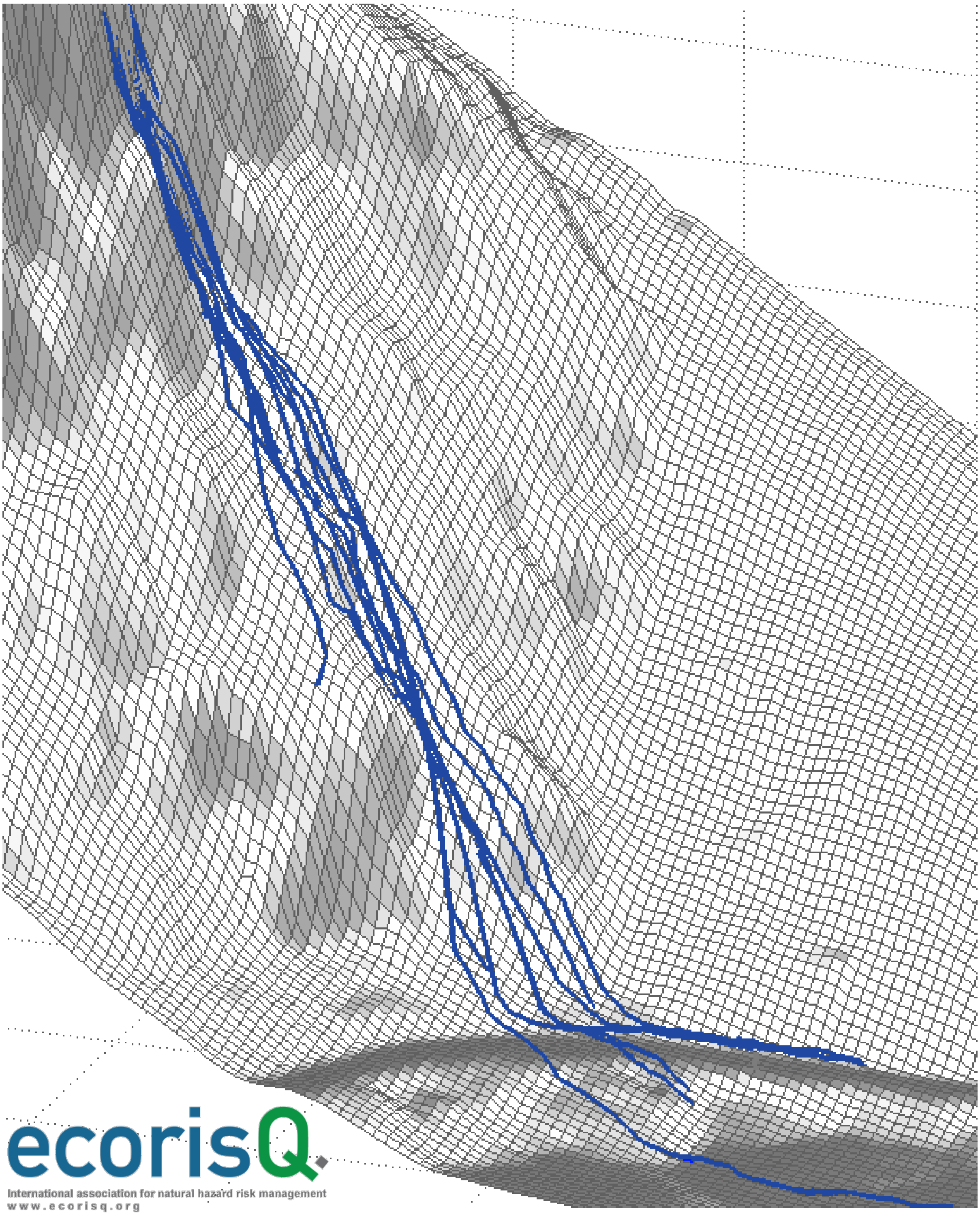
Rockyfor3D (v6.0) revealed

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 (INRAE Grenoble, at those times called CEMAGREF) 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, 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.

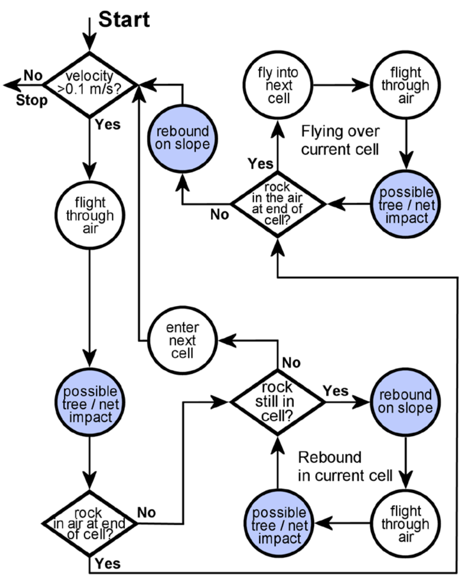


Fig. 1. Flow diagram of Rockyfor3D. The blue coloured circles indicate modelling steps where changes in the fall direction of the simulated block may occur.

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 Rockyfor3D, 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 6 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 (cf. Dorren and Heuvelink, 2004). However, experience also showed that an ideal resolution is 2 m × 2 m, because in some cases 1 m × 1 m and smaller resolution does lead to trajectories that are too long.

