RAMMS::ROCKFALL User Manual

RAMMS

rapid mass movement simulation

A numerical model for rockfall in research and practice

User Manual v1.8

Rockfall

RAMMS AG

RAMMS - Your Rapid Mass Movement Solution

Predict. Protect. Prevent

SLF

spin off

WSL

ETH

Eidgenössische Technische Hochschule Zürich

Swiss Federal Institute of Technology Zurich

Title picture: Rockfall event at Brienz (GR), Photo: SLF, 24.07.2014

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July 2024

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1 Introduction

1.1 Motivation

Mitigation of natural hazards relies increasingly on numerical process models to predict the area inundated by rapid geophysical mass movements. These movements include

- snow avalanches,
- torrent based debris flows and hillslope debris flows,
- mudslides,
- ice avalanches and glacier lake outbreaks
- rockfalls and rock avalanches.

Process models are used by engineers to predict the speed and reach of these hazardous movements in complex terrain. The preparation of hazard maps is a primary application. The models are especially helpful when proposing technical mitigation measures, such as dams and embankments or rockfall protection barriers. The models allow hazard engineers to optimize limited financial resources by studying the influence of different hazard scenarios on defense options.

1.2 RAMMS

The RAMMS (**RA**pid **M**ass **M**ovements **S**imulation) software system contains three process modules:

- RAMMS::AVALANCHE
- RAMMS::DEBRISFLOW
- RAMMS::ROCKFALL

The RAMMS::AVALANCHE and RAMMS::DEBRISFLOW modules are designed for flow phenomena containing fast moving particulate debris of snow and rocks. In the avalanche module, the interstitial fluid is air, whereas in the debris flow module the interstitial fluid is mud. The RAMMS::AVALANCHE and RAMMS::DEBRISFLOW models are used to calculate the motion of the movement from initiation to runout in three-dimensional terrain. The models use depth-averaged equations and predict the slope-parallel velocities and flow heights. This information is sufficient for most engineering applications. Information in the slope-perpendicular direction (e.g. mass and velocity distribution) is lost; however, this is seldom of practical interest. Both models require an accurate digital representation of the terrain. Engineers specify initial conditions (location and size of the release mass) and friction parameters, depending on terrain (e.g. roughness, vegetation) and material (e.g. snow, ice or mud content of the debris flow).

The RAMMS::ROCKFALL module is used to study the rigid body motion of falling rocks. The model predicts rock trajectories in general three-dimensional terrain. Rock trajectories are governed by the interaction between the rock and ground. The model contains six primary state variables: three translational speeds and three rotational velocities of the falling rock. From these, kinetic energy, runout distance and jump heights can be derived. Generalized rock shapes are modeled. Rock orientation and rotational speed are included in the rock/ground interaction. The RAMMS::ROCKFALL module is therefore fundamentally different from the RAMMS::AVALANCHE and RAMMS::DEBRISFLOW modules because it is based on hard-contact, rigid-body Lagrangian mechanics, not Eulerian flow mechanics. It also differs from existing rockfall modules because the rock/ground interaction is not governed entirely by simple rebound mechanics, but frictional (dissipative) rock/ground interactions. These govern the onset of rock jumping. The RAMMS::ROCKFALL module predicts all rigid-body motions – rock sliding, rolling, jumping and skipping.

The RAMMS::ROCKFALL module was coupled to the same user-friendly visualization tool used in the RAMMS::AVALANCHE and RAMMS::DEBRISFLOW modules. The visualization tool allows easy preparation, execution, visualization and interpretation of simulations.

In all RAMMS modules, new constitutive models have been developed and implemented, thanks to calibration and verification at full scale test sites such as St. Léonard/Walenstadt (rockfall, mitigation measures), Vallée de la Sionne (snow avalanches) and Illgraben (debris flow). At present, two new scientific RAMMS modules are under development: RAMMS::EXTENDED and RAMMS::DBF_2PHASE.

The RAMMS website https://www.ramms.ch provides useful information such as more information about the modules, frequently asked questions (FAQ) or recent software updates. Please visit this web page frequently to stay up to date.

1.3 RAMMS::ROCKFALL Model

The RAMMS::ROCKFALL model was developed by the Centre of Mechanics at the ETH Zurich and the RAMMS team of the WSL Institute for Snow and Avalanche Research SLF. This joint project was supported by the Swiss National Science Foundation (Grant: SNF 200021-19613). The Centre of Mechanics was responsible for the development of the simulation code in close contact with geological, geophysical and software engineering experts from the SLF/WSL to discuss modeling issues specific to rockfall mechanics. The SLF/WSL calibrated and validated the simulation code and provided rock shapes. The RAMMS team of SLF/WSL integrated the simulation code in an extensive and easy-to-use graphical user interface (GUI). This manual describes the features of the RAMMS program, allowing beginners to get started quickly as well as serving as a reference to expert users.

1.4 Learning by doing

This manual provides an overview of RAMMS::ROCKFALL. Exercises exemplify different steps in setting up and running a RAMMS simulation especially in Chapter 2 *'Setting up a simulation'*. However, to get the most from the manual, we suggest reading it through while simultaneously having the RAMMS program open, learning by doing. We assume RAMMS users to have a basic level of familiarity with windows-based programs, commands and general computer terminology. We do not describe the basics of windows management (such as resizing or minimizing). RAMMS windows, click options and input masks are similar to other Windows-based programs and can be used, closed, reduced or resized in the same way.

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Users of the RAMMS software models assume all risk associated with the use of these models. RAMMS AG shall not be held liable for any loss, injury, or damage resulting from the use or reliance on these models, including but not limited to personal injury, property damage, or financial loss.

The RAMMS software models are intended to supplement, not replace, the judgment and expertise of professionals in the fields of geology, engineering, and hazard management. Users should not rely solely on the models for making decisions related to hazard mitigation, land use planning, or emergency response.

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By using the RAMMS software models, you acknowledge that you have read, understood, and agree to be bound by the terms of this disclaimer.

Swiss law applies. Court of jurisdiction is Davos. If you encounter problems, please contact info@ramms.ch.

2 Installation and Setup

2.1 System requirements

We recommend the following minimum system requirements for running RAMMS::ROCKFALL:

- Operating System: Windows 10 or higher
- RAM (memory): 8 GB (more recommended)
- CPU: Intel Pentium 1 GHz (multi core recommended), only 64-bit supported!
- Graphic Card: OpenGL support recommended

2.2 Installation

Please download the RAMMS::ROCKFALL setup file *"ramms_rock_user_setup_64.zip"* from https://www.ramms.ch/ramms-rockfall/ (Downloads section). Please make sure that you have a 64-bit Windows system.

Please do the following steps before beginning to install RAMMS:

- Click on the path given above or copy the path to any browser. A window pops up and the automatic download of the file *ramms_rock_user_setup_64.zip* starts after clicking *Yes*.
- Unzip the file to a temporary location.
- You must have *Administrator privileges* on the target machine. If you do not have such privileges, the installer cannot modify the system configuration of the machine and the installation will fail. Note that you do not need *Administrator privileges* to run RAMMS afterwards.
- Read first, install afterwards! Please read the whole installation process once before you begin the installation.
- Start the file "*ramms<version>_rock_user_setup_64.exe".*

Step 1: Welcome

The welcome dialog introduces you to the English setup program and will guide you through the installation process. Click *Next* to continue.

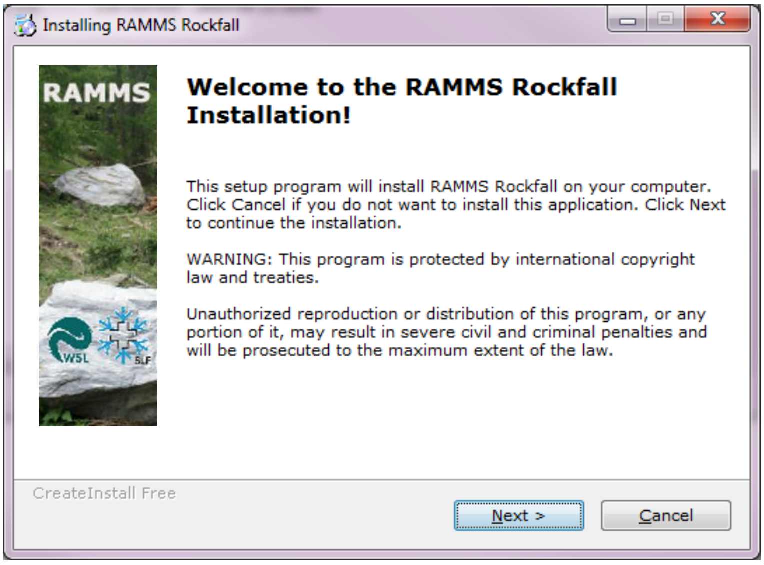


Figure 2-1: Installation - welcome dialog window.

Step 2: Readme

Short introduction to RAMMS. Click *Next* to continue.

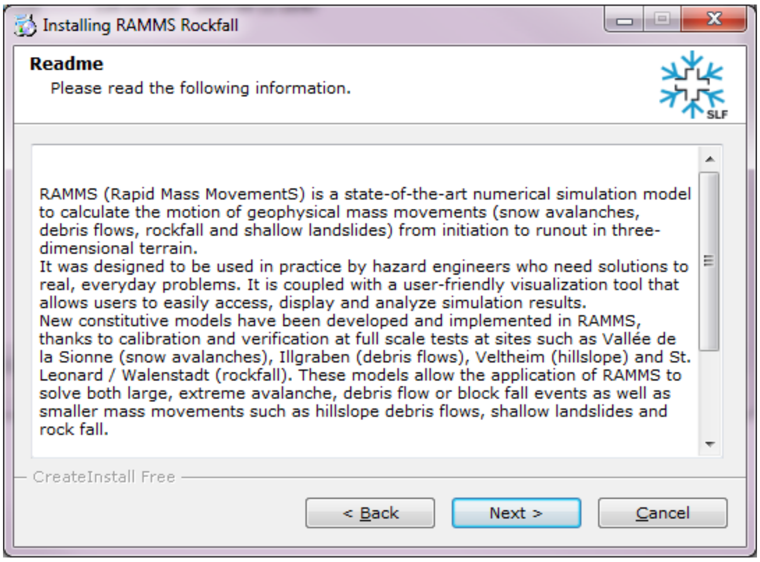


Figure 2-2: Installation - readme dialog window.

