\frac{R^2 * (I * V_{rot1}{}^2 + RockMass * V_{t1}{}^2) * R_t}{I + RockMass * R^2}} \tag{9}$$

where, V_{t1} = the tangential velocity component of the block before the rebound, V_{rot1} is the rotational velocity before the rebound and I is the moment of inertia of the defined block form.

Before the actual calculation of V_{t2}, the model randomly varies the value of the calculated R_t with +/- 10% to represent the variance in surface roughness observed in nature. The same accounts for the normal coefficient of restitution (R_n), which is used for calculating the normal velocity component of the block after the rebound V_{n2} following Pfeiffer and Bowen (1989):

$$V_{n2} = \frac{-V_{n1} * R_n}{1 + (abs(V_{n1})/9)^2} \tag{10}$$

where V_{n1} is the normal velocity component of the block before the rebound. The factor $(abs(V_{n1})/9)^2$ adjusts for the decrease in normal coefficient of restitution as the impact velocity increases. This factor represents a transition from more elastic rebound at low normal velocities to much less elastic rebound caused by increased fracturing of the block and cratering of the slope surface at higher normal velocities (Habib 1976). As such, the model indirectly accounts for the effect of the impact angle on the character of the rebound (cf. Wu 1984).

The rotational velocity after the rebound V_{rot2} is calculated with:

$$V_{rot2} = \min\left[\frac{V_{t2}}{R}; V_{rot1} + \frac{(Vt_1 - Vt_2) * 2}{5 * R}\right] \qquad (11)$$

Similar to Pfeiffer and Bowen (1989), the slope angle at the position of the rebound is uniform randomly decreased during each rebound, however, the maximum decrease of the slope angle is fixed to 4°. Rolling is represented by a sequence of short-distance rebounds with a distance in between that is equal to the radius of the block and an absolute minimum distance of 0.2 m. These last two conditions only account for slopes with a gradient between 0° and 30°.

3.4 Impact against a tree

Since the model uses analytical solutions instead of time step iterations, the exact position of the simulated block is continuously known. Therefore, the impact position on tree stems and its influence on the energy dissipation during such impacts can be calculated. In addition to the impact position on the tree stem, the model uses the diameter of the impacted tree, the tree type (coniferous or broadleaved) and the block energy. The positions and the diameters of the trees in the direct surrounding of the simulated block are constantly available in a sub-list with x- and y-coordinates and DBH values. If an impact against a tree takes place, the block loses a fraction of its kinetic energy according to four main functions, which are visualised in Fig. 7. These functions will be explained in the following paragraphs.