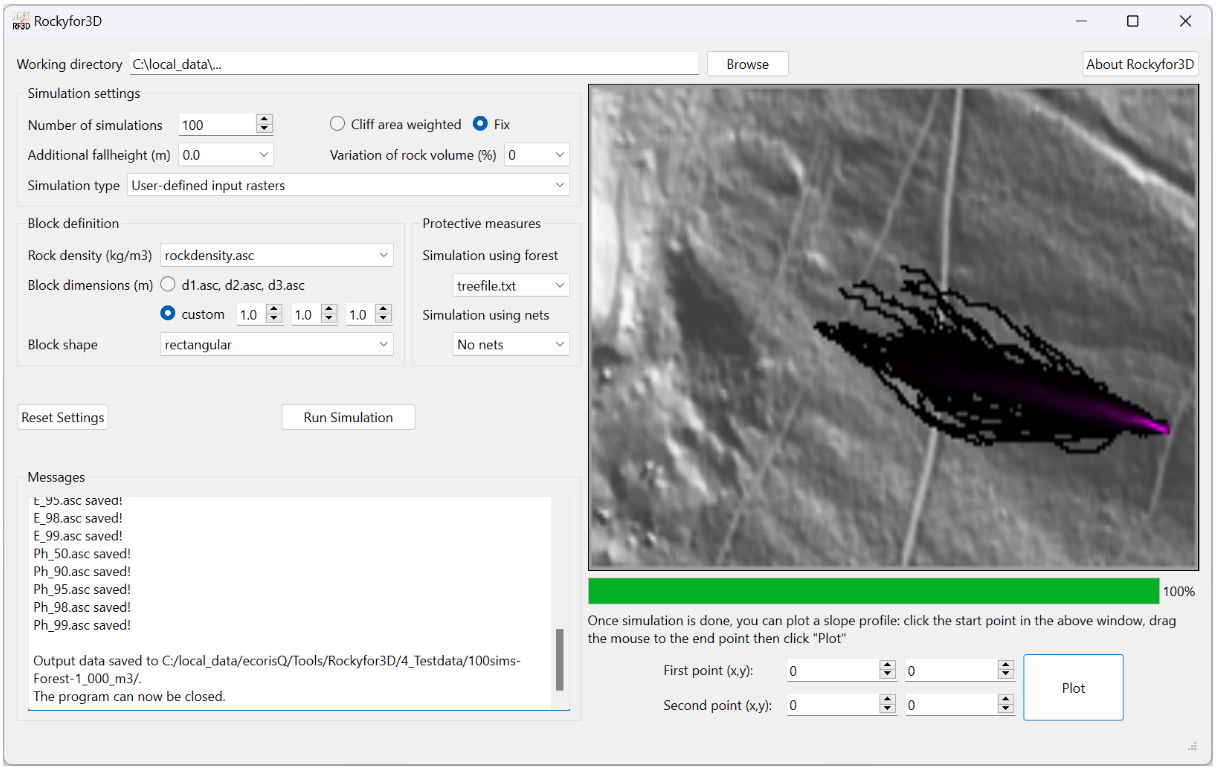


Fig. 2. The Graphical User Interface (GUI) of Rockyfor3D.

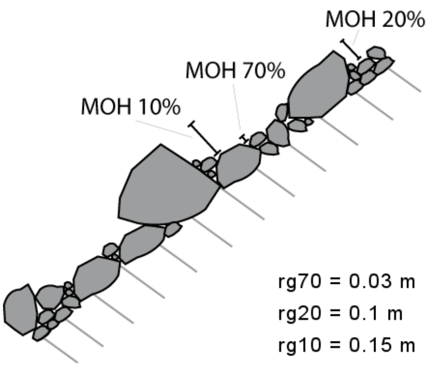
All rasters should be in ESRI ASCII Grid format, which is readable by all text editors. Below, an example of a small raster in such format is presented. The header provides information on the number of rows and columns in the raster (nrows and ncols), the cellsize or resolution of the raster (in m), 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 rasters are minimally required for a simulation in Rockyfor3D using your own field data (GUI setting: simulation type -> user defined input rasters; the option “rapid automatic simulation” only requires the raster dem.asc – the respective details can be found on page x):

Raster name	Description

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 123456.2`
	`yllcorner 1234567.2`
	`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`

rockdensity.asc	a raster map with the rock density in each source or start cell (integer type raster; [values 0 or 2000 – 3400 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 2700, a block with a density of 2700 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 will not be taken into account in the simulation!**
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.
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 uses 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 the rebounds of the rocks on asphalt roads are unrealistically high, a soiltype of 3 or less could be used for asphalt roads that absorb more energy. Feedback from users is always appreciated for further improvement of the model.

The following rasters are optional, since these characteristics can be defined (for all start cells then) in the GUI :

Raster name	**Description**
d1.asc *d2.asc* *d3.asc*	These three raster maps allow defining the size of the block for every start cell by giving a height, width, and length value (double type raster; [values 0.00 – 20.00 m]). These raster maps must contain values in meters. If a dimension value defined in one of the three rasters equals to 0.00, that raster cell will not be considered as source cell. The three block dimensions defined in each source cell are varied uniform randomly based on the defined volume variation (between ±0% and ±50% in the GUI) 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%.
blshape.asc	This raster map allows for a spatial definition of 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).