Step 3: Accepting the license agreement

Read the license agreement carefully and accept it by activating the check box in the lower left corner. If you do not accept the license agreement, you are not able to proceed with the installation. After accepting the license agreement, click *Next* to continue the installation.

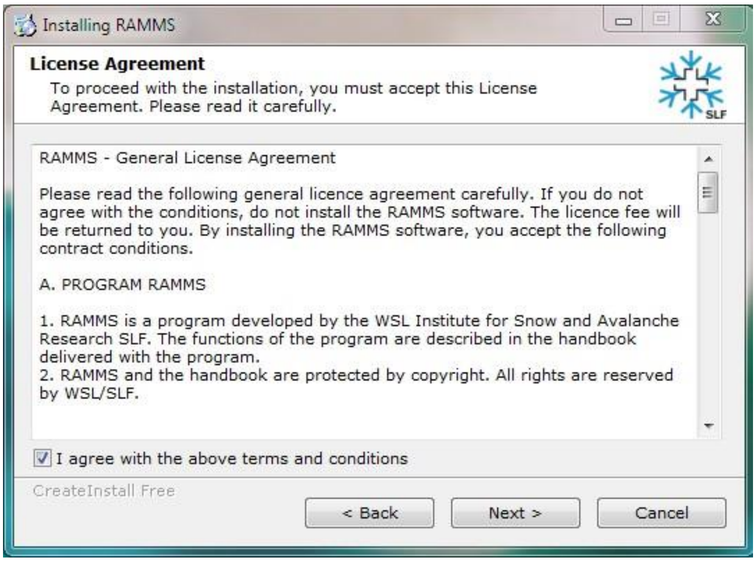


Figure 2-3: Installation - license agreement dialog window.

Step 4: Select destination directory

Choose your destination directory. This dialog shows the amount of space available on your hard disk and required for the installation. Click *Next* to start the installation process.

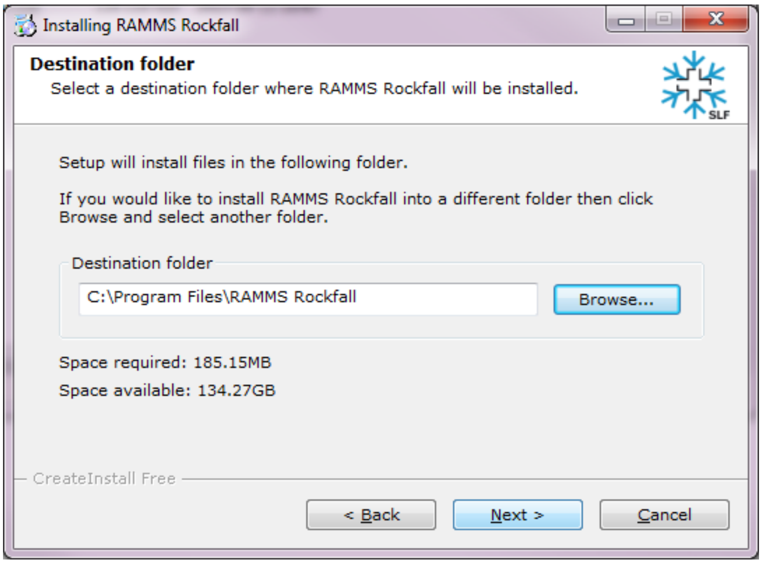


Figure 2-4: Installation - destination directory dialog window.

Step 5: Installing the files

RAMMS is copying the files to the destination location. The window shows the installation progress.

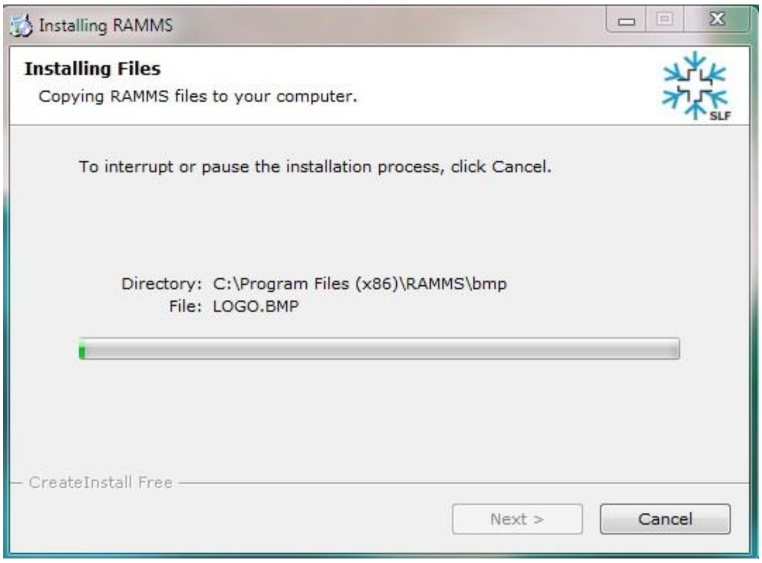


Figure 2-5: Installation - installing files dialog window.

Step 6: Finished installing the files

RAMMS finished copying the files. Click *Next* to finish the installation process.

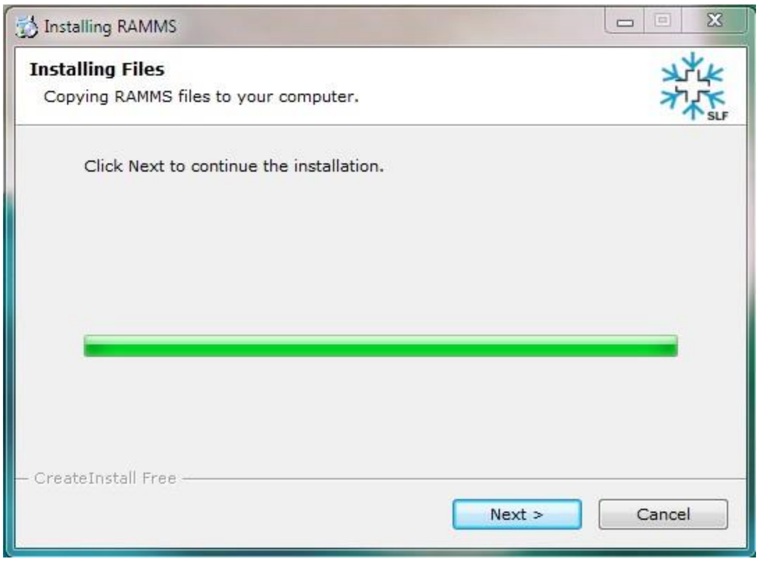


Figure 2-6 : Installation - finished installing files dialog window.

Step 7: RAMMS installation finished!

RAMMS successfully finished the installation. Click *Finish*.

Figure 2-7: Installation - finished installation dialog window.

Step 8: Welcome to IDL Visual Studio Merge Modules

To ensure that all important system libraries are installed on your target machine follow the instructions below:

The welcome dialog introduces you to the English setup program and will guide you through the installation process of the IDL Visual Studio Merge Modules. Click *Next* to continue.

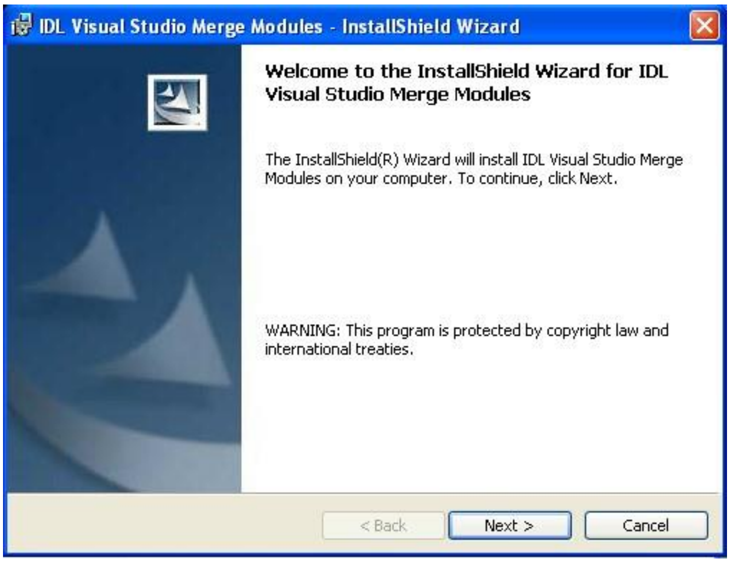


Figure 2-8: IDL Visual Studio Merge Modules - welcome dialog window.

Step 9: Ready to install the program

Click *Next* to continue.