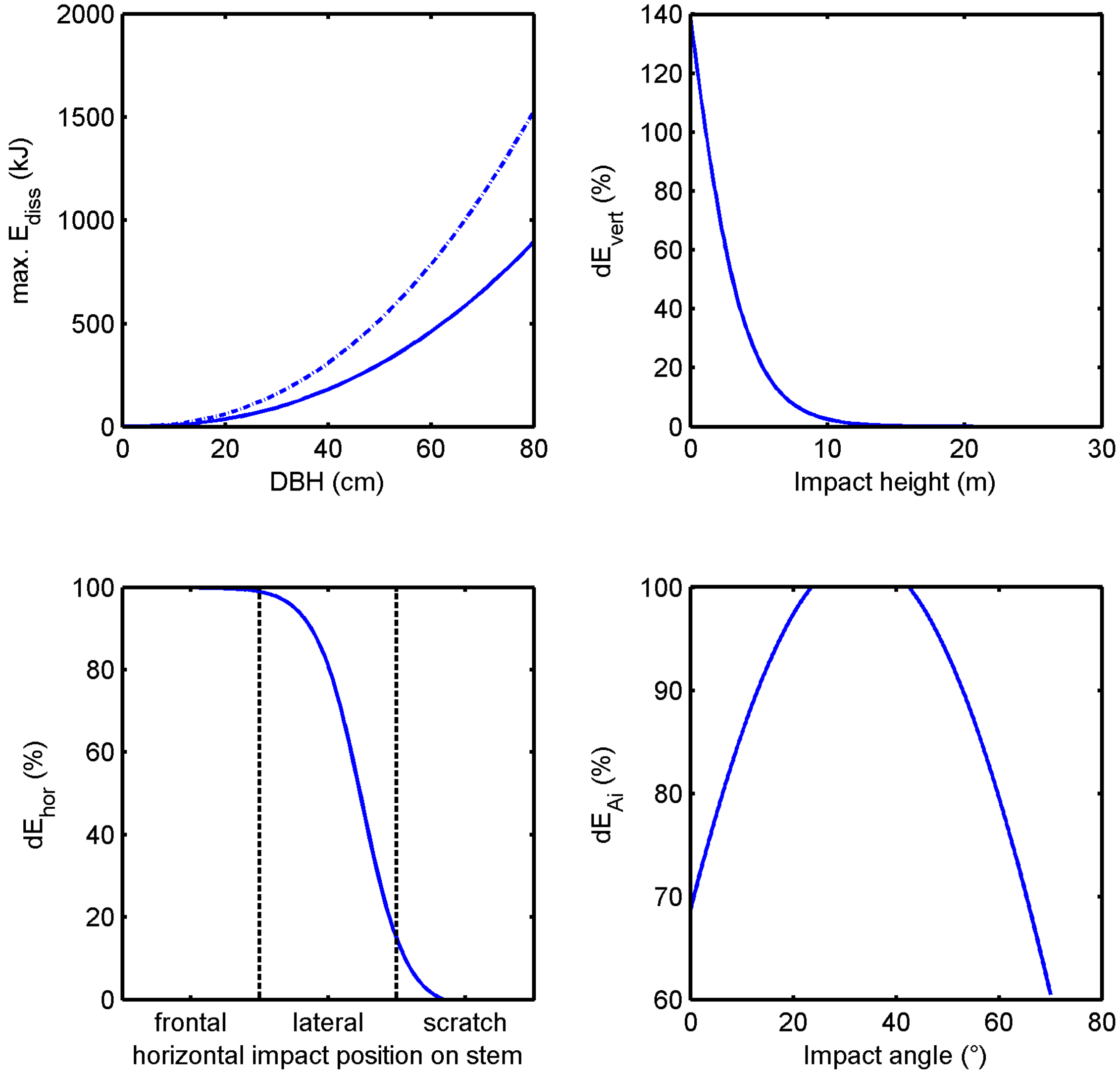


Fig. 7. Visualisation of the four main functions for calculating the energy dissipation during a tree impact. The upper right graph is calculated with a tree height of ~13 m (DBH = 20 cm).

Following Dorren and Berger (2005), the maximum amount of kinetic energy (E_{dissM}) that could be absorbed and consequently dissipated by a tree is determined by the stem diameter and the tree type following:

$$E_{dissM} = FE\_ratio * 38.7 * DBH^{2.31} \qquad (12)$$

where, E_{dissM} = maximum amount of kinetic energy that can be dissipated by the tree (in J), $FE_{\_ratio}$ = the fracture energy ratio of a the tree type (based on Dorren and Berger 2005) and the stem diameter at breast height (DBH) in cm. Rockyfor3D uses only two values for the $FE_{\_ratio}$: 0.93 for coniferous trees and 1.59 for broadleaved trees.