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 input data preparation:

Download shapefile templates for digitizing terrain, forest and rockfall nets as well as automatic data preparation scripts, based on SAGA-GIS, for Rockyfor3D from the tools menu on our website (after login). 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****. If you can/do not use the scripts described above, see this document for more details on data preparation. A test raster dataset for running Rockyfor3D 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)

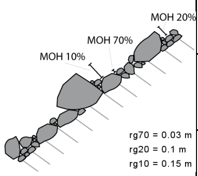
Rock density (kg.m^{-3}):

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

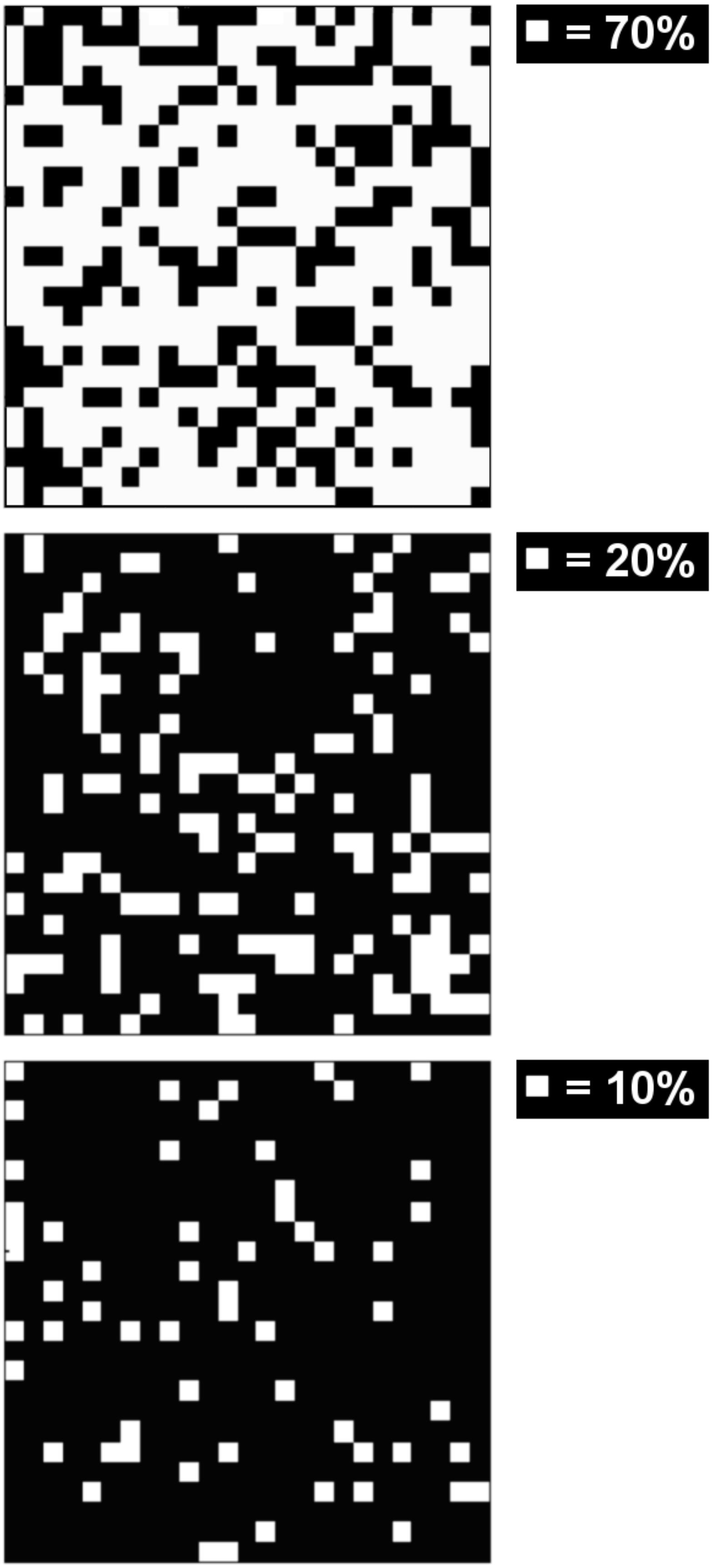


Fig. 3. Images to assist in estimating the three size-probability classes in the field.