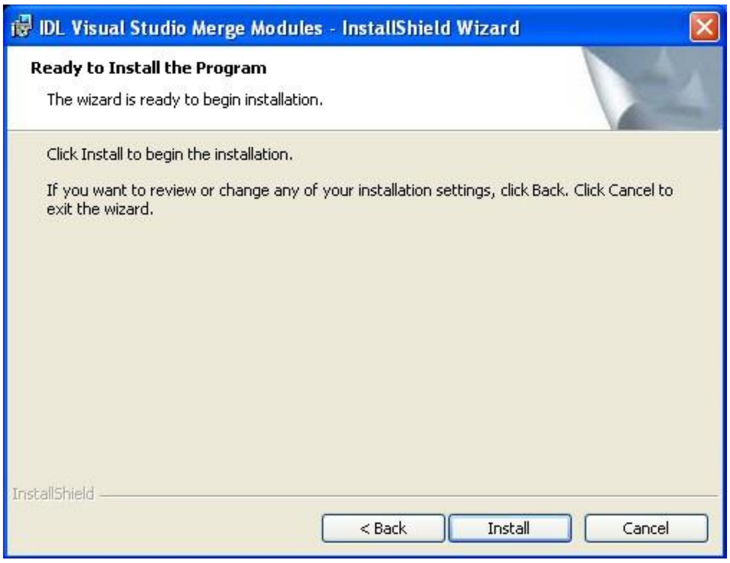


Figure 2-9: IDL Visual Studio Merge Modules - ready to install the program.

Step 10: Installing IDL Visual Studio Merge Modules

The wizard is installing the files. Please wait until it is finished.

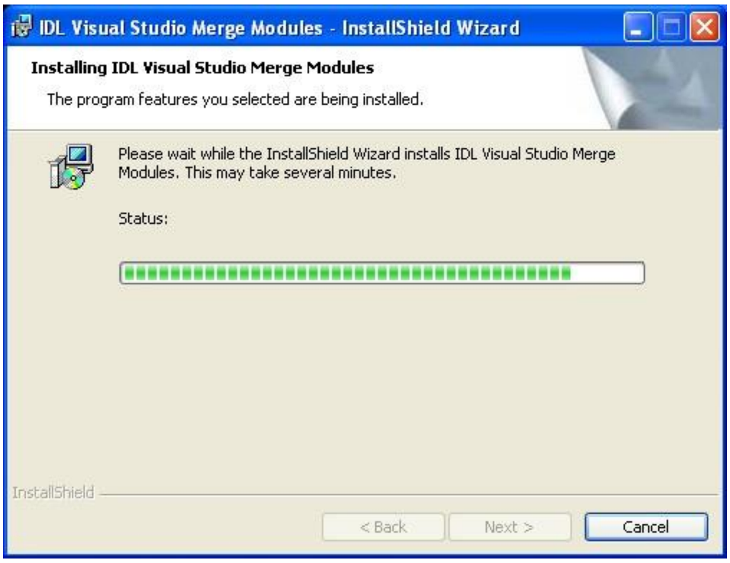


Figure 2-10: IDL Visual Studio Merge Modules - installing...

Step 11: InstallShield Wizard Completed

The wizard completed the installation. Click *Finish*.

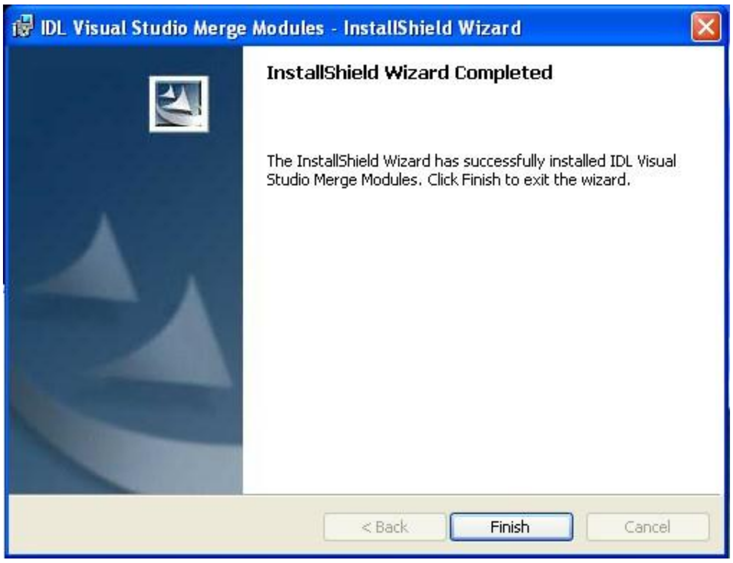


Figure 2-11: Installation - destination directory dialog window.

After having successfully installed RAMMS and the necessary files on your personal computer, you will notice the RAMMS icon on your desktop (for all users):

Figure 2-12: RAMMS icon.

Additionally, a new application folder is created in *Start* → *Programs* (for all users):

- *RAMMS Rockfall* → *Run RAMMS Rockfall*
- *RAMMS Rockfall* → *Uninstall RAMMS Rockfall*

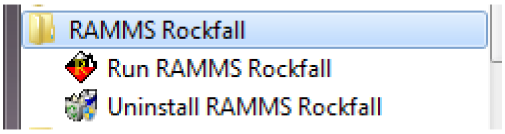


Figure 2-13: RAMMS program group

2.3 Licensing

Access to RAMMS is controlled by a personal use license. Personal use licenses are time limited licenses tied to a single personal computer. This method of licensing requires a machine's unique host ID to be incorporated into a license request file. After the license request file is sent to RAMMS AG, you will receive a license key. Entering the license key on a personal computer enables full RAMMS functionality for the specific personal computer. For more information, please visit https://www.ramms.ch Alternatively, the license can also be installed on a Windows Server and accessed by different users (only one at a time) by RDC (Remote Desktop Connection). This only works for one license per module.

Double-click the RAMMS icon or use ***Start*** → ***Programs*** → ***RAMMS Rockfall*** → ***Run RAMMS Rockfall*** to start RAMMS for the first time. Whenever you start RAMMS, the splash screen below will pop up:

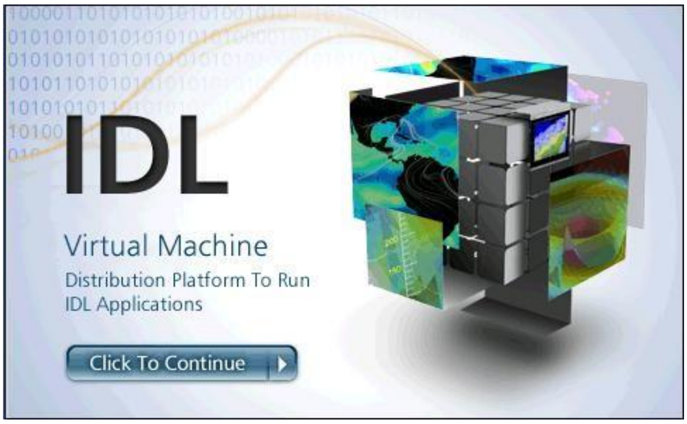


Figure 2-14: RAMMS start window.

Click on the image. It will disappear and RAMMS will start up. The following dialog window appears:

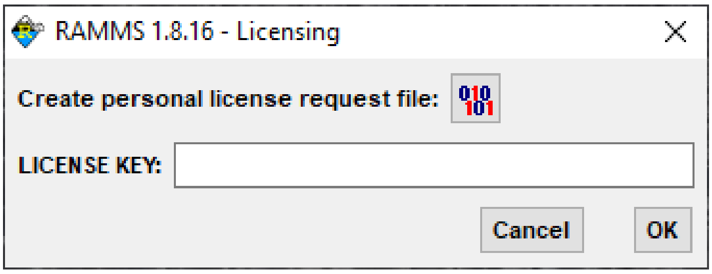


Figure 2-15: RAMMS licensing window

2.3.1 Personal license request file

Click the button  to create your personal license request file. In Figure 2-16 enter your full name and the name of your company.

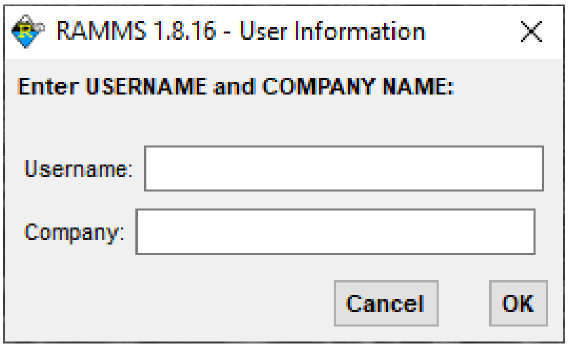


Figure 2-16: Enter user name and company name.

In the next dialog window, choose the destination directory of your personal license request file and save it to your target machine. Your personal license request file should look like Figure 2-17.

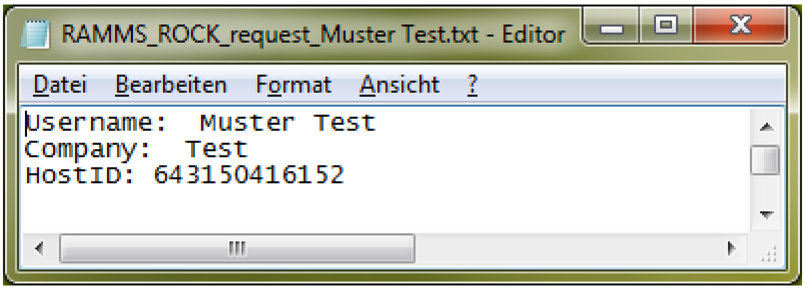


Figure 2-17: Personal license request file RAMMS_ROCK_request_Muster.txt

2.3.2 Getting the personal license key

You find order forms on the RAMMS website (*Full License, Demo License or Student License*) at [https://www.ramms.ch/order-a-students-license/.](https://www.ramms.ch/order-a-students-license/) Fill in all your personal information, choose the license period, license type and number of licenses you wish to order, attach your personal license request file(s), accept the license agreement, and click Submit *Order*.

An order confirmation email is sent to your email address. We then process your order and send you an invoice. You will find all the banc details on this invoice for a banc transfer. Please let us know if you wish to pay by credit card. As soon as we received your payment, we will send you your personal license key. Your personal license key is named like *ROCK_Muster_Test_RAMMS.txt*. Open the file in a text editor. It should look like Figure 2-18.