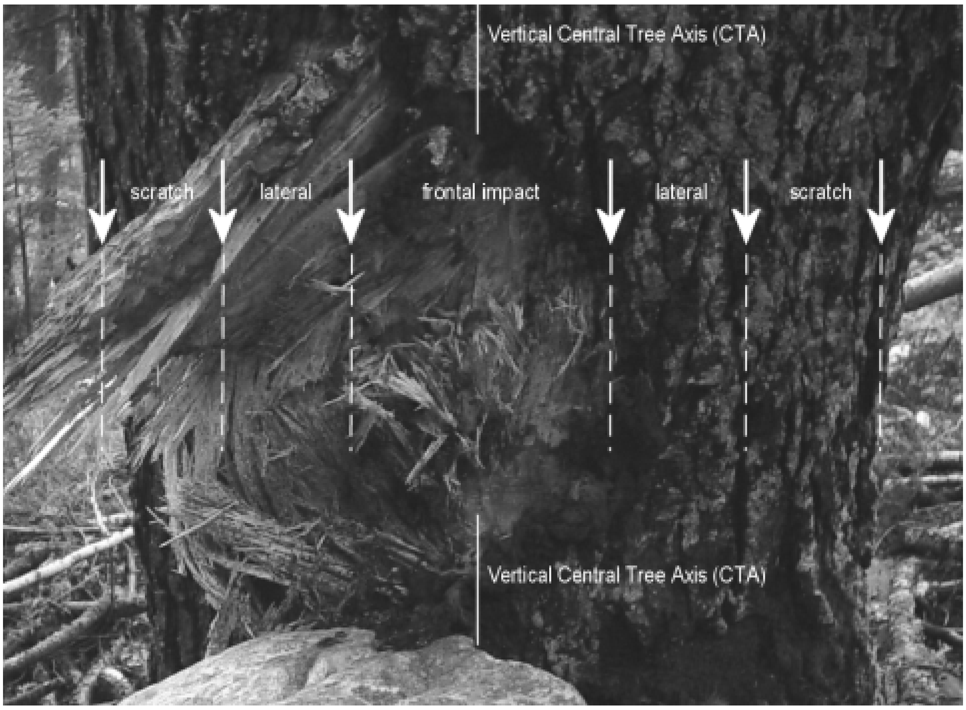


Fig. 8. Three main impact types according to the horizontal distance between the impact centre and the vertical central tree axis (CTA), as seen from the direction of impact.

Whether this maximum amount of energy is actually dissipated during the impact depends on the horizontal (cf. Fig. 8) and the vertical position of the impact on the tree stem. The effect of the horizontal position (dE_{hor}) is determined by the following function (after Dorren and Berger 2005):

$$dE_{hor} = -0.046 + \frac{0.98 + 0.046}{1 + 10^{(0.58 - ((Pi - CTA)/0.5 \times DBH)) \times (-8)}} \tag{13}$$

where, dE_{hor} = maximum amount of energy that can be dissipated by the tree, related to the horizontal position of the impact [-], Pi-CTA = horizontal distance between the impact and the vertical central tree axis (in m) and the DBH (in m).

The effect of the vertical position, or impact height, is calculated with the three following equations. Firstly the theoretical height of the tree (H_{tree} in m) is calculated on the basis of the DBH (in cm):

$$H_{tree} = 1.22 * DBH^{0.8} \tag{14}$$

Then, the percentage of maximum amount of energy that can be dissipated by the tree (dE_{vert} [-]), related to the vertical position of the impact (Z_i in m) is calculated following:

$$dE_{vert} = 1.62 * \left(\frac{1}{1 + e^{18.04*(Z_i / Htree) + 0.02*DBH - 2.35}} - \frac{1}{1 + e^{15.69 + 0.02*DBH}} \right) \tag{15}$$

Equation 13 is based on the analysis of thousands of measured trees throughout the Alps. Equation 14 and 15 are based on a recent analysis of data published by Dorren and Berger (2005), Jonsson (2007) and Lundström et al. (2009). These newly developed functions and the underlying analysis will be published as soon as possible by Berger and Dorren.

The percentage of maximum amount of energy that can be dissipated by the tree, related to the impact angle (α_imp in degrees) of the block with respect to the vertical standing tree (dE_{α_imp} [-]) is calculated following Jonsson (2007):

$$dE_{\alpha\_imp} = \min(1,(1.03 * \sin(1.46 * \frac{\min(\alpha\_imp,70)}{180°} * \pi + 0.73)) \quad (16)$$

Finally, the total amount of energy dissipated by the tree (E_{dtree} in kJ) is calculated by:

$$E_{dtree} = E_{dissM} * dE_{vert} * dE_{hor} * dE_{\alpha\_imp} / 1000 \quad (17)$$

3.5 Calculation of the fall direction

Direction change due to a rebound on the slope surface

The fall direction of the simulated block is initially determined by the aspect of the source cell. Then the direction of the falling block changes due to rebounds on the slope surface or impacts against trees. The deviation angle after a rebound on the slope surface is determined by the topography, the fall direction of the block before the rebound and the velocity of the falling block.