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
...
```

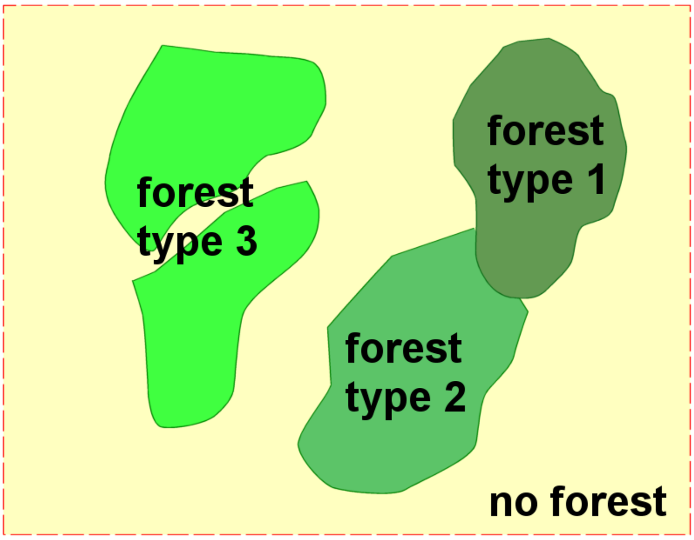
   In addition to the file *treefile.txt*, a raster called *conif_percent.asc* needs to be available in the working directory (integer type raster; [values 0 – 100 %]). In this raster map, the cell values represent the mean percentage of coniferous trees (%) within each cell (cf. Fig. 4). This raster needs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

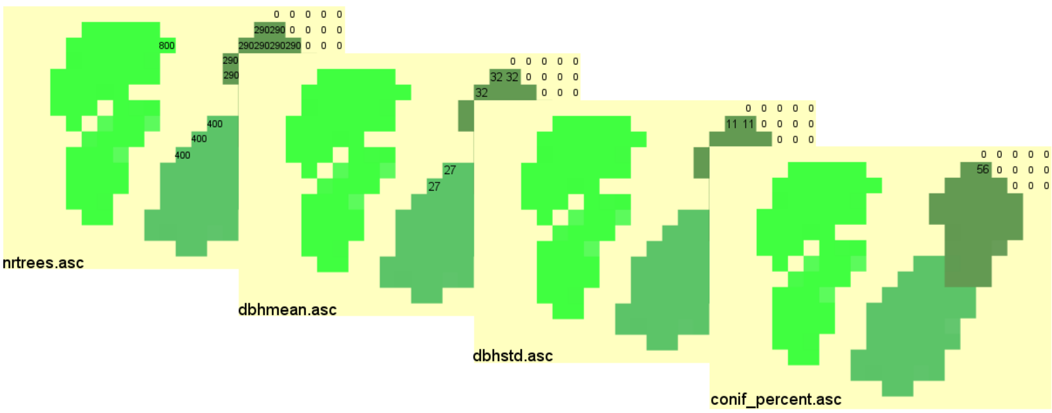


Fig. 4. A workflow for creating the forest raster maps required for option B.

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_v6_ 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 line, without accounting for the barrier effect of a rockfall 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, but it is good to make sure that the net lines do not overlap in the created rasters.

The following data are recorded for each block arriving in the net (calculation screen):
1. velocity (V in m.s^{-1})
2. kinetic energy (E = translational and rotational in kJ)
3. vertical passing height (*Ph_vert* in m)
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 – set to 100 to ensure enough simulations for sound statistical values.
- Option "Fix" / "Cliff area weighted": "Fix" simulates the defined number of trajectories from all defined start (or release) cells. "Cliff area weighted" calculates the number of simulations per cell based on the cliff area in the cell following:

$$Nr\_simulations_{cell} = ceil(\frac{0.5 * Nr_{simulationsGUI}}{\cos(Slope_{cell})}) \quad (1)$$

- Variation of rock volume (%): 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 (m): this is the height 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.
- Simulation type:
  - Using input rasters: the simulation will be based on your own input rasters *rg70.asc*, *rg20.asc*, *rg10.asc* and *soiltype.asc*
  - Rapid automatic simulation (low roughness): Rockyfor3d will create the required input rasters on roughness and soiltype based on the slope gradient and the following rules:

Terrain	**Soil type**	**Low roughness**			**Medium roughness**		
		Rg70	Rg20	Rg10	Rg70	Rg20	Rg10
Sources area	6	0	0	0	0	0	0
Slope > 38°	5	0.05	0.05	0.1	0.05	0.1	0.1
Slope 32° - 38°	4	0.05	0.1	0.2	0.1	0.2	0.3
Slope 20° - 32°	3	0.05	0.1	0.15	0.1	0.15	0.25
Slope 10° - 20°	2	0	0	0.1	0	0.1	0.1
Slope < 10°	1	0	0	0	0	0	0

  - For all three simulation types a rock density raster can be used to define source cells. Or sources areas are defined by Rockyfor3D all cells steeper than a given slope threshold α, which is calculated following Eq. 1. This is done when choosing a rock density value in the GUI.

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):

$$\alpha = 55 * cellsize^{-0.075} \quad (2)$$

- 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 in the GUI

Protective measures

- Simulation using forest: this defines if forest is accounted for 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 define the working directory (cf. Fig. 2) 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. After finishing the simulations, the output raster data (cf. chapter 4) are saved in a subdirectory of the defined working directory and a hillshade combined with a map showing the nr. of passages is presented 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, e.g., QGIS.

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), e.g, in a MS-DOS command window, which allows automatizing repeated simulations with various settings using a batch file (see internet for help on these).

To run RF3D_cmd.exe, find the path to the directory of the command line .exe file, go to the windows dos command window and type for example:

```
C:\>cd Full_path_to_dir_of Rockyfor3D_cmd_exe_file
C:\ Full_path_to_dir_of Rockyfor3D_cmd_exe_file>RF3D_cmd_64.exe
```

These are the available options with the command line version:

-h [--help]	produce help message
-p [--path] arg	the directory with the input data
-s [--nsim] arg	the number of simulations. Default is 1
-w [--cliff_w] arg	cliff area weighted nr. of simulations (0- no (this equals the option “fix” in the GUI), 1- yes). Default is 0 (for explanation see section 2.5)
-t [--trees] arg	use of tree data (0- no trees, 1- use treefile.txt, 2- use forest rasters). Default is 0
-n [--nets] arg	use of nets (0- no nets, 1- with nets). Default is 0
-c [--cores] arg	number of cores used for the processing (advanced)
-i [--inifall] arg	the additional fall height (in m). Default is 0
-v [--dv] arg	random variation of the rock volume per simulation (use 0 for no variation, 1 for +/-5%, 2 for +/-10%, 3 for +/-20%, 4 for +/-50%). Default is 0
-y [--density] arg	rock density (0- rockdensity.asc, all other values in kg/m3). Default is 0
-1 [--d1] arg	first block dimension (0- d1.asc, all other values in m). Default is 0
-2 [--d2] arg	second block dimension (0- d2.asc, all other values in m). Default is 0
-3 [--d3] arg	third block dimension (0- d3.asc, all other values in m). Default is 0
-e [--shape] arg	the block shape (0- bl_shape.asc, 1- rectangular, 2- ellipsoid, 3- sphere, 4- disc). Default is 0
-m [--mode] arg	Simulation type (0- input files, 1- Automatic simulation, low roughness, 2- Automatic simulation, medium roughness. 1- and 2- require custom values for block dimensions and shape. Default is 0

-r [--random]	This activates a "true" random mode. With this mode, the pseudorandom number generator is never reset, so each set of simulations will provide different results.
-f [--treefactor]	Use custom tree energy dissipation factors [>0 – 1.3] according to Moos et al. (2019) in the treefile.txt
-o [--treeout]	generate an output file called TreeImpact_Info.csv with the coordinates and DBH of each impacted tree, the tree factor used for calculating the max. energy dissipation by the tree, the number of times the tree was impacted by a block and how many times the tree stem broke during impact
-a [--impact]	generate an output file called RockInfo_at_TreeImpacts.csv with the coordinates of the block during tree impact, the impact height, the impact type (frontal, lateral or scratch), the DBH of the impacted tree, the energy dissipated during impact (in kJ), and the total energy of the block before impact (in kJ) and this for all tree impacts. It is not recommended to use this options while executing many simulations, since the generated csv file will be huge.

The following command example:

RF3D_cmd_64.exe -p c:\local_data\casestudy -s 100 -t 1 -e 3 -1 1.0 -2 1.0 -3 1.0

Launches the command line version of Rockyfor3D, retrieves the input data from c:\local_data\casestudy, executes 100 simulations from each start cell defined in rockdensity.asc, with the effect of a forest represented by treefile.txt, with a spherical block that has the following dimensions: 1.0 x 1.0 x 1.0 m (= 0.52 m^3).

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 based on 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).

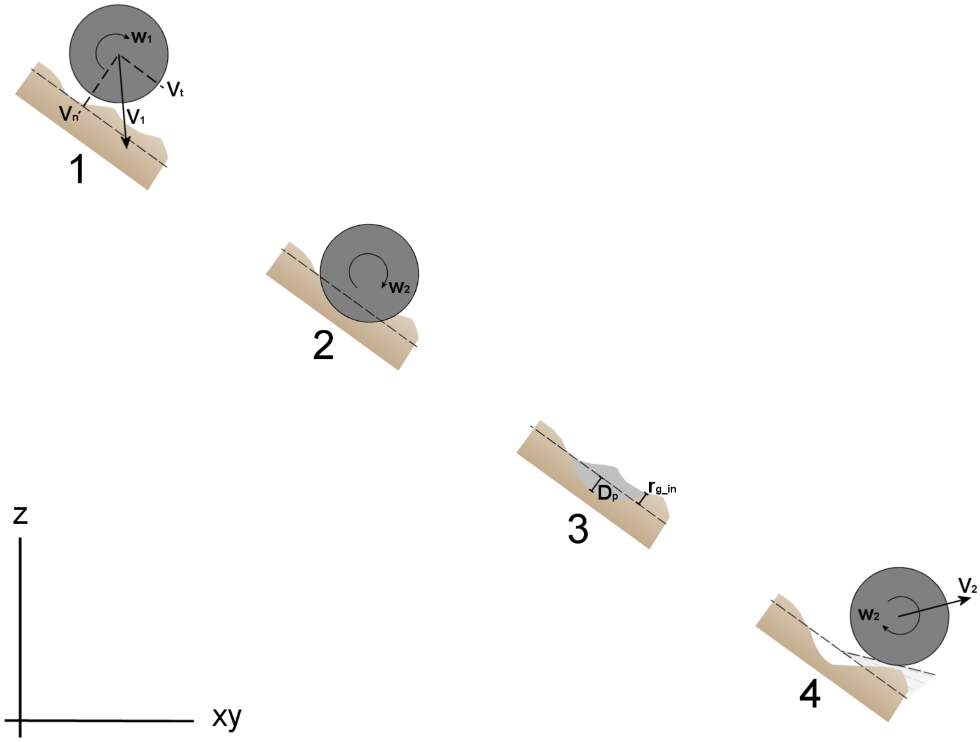


Fig. 6. The rebound as represented by the algorithms used by Rockyfor3D.

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:

$$\frac{D_p}{d} = \frac{2}{\pi} N \, ln\left[\frac{1+I_e/N}{1+k\pi/4N}\right] + k \quad \text{for } \frac{D_p}{d} > k \qquad (3)$$

$$\frac{D_p}{d} = \sqrt{\frac{1+k\pi/4N}{1+I_e/N}\frac{4k}{\pi}I_e} \quad \text{for } \frac{D_p}{d} \le k \qquad (4)$$

where,

$$I_e = \frac{RockMass*V^2}{R_i*d^3} \qquad (5)$$