Figure 2-18: Personal license key

Now, restart RAMMS (as explained before). The IDL splash screen appears (Figure 2-14) and then the dialog window of Figure 2-15 shows up (RAMMS - Licensing). Copy the license key (in this example: *ROCKFALL ebei-flhl-ilkq-behe-1i5m*) and paste it in the field *LICENCE KEY* (see Figure 2-15). Notice that there is the prefix ROCKFALL. This prefix is part of the license key and must be inserted as well! If RAMMS accepts your installation key, you successfully finished the installation.

2.4 Update

When you start RAMMS it will automatically check for updates on the internet. This can lead to an error message, if your firewall blocks the executable idlrt.exe (this file starts the IDL-Virtual Machine you need to run RAMMS). Please unblock this file for your firewall. You can also disable the AutoWebUpdate-function by unchecking ***Help*** → ***Advanced...*** → ***AutoWebUpdate***. In the same way you can enable the AutoWebUpdate-function by checking ***Help*** → ***Advanced...*** → ***AutoWebUpdate***.

3 Theory

3.1 Overview

The RAMMS::ROCKFALL model utilizes a ***hard- contact, rigid-body*** approach to model rockfall trajectories in general three-dimensional terrain (Leine et al., 2013). The program is designed to be used by hazard engineers to predict rockfall velocity and runout for hazard mapping and planning of rockfall mitigation measures. The calculation engine and user interface were developed as part of a joint research project between the *WSL Institute for Snow and Avalanche SLF* and the *Institute of Mechanics, Swiss Federal Institute of Technology* (ETHZ) between the years 2010-2013. The rockfall model is the third RAMMS module, following the RAMMS::AVALANCHE and RAMMS::DEBRISFLOW modules and offers many of the same user-friendly features. The RAMMS::ROCKFALL model was officially released in April, 2015 after a period of calibration and application testing.

To date most rockfall models utilize simple rebound mechanics to describe the complex interaction between the rock and the ground (Bourrier et al. 2012; Dorren 2003; Dorren and Seijmonsbergen 2003; Schweizer 2015, Volkwein et al. 2011). Rock geometries consisted of simplified shapes, mostly spheres or ellipsoids. The rock-ground interaction was parameterized using apparent restitution coefficients to model the rock jumping. To account for the wide variation of possible jump distances and heights (even in homogenous terrain, see Glover 2015), random, stochastic methods were used to define the bandwidth of possible restitution coefficients. Rockfall modeling was therefore both quasi-deterministic and quasi-stochastic.

In RAMMS::ROCKFALL, the rock-ground interaction is parameterized by frictional operators that act at the rock surface. Compared to rebound models (that employ apparent restitution coefficients to model entire ground-rock interaction), the hard-contact, rigid-body approach applies contact forces to the rock's edges and corner points. The primary advantage of using hard-contact approach is that the role of rock shape is accounted for in the ground-rock interaction. This facilitates a natural modeling of the four primary modes of rock motion: ***sliding***, ***rolling***, ***skipping*** and ***jumping*** – without the use of random, stochastic methods to define the rebound parameters. All four modes of rock propagation are modeled in RAMMS::ROCKFALL. Long and widespread rock runout is generally associated with the jumping mode; however, rock stopping requires a transition from jumping to a rolling/sliding mode. Modeling ***all*** four modes is essential for a realistic, self-consistent and risk-based rockfall hazard analysis. The natural variation of jumps is defined automatically by the rock shape and orientation at impact. The statistical spread of rockfall runout and dispersion is generated only by changing the initial conditions. Ground parameters are not random: they are deterministic in the sense that one material type is assigned to describe hardness and the general tendency of the terrain to react to a rock impact. In RAMMS the clear separation between ***stochastic initial conditions*** and ***deterministic boundary conditions*** simplifies and enhances the construction of engineering-based hazard scenarios and the interpretation of model results. At present, the RAMMS::ROCKFALL model contains 13 default soil categories: ***river/swamp, surface soil, subsoil, forest soil, talus vegetated, talus fine, talus coarse, talus blocs, boulder field, mountain road, asphalt, bedrock, and snow.***

Applying RAMMS::ROCKFALL to a rockfall problem necessitates that rocks of different shapes and sizes can be easily specified. In RAMMS::ROCKFALL the rock-body is modelled as a ***convex hull***

polyhedron. The shape of a rock-body is user defined by providing a point cloud file, defining the surface geometry of the rock. Shapes can be simple geometric forms, such as ***equant***, ***platy*** or ***columnar***. A unique feature of RAMMS::ROCKFALL is that ***real rock geometries*** obtained from laser scans during field investigations can be used in a modeling application. Over time, the user can build-up and manage a rockfall library containing rock shapes representative of different geologic settings. At present, the rocks are considered indestructible; that is, they do not fragment or change form during the analysis.

Over and above weathering processes, the geometric relationships of rock-mass discontinuities (***joints***, ***fractures***, ***contacts***, ***bedding***, ***asperities,*** and ***schistosity***) govern block shape, size and release mechanism (Jaboyedoff, 2011). With RAMMS::ROCKFALL, preconditioning the shape and size and number of possible release orientations of detachable rocks is an essential part of the analysis. The observation that different basic geological settings produce characteristic rock shapes has been well documented by Fityus et al. 2013, among others. Some commonly encountered rock shapes and the associated geological setting are given below (Figure 3-1).

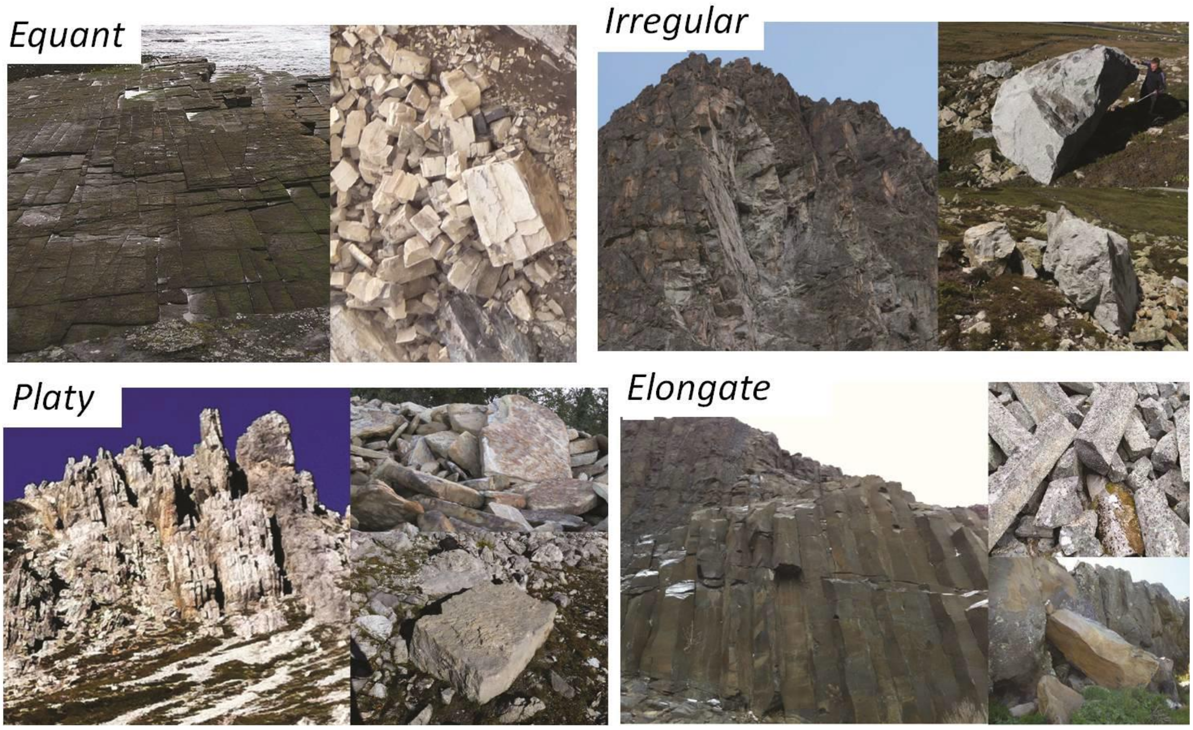


Figure 3-1: Photographs of rock masses and their aggregate forms. Top left: An example of equant cubic rock forms generated in a sequence of sandstones exposed to an extensional deformation regime, the primary joint sets are near equally spaced and orthogonal to one another. Topright: The complex joint of this granodioritic rock mass results in highly irregular and angular rock block forms. Bottom left: The uplifted and folded limestone sequence is well bedded producing distinguished slabs which detach as pronounced platy rock forms. Bottom right: Distinguished columnar jointed basalt sequence produces the characteristic elongate rock forms (Glover 2015).

The specification of general rock geometries will be discussed in the next section 3.2.

Another feature of the RAMMS::ROCKFALL model is the inclusion of rock rotations in both the airborne phase and during the interaction with the ground. The RAMMS::ROCKFALL model includes ***gyroscopic***

forces induced by rock rotations. These forces are necessary to model wheel-like rock skipping and jumping modes that are often responsible for extreme runout. To model ground interaction considering rocks with arbitrary geometry and rotational speed requires methods to accurately track the rock orientation relative to the ground. RAMMS::ROCKFALL employs ***quaternion algebra*** for this purpose. This method tracks rotation sequences even when non-linear contact forces change the translational and rotational direction of the rock. Modeling the rock-ground contacts in this way permits the entire mechanics of an impact to be simulated deterministically. The moment arms and torques responsible for how different rock-shapes convert translational movement into angular momentum and influence rebound heights are computed, and therefore allows an accurate modeling of rolling, skipping, sliding, and jumping.