During each rebound, the model allows the block to deviate from its direction before rebound towards the direction of the aspect of the raster cell in which the block rebounds (Fig. 9). The slope aspect is the downslope direction of the maximum rate of change in value from each cell in a raster to four neighbouring ones (the 2 cells above and below and the 2 cells to the left and right). As such, the aspect represents the steepest slope direction in each cell and is calculated following Zevenbergen and Thorne (1987). How much the block deviates from its fall direction before the rebound towards the slope aspect in the raster cell is finally determined by a random number and the velocity of the block (cf. Table 3).

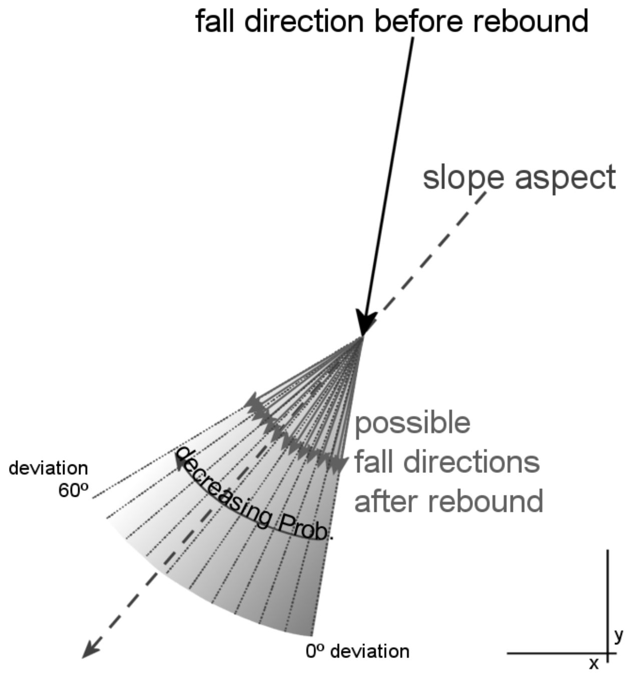


Fig. 9. The principle of the algorithm calculating the fall direction after a rebound on the slope surface.

The random number defines whether the block is deviated between 0 and 5° from its original direction, or between 5° and 10°, 10° - 15°, 15° - 20°, … , 50°- 55°. All these cases have predefined accompanying probabilities of occurrence, which are determined by the velocity of the block before the rebound as presented in Table 3.

Table 3: probabilities (in %) for deviation angle ranges after the rebound for three velocity classes used by Rockyfor3D.

Deviation Angle (°)	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	40-45	45-50	50-55
$V<10\ m.s^{-1}$	49	15	9	6	5	4	3	3	3	2	2
$10\leq V<15\ m.s^{-1}$	53	14	8	6	4	4	3	3	2	2	2
$V\geq 15\ m.s^{-1}$	46	16	10	7	5	4	4	3	3	2	0

The values in Table 3 are based on statistical analyses of rockfall trajectories and velocities observed during the rockfall experiments presented in Dorren et al. (2006). If the block moves upslope in the model, the above-described deviation ranges are allowed for both directions lateral to the direction before rebound. If the block enters a pit (a small depression) in the digital elevation model (DEM), the direction before and after rebound remains unchanged.