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

$$Ri = 55 * 10^9 * {R_n}^7 \tag{6}$$

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

$$N = \frac{RockMass}{\rho_{soil} * d^3 * B * 0.5} \tag{7}$$

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

$$\rho_{soil} = \max(1000;\ 1200 * ln(R_n) + 3300) \tag{8}$$

This function provides values between approx. 1400 kg/m^3 for fine soil and 2650 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:

$$R_t = \frac{1}{1 + ((MOH + D_p)/R)} \tag{9}$$

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* based on 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. 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 obtained R_t is used for calculating the tangential velocity component of the block after the rebound (V_{t2}) following Pfeiffer and Bowen (1989) and Noel et al. (2021):

$$V_{t2} = \sqrt{\frac{R^2*(I*V_{rot1}{}^2+RockMass*V_{t1}{}^2)*Ff*Sf}{I+RockMass*R^2}} \quad (10)$$

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.

$$Ff = Rt + \frac{1-\mathrm{Rt}}{1.5+\left(\frac{\mathrm{Vt1}-\mathrm{Vrot1}*\mathrm{R}}{3.048}\right)^2} \quad (11)$$

$$Sf = \frac{\mathrm{Rt}}{1+\left(\frac{\mathrm{Vn1}}{15.24}\right)^2} \quad (12)$$

The normal coefficient of restitution (R_n) is used for calculating the normal velocity component of the block after the rebound V_{n2} following Pfeiffer and Bowen (1989):

$$V_{n2} = \frac{-V_{n1}*R_n}{1+(\frac{V_{n1}}{9.144})^2} \quad (13)$$

where V_{n1} is the normal velocity component of the block before the rebound. The factor $(V_{n1}/9.144)^2$ 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 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:

$$V_{rot2} = min\left[\frac{V_{t2}}{R}; V_{rot1} + \frac{(Vt_1-Vt_2)*2}{5*R}\right] \quad (14)$$

The max. value of Vrot [in rad/s] finally depends on the block shape following Caviezel et al. (2021). For blocks where one block dimension is 50% (or less) of both other dimensions, the maximum value V_{rot2} is calculated following:

$$V\_rot2 = min\,[V_{rot2}, 12480 * RockMass^{\left(-\frac{1}{3}\right)} * \pi/180] \quad (15)$$

For all other blocks, the maximum V_{rot2} is calculated following:

$$V\_rot2 = min\,[V_{rot2}, 9278 * RockMass^{\left(-\frac{1}{3}\right)} * \pi/180] \quad (16)$$

The last step of the rebound calculation consists of checking if sufficient has been lost during the rebound. This is done on the basis of the relationship between the total deviation angle (TOTdev) and the total energy loss published by Noël et al. (2023). If the total deviation is larger than 55°, then the ratio between total kinetic energy before and after the rebound (E_{ratio_impact}) cannot be larger than:

$$E_{ratio\_impact} = -0.01 * TOTdev + 1.3 \quad (17)$$

If necessary, the E_{ratio_impact} value is used to reduce the tangential, normal and rotational energy components, where the proportion of those components to the total kinetic energy after rebound remains unchanged.

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. The latter condition only applies for slopes with gradients less than 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.

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

$$E_{dissMax} = FE\_ratio * 38.7 * DBH^{2.31} \quad (18)$$

where, $E_{dissMax}$ = maximum amount of kinetic energy that can be dissipated by the tree (in J), $FE_{\_ratio}$ = the fracture energy ratio of the tree type (see Dorren and Berger 2005, Toe et al., 2017, Moos et al., 2019) and the stem diameter at breast height (DBH) in cm. Rockyfor3D uses standard only two values for the $FE_{\_ratio}$: 0.95 for coniferous trees and 1.3 for broadleaved trees. There is also an option to provide custom tree energy dissipation factors (values from [max 1.3] following Moos et al., 2019), for every single tree in the treefile.txt. To do so, the tree factors should be given in the fourth column after the x-coordinate, y-coordinate and the DBH of each tree.