The three-dimensional motion equations including rock rotations and gyroscopic forces will be presented in section 3.3.

Complex mountain terrain is modelled using a high-resolution digital elevation model (DEM). The specification of the DEM will be discussed in more detail in section 3.10.

3.2 Modeling Rock Shape

Rock bodies are introduced into the simulation domain coordinate frame with origin (O) as a cloud of points based in a coordinate system of their own with origin (K). The coordinate frame (K) serves to map the rotations of the rock-body. Points are given in x, y, z format as *.pts files, and can be artificially generated or gathered from a laser scan of rock deposits (Figure 3-1 and Figure 3-2). A convex hull of the rock-body's point cloud is created, in doing so an entirely convex body is created; concavities are closed over in the process. The next step is to calculate the center-of-mass of the body, for which the density is assumed homogeneous. Finally, the inertial tensor of the body is calculated finding the three principal moments of inertia; the origin is the rock's gravity center (S). The translations of the rock-body in the simulation domain are mapped using coordinate frame S in relation to O (Figure 3-3). The rock's mass m is given from its volume calculated from the convex hull of the point cloud and a density ρ which is user defined (typically 2700 kg m^{-3}). The rock has three translational (linear momentum) and three rotational degrees of freedom (spin) to describe the rocks mass center position $q^T = (X, Y, Z)$ at any time t in the terrain coordinate frame O. Rotational motions capture the orientation of the rock's external geometry in space. At time $t = 0$ the rock is released from position $q_0^T = (X_0, Y_0, Z_0)$, which, of course, must be located some distance above the terrain, $Z_0 > Z_m$, and thus the release height $h_0$is $Z_0 - Z_m$.

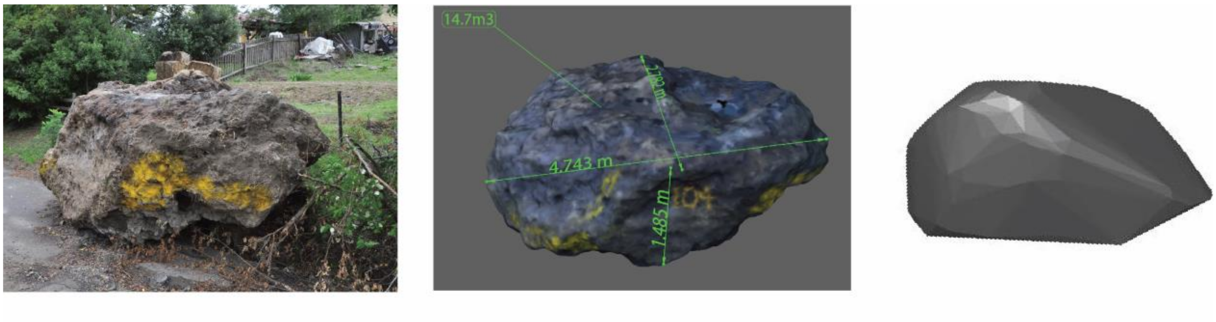


Figure 3-2: Laser scans of real rocks are captured in the field. The point cloud representing the rocks geometry are then used by the rockfall model to create a convex-hull polyhedron representative of the rock-body.

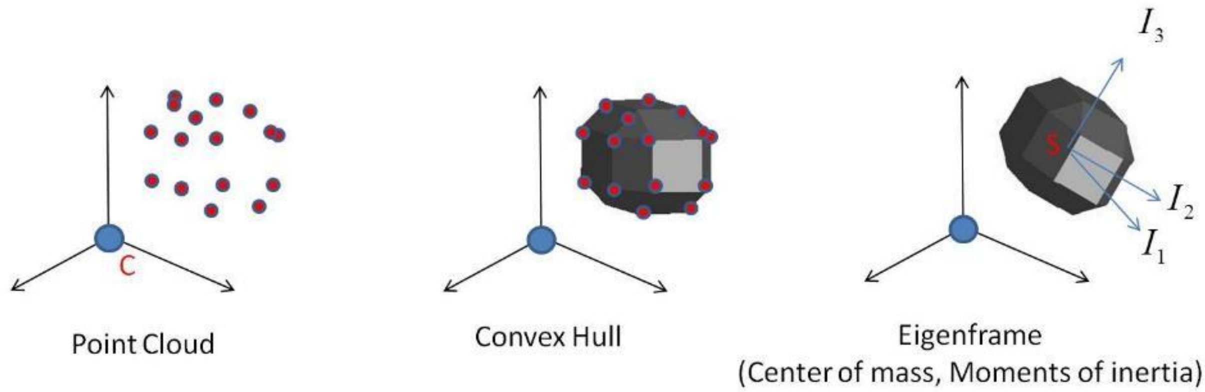


Figure 3-3: Rock is generated from a point cloud and converted into a rigid-body polyhedral.

3.3 Equation of Motion and Free Flight

The general equation of motion for a rock is

$$\boldsymbol{M}\dot{u} - \boldsymbol{h}(q,u) = \boldsymbol{W}(q)\boldsymbol{\lambda} \qquad (3.1)$$

where **M** is the constant and diagonal mass matrix (containing the mass and three moments of inertia **I**) and $\dot{u}$ is the second derivative of the generalized coordinate vector q (position r_{OS}^{I} and orientation p_{IK}):

$$\dot{u} = \frac{\partial^2}{\partial t^2}\begin{pmatrix} r_{OS}^{I} \\ p_{IK} \end{pmatrix} \qquad (3.2)$$

The force term $\boldsymbol{h}(q,u)$ contains all gyroscopic terms and finite external forces, such as viscous drag forces, gyroscopic forces, and gravity. The right-hand side of equation (3.1) consists of the so-called matrix of generalized force directions **W**(q) and a vector $\boldsymbol{\lambda}$ containing all contact forces. Both terms are additions to the equation of motion to account for the contributions of unilateral constraint forces and friction forces during hard contact.

Free Flight Motion with Gravity and Gyroscopic Forces

In free flight, the contact forces $\boldsymbol{\lambda}$ are zero. The governing equation of motion is therefore reduced to (see Leine et al., 2013)

$$\boldsymbol{M}\dot{u} - \boldsymbol{h}(q,u) = 0 \qquad (3.3)$$

The rock-body's motion is governed by several forces which determine its trajectory. The gravitational force (F_g) acts globally along with gyroscopic forces G which can cause rocks of irregular shape to become upright and rotate about a rolling axis. All force terms **h** are a function of the rock's position q and velocity u forming the force vector **h**:

$$\boldsymbol{h}(q,u) = \begin{bmatrix} F_g \\ G \end{bmatrix} \qquad (3.4)$$

3.4 Terrain Interaction Phases

To simulate rock-ground interaction, the terrain is divided into a plastic, deformable scarring layer and a non-deformable, hard contact "slippage" plane. Both the scarring layer and the rebound plane are located below the digital elevation model. The interaction between rock and terrain can be summarized in four characteristic phases.

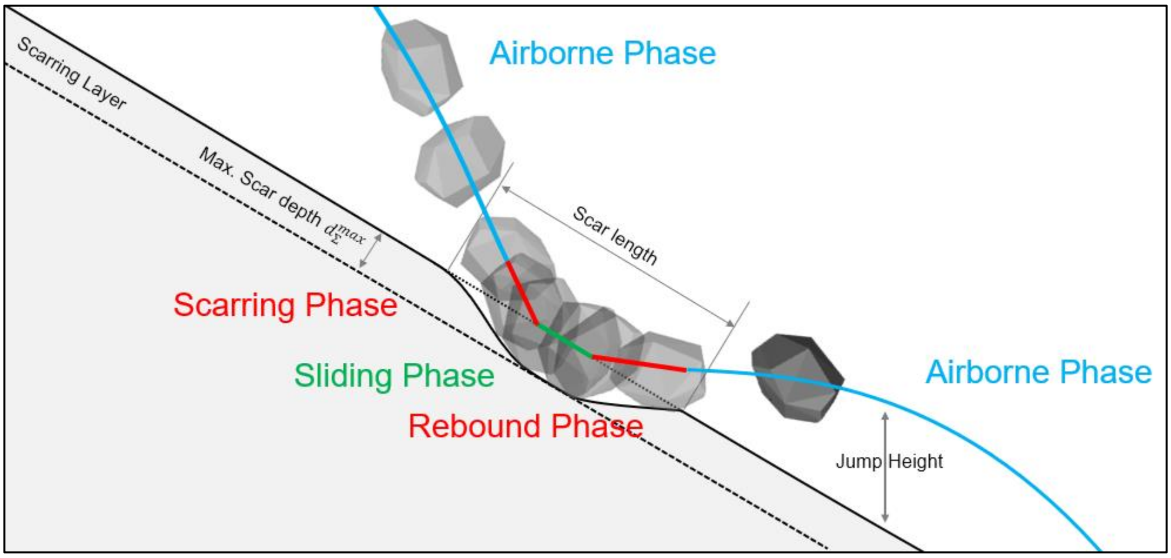


Figure 3-4: The four characteristic phases during the interaction between a rock and compactible soil.

- **Airborne Phase:** The rock is not in contact with the terrain surface. Only gravity and gyroscopic forces are acting during this free flight motion (see chapter 3.3).
- **Scarring Phase:** The rock penetrates the soil. Additional viscous drag forces are acting on the rock due to soil compaction. The soil density continuously increases. The physics during this phase is described in chapter 3.5.
- **Sliding Phase:** The soil cannot be compacted any further by the rock. The compacted soil acts as an infinitely hard frictional plane. We model this phase with a ***hard- contact*** approach, which

is described in chapter 3.6. The rock then slides on this plane until the friction and eccentricity is so high that the rock stumbles forward and loses contact with the plane.