Direction change due to a tree impact

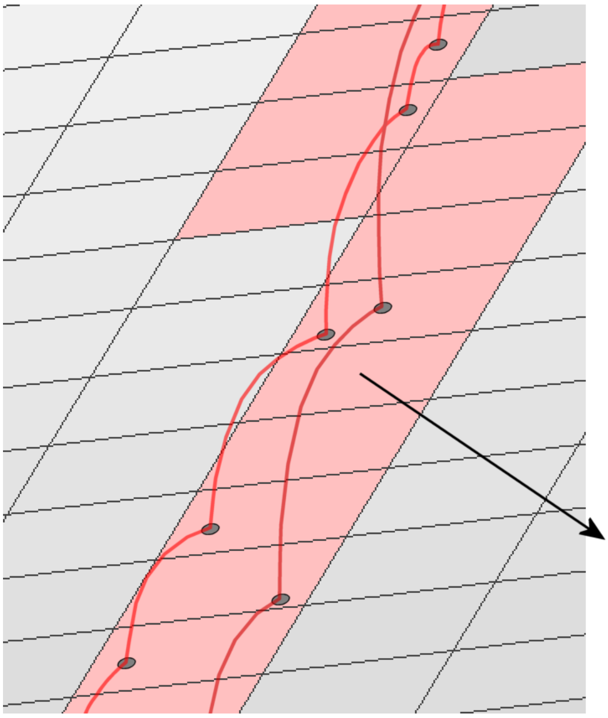
As observed during the experiments described in Dorren et al. (2005), the trajectory of a block can be deviated laterally up to 76° from its initial fall direction due to a tree impact. This accounts for the incoming and outgoing direction in a circle with a radius of 5 m around the impacted tree. Locally, meaning close to the tree stem, this deviation between the fall direction before and after the impact can be even 180°. The deviation of the block after a tree impact depends on the position of the block center with respect to the tree stem at the time of impact. On that basis, three main impact types have been defined (see also Fig. 8). Based on these three types, the probabilities given in Table 4, in combination with a uniformly distributed random number, are used to calculate the deviation.

Table 4. Probabilities (in %) for deviation in the fall direction due to a tree impact.

Impact type	Probabilities (%)		
	0 – 22.5° Deviation	22.5° - 67.5° deviation	67.5° - 76° deviation
Frontal	44	50	6
Lateral	11	84	5
Scratch	72	24	4

4 Model output data

Each time a simulated block surpasses or rebounds in a given raster cell, the maxima of different variables simulated in that cell are recorded (see also Fig. 10) in separate rasters in the concerning cell. All output of Rockyfor3D is therefore in raster format, having the same extent, cellsize and format as the input rasters.



	mean	95%cl	max	sum
Ekin	*	*		
H	*	*		
Nr				*
EL°	*			
Rvol			*	

Fig. 10. From a 3D vector trajectory to raster output data.

The output rasters created by Rockyfor3D are:

- *E_mean.asc*: the **mean of the maximum kinetic energy values** (translational + rotational; in kJ) of all the simulated blocks in a given cell
- *E_50.asc, E_90.asc, E_95.asc, E_98.asc, E_99.asc*: These rasters represent resp. the median, the 90th, 95th, 98th and 99th percentile of the simulated energy per cell. The output is given in integers and corresponds to the following energy class limits: 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 200, 250, 300, 500, 750, 1‘000, 1‘500, 2‘000, 3‘000, 5‘000, 8’000, 10’000, 15’000, 20’000, 50’000, 99‘999 (in kJ). In these rasters, the value 99’999 represents all values larger than 50’000 kJ.
- *E_95CI.asc*: the 95% confidence interval (CI) (**95% CI = E_mean + 2 * standard deviation of the maximum values in a cell, assuming a normal distribution**) of all maximum kinetic energy values (in kJ) recorded in each cell. Standard deviation (σ) values in Rockyfor3D are calculated following:

$$\sigma = \sqrt{\frac{1}{n(n-1)}\left(n\sum_{i=1}^{n} x_i^{\,2} - \left(\sum_{i=1}^{n} x_i\right)^2\right)} \qquad (18)$$

The E_95CI values can be considered as the maximum energy value recorded in the given cell. For dimensioning rockfall hazard mitigation measures, we recommend to use the 95th percentile of the energy values and passing heights collected in calculation screens.