Whether this maximum amount of energy is indeed dissipated during the impact depends on the horizontal (cf. Fig. 8) and the vertical position of the impact on the tree stem.

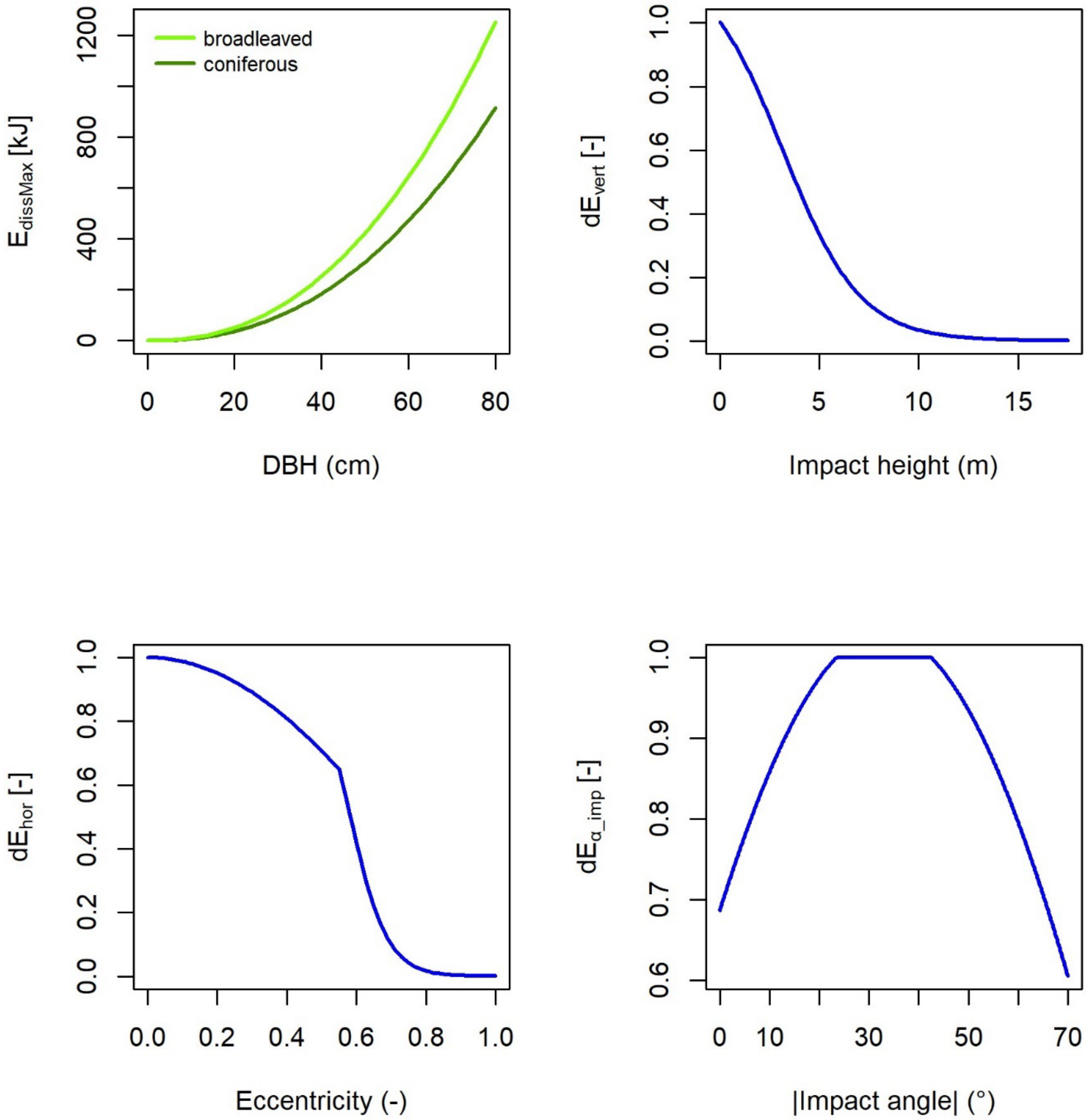


Fig. 7. Visualisation of the four main functions for calculating the energy dissipation during a tree impact. The upper right graph is calculated with a tree height of 35 m (DBH = 66 cm).

The effect of the horizontal position (dE_{hor}) is determined by the following functions (modified from Dorren and Berger 2005):

$$\mathrm{Dist}_{\mathrm{IPCT}} = \frac{Pi - CTA}{0.5 \times DBH} \tag{19}$$

$$dE_{hor} = \cos\left(Dist_{IPCT} * \frac{\pi}{2}\right) \quad for\ Dist_{IPCT} < 0.543 \tag{20}$$

$$dE_{hor} = \max\left(0, \frac{0.98+0.046}{1+10^{(-8*(0.58-Dist_{IPCT}))}}\right) \quad for\ Dist_{IPCT} \geq 0.543 \tag{21}$$

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 tree center point and the impact point projected on the normal line from the tree center to the fall direction before impact (in m) and the DBH (in m).

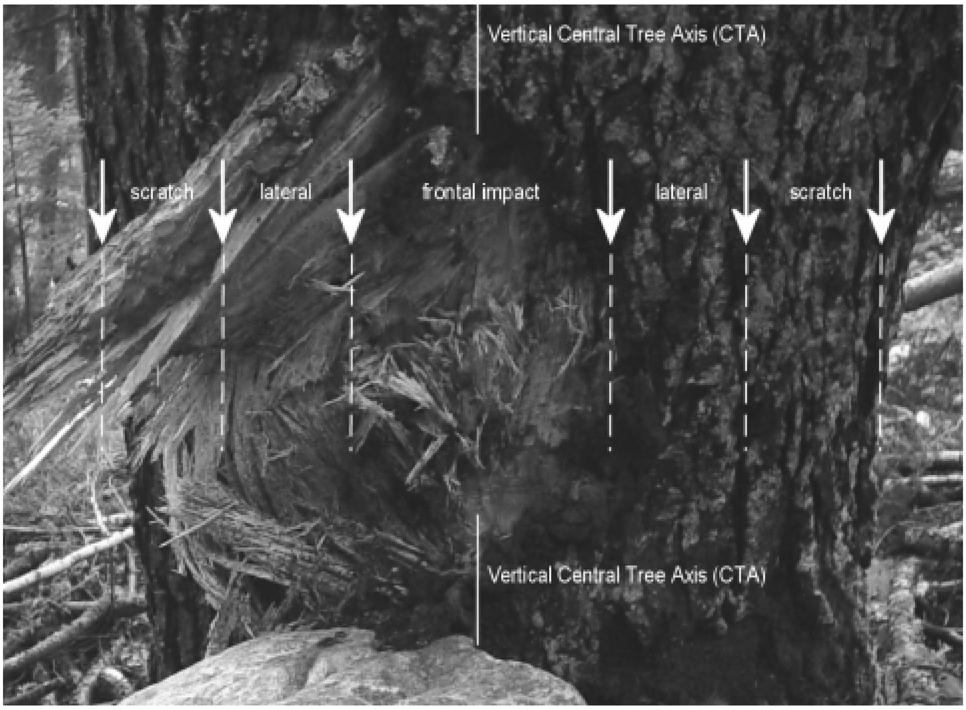


Fig. 8. Three main impact types according to the horizontal distance between the impact centre and the vertical central tree axis (CTA), as seen from the direction of impact.

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):

$$H_{tree} = 1.22 * DBH^{0.8} \quad (22)$$

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:

$$dE_{vert} = 1.2 * \left(\frac{1}{1+e^{18.04*(Z_i/Htree)+0.02*DBH-2.35}} - \frac{1}{1+e^{15.69+0.02*DBH}}\right) \quad (23)$$

Equation 14 is based on the analysis of thousands of measured trees throughout the Alps. Equation 15 is based on a recent analysis of data published by Dorren and Berger (2005), Jonsson (2007) and Lundström et al. (2009).

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):

$$dE_{\alpha\_imp} = min(1, (1.03 * sin(1.46 * \frac{min(\alpha\_imp, 70)}{180^{\circ}} * \pi + 0.73)) \quad (24)$$

Finally, the total amount of energy dissipated during the tree impact ($E_{dissTree}$ in J) is calculated by:

$$E_{dissTree} = E_{dissMax} * dE_{vert} * dE_{hor} * dE_{\alpha\_imp} \quad (25)$$

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).

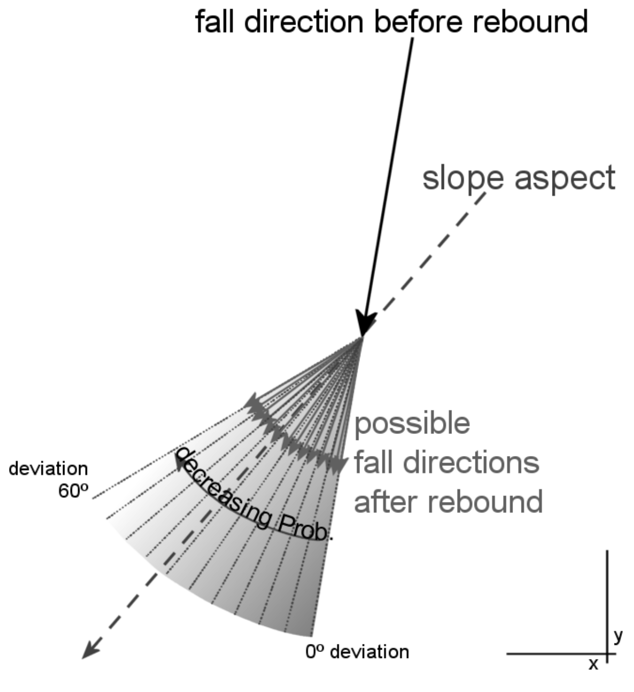


Fig. 9. The principle of the algorithm calculating the fall direction after a rebound on the slope surface.

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

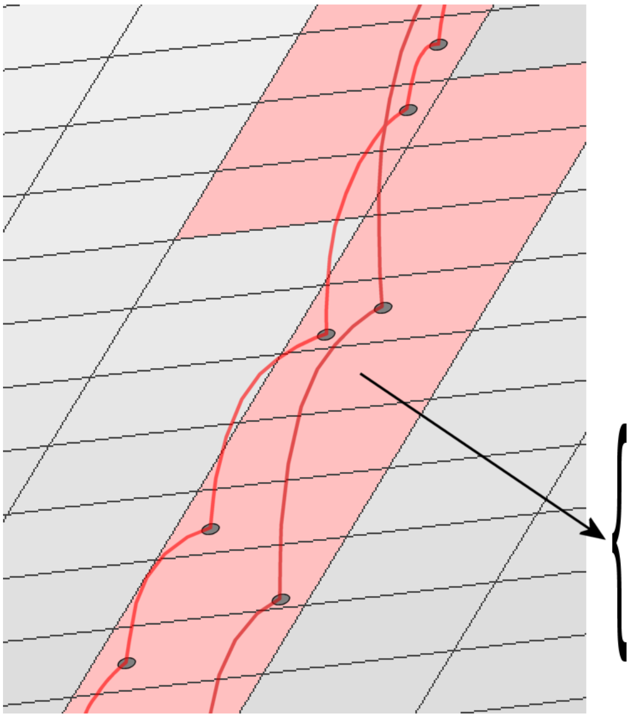
As observed during the experiments described in Dorren et al. (2005), the trajectory of a block can be deviated laterally up to 76° from its initial fall direction due to a tree impact. This accounts for the incoming and outgoing direction in a circle with a radius of 5 m around the impacted tree. Locally, 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_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.
- *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.
- *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_sourcecells* Nr_simulations_from_source_cells) [%]. 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 m^3] 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 [in s]
- *V_max.asc*: the absolute maximum simulated velocity per raster cell [in $m.s^{-1}$]. 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 1.1% 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 [in 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.

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