- **Rebound Phase:** The rock has already changed its moving direction but is still below the terrain surface. Viscous drag forces act on the rock, as soil is pushed in front of it until every vertex of the rock is above the terrain surface, leaving behind a permanent scar.

3.5 Energy dissipation due to rock-ground scarring

3.5.1 Drag Forces

As soon as one vertex of the rock intersects the terrain, the rock starts penetrating the ground. This penetration leads to a compaction of the soil. Due to the generally very fast and high energy process, soil compaction is assumed to be purely plastic. The fine particles of the soil act similarly to a fluid and exert a drag force against the rock motion [De Blasio et al., 2018]. The soil resistance force on the rock is modelled with a velocity squared resistance law parameterized by the scarring coefficient C_d, which is equivalent in form to drag defined in fluid dynamics:

$$F_T(t) = \frac{1}{2}\, C_d\, \rho\, A(t)\, \left|\left|v_T(t)\right|\right|^2 \tag{3.5}$$

Where A(t) is the cross-sectional area of the penetration scar at time t, ρ is the soil density and $v_T(t)$ is the translational velocity of the rock at time t. This viscous drag force F_T acts on the center of mass of the rock in opposite direction to the velocity vector, see Figure below.

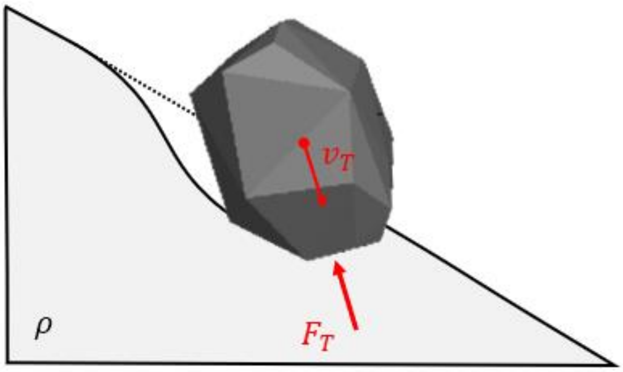


Figure 3-5: Viscous drag force F_T acting against translational velocity vector v_T

This force generally increases during an impact, because the cross-sectional area of the penetration scar A(t) increases as the rock goes deeper into the scar.

3.5.2 Drag Torques

Due to partial immersion (eccentricity) and rotational velocity of the rock into the soil, there is an additional rotational drag torque acting. This torque consists of two parts:

Translational torque occurs due to the translational velocity of the rock combined with an eccentricity due to partial immersion. The corresponding forces F_T and torques τ_T referring to Figure 3-6a are:

$$F_T(t) = \frac{1}{2}\, C_d\, \rho\, A_T(t)\, \left||V_T(t)|\right|^2 \qquad (3.6)$$

$$\tau_T = -F_T \times d \qquad (3.7)$$

The translational drag force always acts on the center of mass of the submerged rock and in opposite direction of the velocity vector. The cross-sectional area A_T is always normal to the velocity vector. Depending on the impact configuration and rotational velocity of the rock, the translational torque may act in direction of the current rotational velocity vector or against it.

Rotational torque occurs due to the rotational velocity of the rock during scarring. Due to its spin, the partially submerged rock feels a resistance force perpendicular to the plane spanned by its rotational velocity vector and the connecting vector between its center of mass and the center of mass of its submerged part. The corresponding forces F_Ω and torques τ_Ω referring to Figure 3-6b are:

$$F_\Omega(t) = \frac{1}{2}\, C_d\, \rho\, A_\Omega(t)\, \left||V_\Omega(t)|\right|^2 \qquad (3.8)$$

$$\tau_\Omega = -F_\Omega \times d \qquad (3.9)$$

The rotational drag torque always acts on the center of mass of the rock and against the rotational velocity vector.

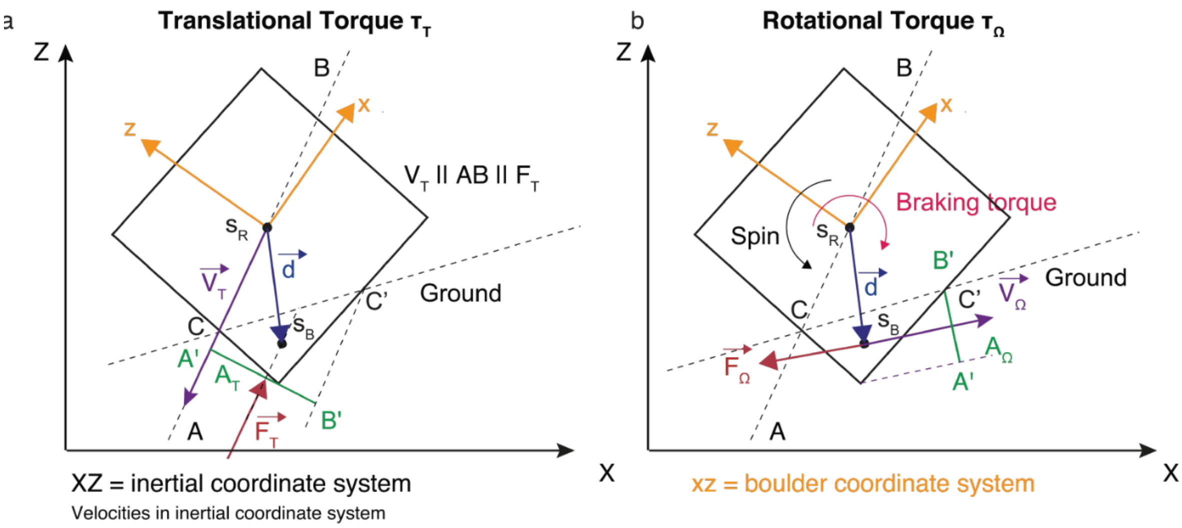


Figure 3-6: Two types of drag torques acting on the rock during scarring. $s_R$is the center of mass of the rock. s_B is the center of mass of the submerged part of the rock.

3.5.3 Maximum penetration depth

As the rock enters the terrain, the soil density increases due to soil compaction. Due to this, it evidently also approaches the point where the rock cannot compact the soil any further. This point marks the depth of the scarring layer. From this point on, the soil is treated as an infinitely hard, non-deformable plane (see chapter 3.6). The rock has reached the maximum scar depth. This scar depth is a function of the compressibility of the soil, the mass of the rock and its velocity. To this end, Gerber (2019) proposed a rock penetration equation obtained through fitting the experimental data for freely, vertically dropped rocks of various masses, soil types and initial heights, and considering Hertz theory for the contact forces calculation. This formula reads as follows:

$$d_{max} = 0.16\, M_r^{0.25}\, M_E^{-0.4}\, \left||V_\perp|\right|^{0.8} \tag{3.10}$$

Where d_{max} is the maximum scar depth [m], M_r is the mass of the rock [kg], M_E is the mechanical strength of the soil [kPa] and $V_\perp$ is the terrain perpendicular component of rock velocity [m/s] right before it touches the terrain.

3.6 Hard Contact and Slippage

3.6.1 Contact forces

On contact detection between the rock-body and the rebound plane, contact forces λ and frictional contact forces (F_c) act about the point of contact. These forces can be considered as external forces that change the direction of the falling rock.

The contact of the rigid rock-body is detected by continually measuring the vertical gap length g_N between the rock-body's corner points (P) and the rebound plane's projections (Q) (Figure 3-7). The gap length is defined as

$$g_N(X, Y, Z) = Z - Z_m(X_{m.}, Y_m) \tag{3.11}$$

Then, when $g_N > 0$, there is no contact and the contact forces λ acting at the contact point P are computed. (The contact forces are denoted using the Greek letter lambda because the contact forces are Lagrangian multipliers that enforce the non-penetration constraint). Minimal penetration with the terrain is permitted to allow the assessment of the contact condition (Eq. 3.3). This is a non-physical penetration and purely for numerical purposes.

Contact forces are modeled as hard unilateral constraints with Coulomb friction using non- smooth contact dynamics approaches (see Acary and Brogliato, 2008, Glocker,2001 and Moreau, 1988). For the case of contact, the governing equations of motion now become

$$\boldsymbol{M}\dot{u} - \boldsymbol{h}(q, u) = \lambda W(q) \tag{3.12}$$

where the direction of the contact forces is given by $W(q)$. There can be several active contact forces depending on the rock-body's configuration at the point of contact. Ultimately it is the combination of these forces λ (and force directions $W(q)$) that allows the complex rotations and trajectory deviations that are inherent to rockfall to be simulated.

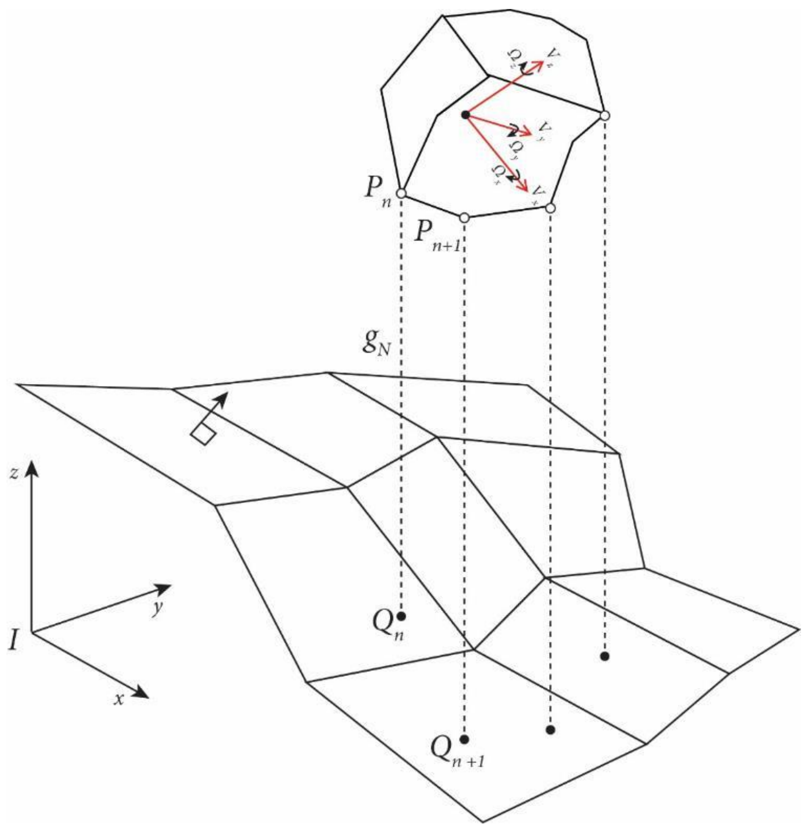


Figure 3-7: Contact detection. Definition of gap length, g_N.