- *Ph_mean.asc*: the mean of the maximum passing height (in m; measured in normal direction to the slope surface) of the centre of gravity of all blocks that passed through the cell.
- *Ph_50.asc, Ph_90.asc, Ph_95.asc, Ph_98.asc, Ph_99.asc*: These rasters represent resp. the median, the 90th, 95th, 98th and 99th percentile of the simulated passing heights (of the centre of gravity of the block, measured in normal direction to the slope surface) per cell. The output is given in integers and corresponds to the following height class limits: 0.5, 1, 2, 3, 4, 5, 10, 20, 99 (in m). In these rasters, 99 represents all values larger than 20 m.
- *Ph_95CI.asc*: the 95% CI of all maximum passing height values (in m; measured in normal direction to the slope surface) recorded in each cell. The calculation principle of the Ph_95CI value is identical to the E_95CI value. It can thus be considered as the maximum passing height in each cell.
- *Nr_passages.asc*: the number of blocks passed through each cell
- *Nr_sourcecells.asc*: the number of source cells “feeding” a given cell [-]. In other words, this map shows for each cell, from how many different source cells the blocks arrived in that given cell.
- *Reach_probability.asc*: (Nr_passages*100) / (Nr_simulations_per_source_cell * Nr_sourcecells) [%]. This map shows whether it is probable (higher values in the map) or improbable (lowest values > 0 in the map) that a rock arrives in a given cell.
- *Propag_probability.asc*: (Nr_passages*100) / (Total_Nr_simulations) [%]. This map can be used for the calculation of the spatial occurrence probability, which is needed in risk analyses.
- *Nr_deposited.asc*: the number of blocks stopped in each cell. *Rvol_deposit.asc*: the maximum block volume (in m3) stopped in each cell
- *EL_angles.asc*: a raster with the minimum recalculated energy line angles per cell (in °). The energy line angle (as described by Heim 1932; Scheidegger 1973; Toppe 1987; Gerber 1998, Jaboyedoff and Labiouse 2003) is the slope angle of a virtual direct line between the stopping location and the source location of a fallen block. This raster map can be useful to compare EL angles calculated from Rockyfor3D simulations with commonly used EL angle values (27° – 33° in the case of non-forested slopes and higher values for forested slopes).
- *Traj_time.asc*: minimum time needed to reach a raster cell from the defined source areas [s]
- *V_max.asc*: the absolute maximum simulated velocity per raster cell ($m.s^{-1}$). This data should be used with caution as there is no further information on the statistical distribution of the block velocities; the output was added on request.

To digitize an intensity or hazard map in a given study area on the basis of the output data of Rockyfor3D, the output rasters *Reach_probability.asc* and *Nr_deposited.asc* are most useful for delineating realistic rockfall runout zones. When using 100 simulations per source cell, the cells in *Reach_probability.asc* with values smaller than 1 to 1.5% can generally be considered as outliers.

In case of a "with-forest" simulation, the following two rasters are additionally created:

- *Tree_impact_heights.asc*: maximum tree impact height per raster cell [m]
- *Nr_tree_impacts.asc*: number of tree impacts per raster cell [-]

All the output raster maps are in ESRI ASCII Grid (raster) format and can be directly opened and visualised in most GIS software. In some cases an import in the GIS program will be necessary.

After each simulation, Rockyfor3D creates a log file, called "*Rockyfor3D_vx_x_logfile_dd-mm-yyyy_HHhMM.txt*", which contains the following information:

```
Rockyfor3D vx.x - Simulations completed on Wed Sep 12 15:12:39 2012

simulation started on Wed Sep 12 15:12:33 2012

simulation settings:
- rock volume variation = +/- 0
- nr. of simulations per source cell = 1
- nr. of simulated falling rocks (total nr. simulations) = 2382
- additional initial fallheight = 0.000000 m
- Simulation without forest and with nets

Overall simulated block volumes:
- min = 0.100000 m3
- mean = 0.100000 m3
- max = 0.100000 m3

Overall simulated energy values:
- maximum of the mean energy values = 323.900000 kj
- maximum energy value = 462.100000 kj

Statistics on Energy Line Angles recalculated from simulated
trajectories:
EL_angle[°]  frequency[-]  frequency[%]
      24.00        1.00        0.04

Output rasters (for explanation see also:
www.ecorisq.org/docs/Rockyfor3D.pdf, chapter 4)

REMARKS
```

It is recommended to add specific information on the completed simulation in the REMARKS section and to save this log file in a separate directory together with all the output rasters. As such, one can always reconstruct the scenarios used for the completed simulation.