```
Rockyfor3D v6.0 - Simulations completed on Wed Sep 12 15:12:39 2012

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

simulation settings:
- defined nr. of simulations = 100
- "fix" / "cliff area weighted" nr. of simulations per source cell
- nr. of simulated falling rocks (total nr. simulations) = 1000
- rock volume variation = +/- 0
- 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

Statistics on Energy Line Angles recalculated from simulated
trajectories:
```

```
EL_angle[°]  frequency[-]  frequency[%]
      24.00         1.00          0.04

Output rasters (for explanation see the manual):
...
...
...


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 in this document

RF3D version	Date	Changes (model changes are listed here)
5.0	24.01.2012	– Manual adapted for version 5.0 (*d*)
5.0	15.02.2012	– Changed the Rn value for asphalt roads
5.0	01.03.2012	– Corrected the description of the distribution (gamma) used for attributing DBH values for the single trees
5.0	30.05.2012	– Included the link to SAGA scripts
5.1	20.09.2012	– Manual adapted for version 5.1 – 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
5.2	25.01.2015	– Manual adapted for version 5.2
	02.03.2016	– Adapted the class values of the energy and passing height output rasters – Added the output raster Propag_probability.asc
6.0	24.10.2024	– Manual adapted for version 6.0
	14.12.2024	– Included adapted logfile of v6.0.1

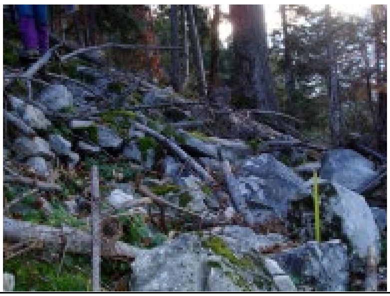
Annexe I. Precision of the surface roughness values

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 (good value for deep rivers and lakes)

Annexe II. Examples of roughness and soiltype values

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 penetrates 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