The advantage of this *hard-contact* rigid-body approach is that the contact forces are applied directly at these contact points, respecting the configuration (orientation and kinetics) of the impact. This is achieved by considering the contact pair (Q, P) within the contact frame C = (n,t_1,t_2) which is attached to the terrain surface at contact point Q (Figure 3-8).

3.6.2 Friction forces

The contact frame C has a normal contact force component λ_N and two tangential components λ_{T1}, λ_{T2}. The contact force λ_N guarantees the unilaterality of the contact, i.e., the non-penetration constraint. The tangential force components are due to Coulomb friction and are governed by the contact laws.

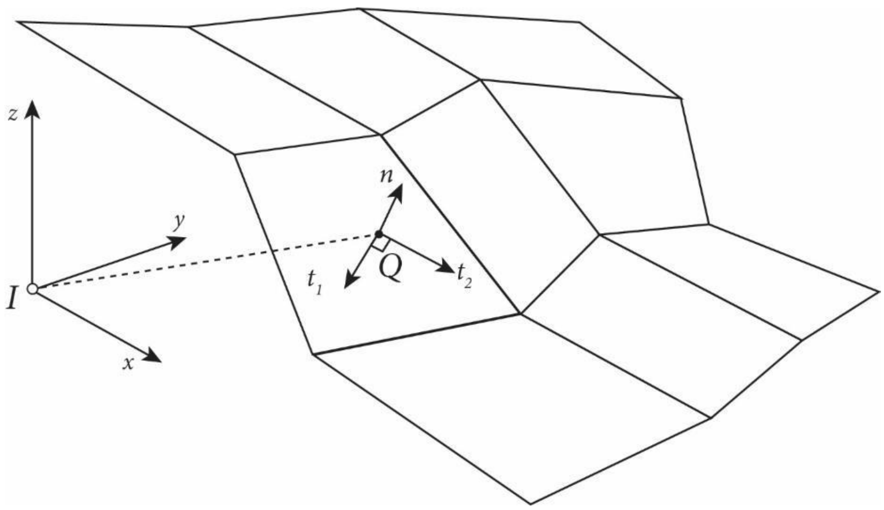


Figure 3-8: Contact frame C at point Q detected with the gap function g_N.

The normal force component λ_N is resolved with a contact cone differential inclusion, in which the transient normal force vector over the finite contact period can be computed. Over the contact period this is a set-valued normal force considering all periods of contact identified with the gap function g_N.

The tangential force component λ_T is assumed to obey spatial Coulomb's friction law (see Figure 3-9). Stiction of the contact $\gamma_T = 0$ occurs as long as the magnitude of the tangential force $||k\lambda_T||$ is less than $\mu\lambda_N$, in which λ_N is the applied normal force and μ the friction coefficient. The direction is also resolved with a normal cone inclusion projecting a friction disc on to the surface (Figure 3-9). The formulation covers both sticking and sliding cases.

3.6.3 Impulsive forces (Rebound)

Impulsive contact forces occur whenever the gap function detects contact with negative velocity $\gamma_N^- < 0$, where the point would theoretically move through the rebound plane if not treated with the impulsive contact force. This requires a velocity jump such that the post impact normal velocity is non-negative $\gamma_N^+ < 0$. This impact law is based on Newtonian impact law in which the relative normal velocities of the contact pair before and after impact are governed by εN the normal restitution coefficient. $\varepsilon N = 1$ corresponds to complete restitution of normal velocity while a smaller εN dissipates energy. This value is set to zero. Newton's action-reaction law is always fulfilled.

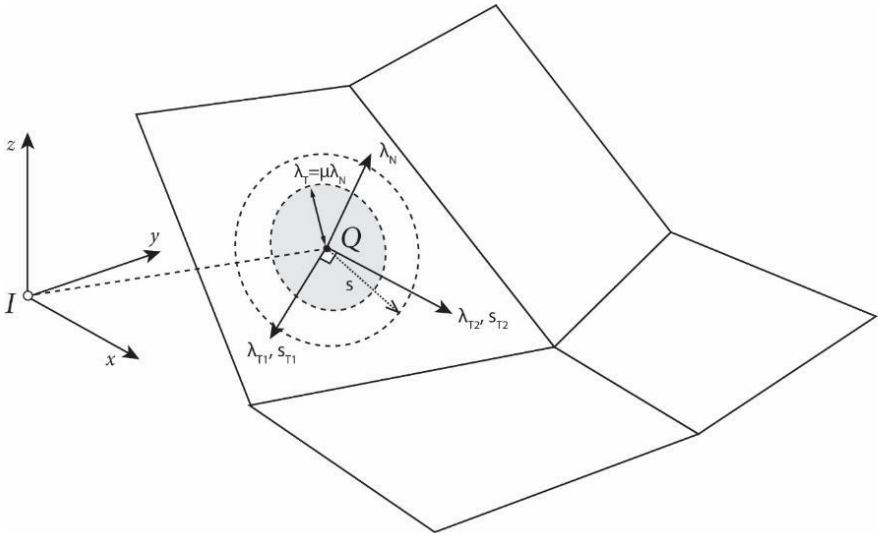


Figure 3-9: Friction forces at the contact point.

$$\gamma_N^+ + \varepsilon\gamma_N^- = 0 \qquad (3.13)$$

Impulsive normal forces can also induce impulsive tangential forces. While this is mainly seen in the elastic impacts of superballs (Cross, 1999), and therefore in the rockfall model ε_T is set at $\varepsilon_T = 0$ since these effects are absent.

To determine the resultant force direction acting on the rock-body the configuration of the impact must be computed. This requires finding the relative velocity between the contact points *P* and the terrain *Q*. Importantly, the velocity of contact point *P* is composed of the translational velocity with respect to the body's center of mass v_S and its angular velocity ${}_K\Omega$ in the fixed body frame (*K*); for which *P* also has a fixed position vector relative to the center of mass *S*. That is, the contact algorithm in the rigid-body approach considers the rotational speed of the rock at contact. Because the forces are then applied at points away from the center of mass, and with a direction respecting the impact configuration to a body with three degrees of translational and rotational freedom, torques and moment, arms can act generating rotations and rebounds that represent the true mechanics of an impact.

3.6.4 Contact Friction

Two physically different forces oppose the motion of a falling rock: sliding friction and drag. Sliding friction acts at points of the rock's surface that are in contact with the rebound plane; it is Coulomb-type friction associated with the distance the rock slides on the ground. When the rock is no longer in contact, this friction no longer acts. However, because this friction acts on a point on the rock's surface, it will generate torques that initiates rotational movements. The parameterization of the friction force is of great importance because it controls when the rock slides, rolls or jumps. Drag forces in the RAMMS::ROCKFALL model account for the viscoplastic drag due to terrain deformation (scarring) during ground contact. These forces are described in section 3.5. They act not only in the scarring phase (when the rock moves in the ground), but also in the sliding phase, when the underlying ground has reached its maximum density and acts as an infinitely hard rebound plane. This is because even though the rock does not penetrate further into the ground, it still pushes the soil in front of it and thus experiences a resistance force.

3.6.5 Coulomb Friction and Slippage

The mechanical contact law considers hard contacts between the rigid-body and the rebound plane.

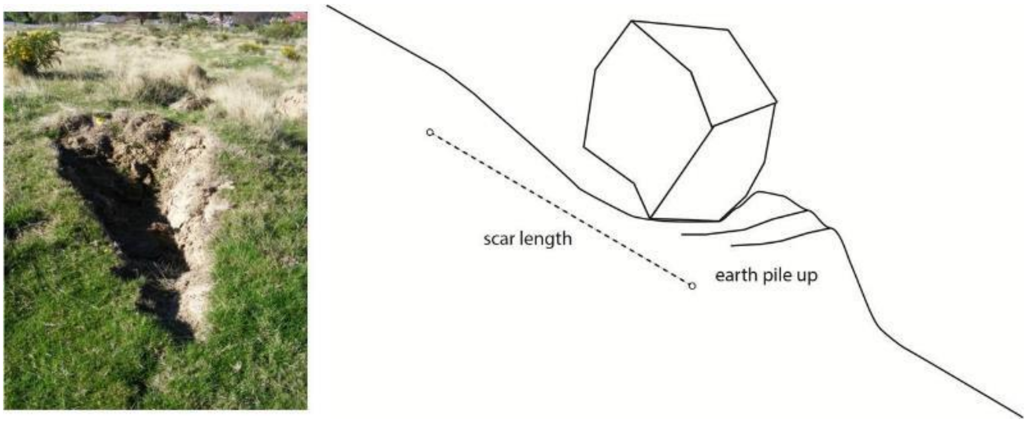


Figure 3-10: Rock impact scar on soft soil; the scar morphology is tapered widening towards the accumulation of earth at the scar end, where an earth ramp structure is formed. This is modeled as a climbing friction from the beginning of the scar s = 0 at first contact which tends towards high friction at the end of the scar.