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List of changes

Rockyfor3D Version	Date	Changes in the model (*m*) or in this description (*d*)
5.0	24.01.2012	– Manual adapted for version 5.0 (*d*) – Adapted the rolling/small rebounds condition for blocks moving upslope (*m*) – treefile.txt cannot contain a header (*m*)
5.0	15.02.2012	– Changed the Rn value for asphalt roads (*m / d*)
5.0	01.03.2012	– Corrected the description of the distribution (gamma) used for attributing DBH values for the single trees (see p. 8) (*d*)
5.0	30.05.2012	– Included the link to SAGA scripts (see p. 5) (*d*)
5.1	20.09.2012	– Manual adapted for version 5.1 (*d*) – Added E_50.asc, E_90.asc, E_95.asc, E_98.asc, E_99.asc, Ph_50.asc, Ph_90.asc, Ph_95.asc, Ph_98.asc, Ph_99.asc as output (*m*)
5.2	25.01.2015	– Manual adapted for version 5.2 (*d*) – Revision of the Graphical User Interface – adding user-friendly simulation options (*m*)
5.2.6	02.03.2016	– Adapted the class values of the energy and passing height output rasters (see p. 24/25) (*m*) – Added the output raster Propag_probability.asc (see p. 25) (*m*)

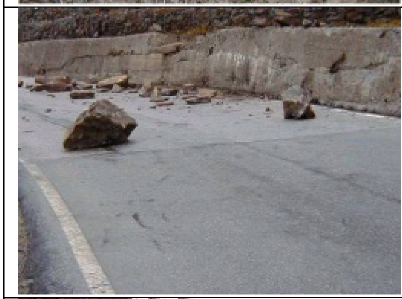
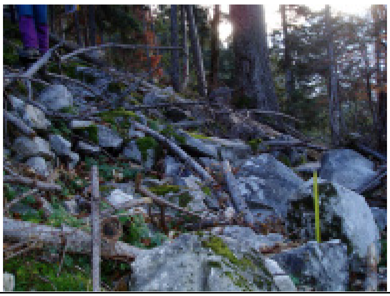
Annexe I. Precision of the surface roughness values

In Rockyfor3D, surface roughness is only determined by the material size of the underground (from very coarse gravel size (> 32 mm) onwards; see http://en.wikipedia.org/wiki/Particle_size_(grain_size)) and not by micro-topography, such a cow steps on grassy slopes. Depending on the size of the rocks/material present in the underground, which form real roughness or even "obstacles" for the falling rock during a rebound on the surface, the surface roughness values have to more or less precise. We propose to use only the values presented in the following table for fixing the values for the parameters rg70, rg20 and rg10.

Size of the surface roughness (MOH)	**Possible Rg values (in m)**
No roughness, obstacles absent	0
> 0 – 10 cm	0.03, 0.05, 0.08, 0.1
> 10 – 50 cm	0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.5
> 50 cm – 1 m	0.6, 0.7, 0.8, 0.9, 1
> 1 – 2.5 m	1.1, 1.2, 1.3, 1.4, 1.5, 2, 2.5
> 2.5 – 10 m	3, 4, 5, 6, 7, 8, 9, 10
> 10 m	100

Annexe II. Examples of parameter values for different slope surface types

Photo	rg70	rg20	rg10	soiltype
	0	0	0.05	6
	0	0.05	0.1	5
	0.25	0.5	0.9	4
	0.03	0.05	0.05	3
	0.05	0.05	0.1	4

	0.05	0.1	0.2	4
	0.03	0.03	0.03	3
	0	0	0.05	3
	0	0	0	7
	0.15	0.15	0.25	4
	0.1	0.35	0.15	4

	0	0	0	1
	100	100	100	0

Soiltype	General description of the underground	mean R_n value	R_n value range
0	River, or swamp, or material in which a rock could penetrate completely	0	0
1	Fine soil material (depth > ~100 cm)	0.23	0.21 - 0.25
2	Fine soil material (depth < ~100 cm), or sand/gravel mix in the valley	0.28	0.25 - 0.31
3	Scree (Ø < ~10 cm), or medium compact soil with small rock fragments, or forest road	0.33	0.30 - 0.36
4	Talus slope (Ø > ~10 cm), or compact soil with large rock fragments	0.38	0.34 - 0.42
5	Bedrock with thin weathered material or soil cover	0.43	0.39 - 0.47
6	Bedrock	0.53	0.48 - 0.58
7	Asphalt road	0.35	0.32 – 0.39