The hard contact friction uses a slip (s) dependent friction that acts during sliding and accounts for the increase in friction due to material accumulation behind the rock-body as it slides on the rebound plane (Figure 3-10 and Figure 3-11). The slip dependent friction is an extension of the Coulomb friction model in which the friction value μ is made dependent on the slip distance (s) travelled by the center of mass μ(s) (Figure 3-11).

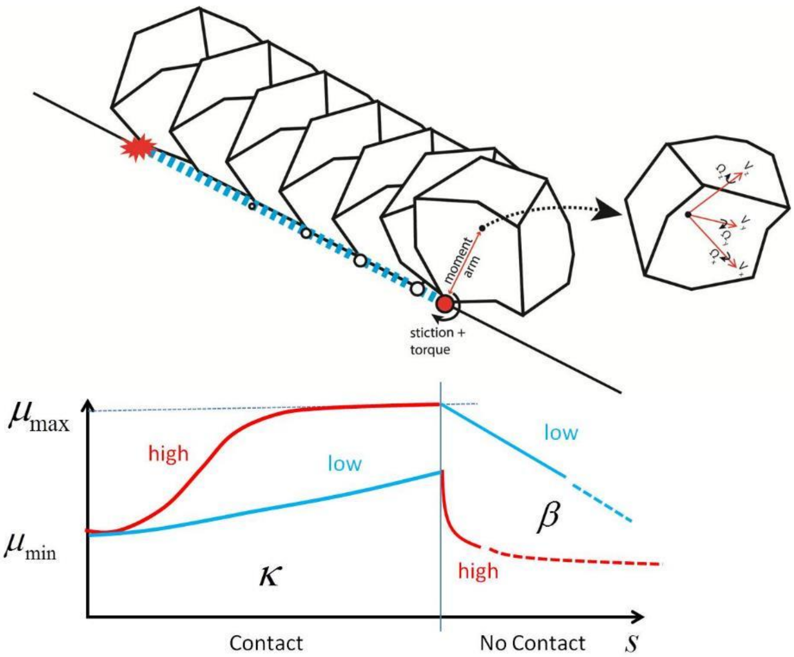


Figure 3-11: Sliding friction on the rebound plane in RAMMS is governed by a slip-dependent material law. At rock impact slip is s=0 and sliding friction is given by μ_{min}; with s>0, friction increases according to the coefficient κ. At some point s the maximum friction μ_{max} is reached. After contact, the friction exponentially decreases with coefficient β. Therefore β describes the duration of the friction as the rock is leaving the scar (ramping).

Moreover,

$$\lambda_T = \mu(s)\lambda_N \tag{3.14}$$

force λ_N enforces the non-penetrability constraint; the force λ_T acts tangentially on the terrain surface (see Figure 3-9). The dependence of the friction coefficient on the slip distance (s) is:

$$\mu(s) = \mu_{min} + \frac{2}{\pi}\,(\mu_{max} - \mu_{min})\,\tan^{-1}(\kappa\, s) \tag{3.15}$$

where μ_{min}, μ_{max} and κ are parameters of the friction model. The initial friction encountered at the contact where s = 0 is μ_{min}. Over the slip period, μ tends toward μ_{max} for large slip values, see Figure 3-11. The parameter κ controls how quickly the friction increases from μ_{min} to μ_{max}. Typically $\mu_{min} < \mu_{max}$ meaning that the friction increases the longer the rock is in contact with the rebound plane. It is entirely possible that there are brittle ground materials where the opposite behavior ($\mu_{max} > \mu_{min}$) is encountered.

The slip distance (s) is a transition state variable having a time evolution which is described by a simple differential equation:

$$\dot{s} = \begin{cases} \|v_S\| & if\, g_N \le 0 \\ -\beta s & g_N > 0 \end{cases} \tag{3.16}$$

The parameter β controls how quickly the friction is released as the rock departs the ground scar. If β is large, friction is immediately removed as the rock moves away from the rebound plane. Conversely, when β is small, sliding friction can act, even after the rock is no longer in contact with the rebound plane.

3.7 Forest/Vegetation

Forests are modeled with randomly distributed single trees. The trees are generated randomly according to the area of a given shapefile, a defined tree density (trees/ha), and a Gaussian distribution for the diameter at breast height (DBH) of the individual trees given by a mean DBH and a standard deviation. Each individual tree is modeled as a rigid truncated cone with a DBH from the Gaussian distribution and a tree height. The tree height depends on the DBH and follows the following empirical relationship of L. Dorren:

$$H_{Tree}\ [m] = DBH\ [cm]^{0.8} \tag{3.17}$$

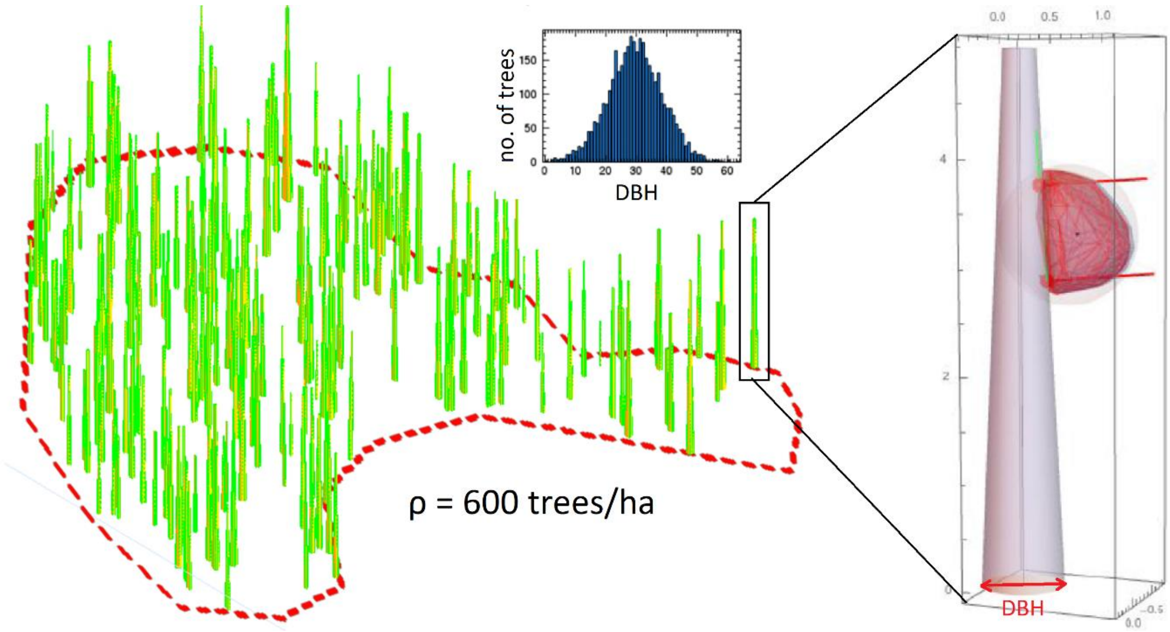


Figure 3-12: Modelled forest in RAMMS:: ROCKFALL with a tree density and a Gaussian distribution of DBH.

RAMMS::ROCKFALL provides three default forest types with the following parameters:

Table 3.1: Default forest types in RAMMS::ROCKFALL.

Forest Type	Tree Density [ha^{-1}]	BHD [cm]	
		μ	σ
Open Forest	200	25	5
Medium Forest	400	28	7
Dense Forest	600	30	9

3.7.1 Energy Dissipation, Tree Contact and Destruction

Trees are modelled as rigid cones. The interaction between tree and rock is therefore an impact between two rigid objects. The impact and rebound physics generally follow the same hard contact and friction principle introduced in chapter 3.6. Additionally, each individual tree is automatically assigned a kinetic energy threshold depending on the DBH (Dorren, 2006):

$$E_{diss,max}\ [J] = 38.7 \cdot\ DBH\ [cm]^{2.31} \quad (3.18)$$

Trees that get hit by rocks with a higher energy than the threshold will be destroyed. As trees are modelled as rigid objects, they can only follow binary states considering tree destruction. This is not problematic for kinetic energies that are a lot higher or lower than the threshold introduced in (3.18). Near the threshold, we can however expect a very complicated transition zone to tree failure, and between full deflection of a rock and punch-through failure. For this reason, a transition-factor (T_f = 2) is introduced, which is used to decide if a rock is deflected, and if a tree is destroyed. If the rock energy is between $E_{diss,max}$ and $(T_f \cdot E_{diss,\max})$, the tree is considered to be destroyed but the rock will still be deflected by the tree. If the rock energy exceeds $(T_f \cdot E_{diss,\max})$, the tree will have no influence on the rock (see table below).

Table 3.2: Interaction properties between rock and tree for different rock energies.
A transition-factor T_f = 2.0 is used.

Rock Energy	Tree destruction	Rock deflection
$E_{Rock} < E_{diss,max}$	No	Yes
$E_{diss,max} < E_{Rock} < T_f \cdot E_{diss,max}$	Yes	Yes
$E_{Rock} > T_f \cdot E_{diss,max}$	Yes	No

3.7.2 Lateral Hits and Scratches

RAMMS::ROCKFALL calculates the eccentricity of the collision between rock and tree. The collision eccentricity C_{ecc} is calculated as the sinus of the angle between the translational velocity vector of the rock and the vector connecting the center of mass of the rock and the center of mass of the tree, when looking from above. C_{ecc} ranges from 0 to 1.

Because we assume, that lateral hits are less severe than direct (frontal) hits, we use a special rule to increase the transition-factor T_f for C_{ecc} > 0.67 gradually from 2 to 10. This will prevent trees to be completely destroyed (and thus the rock still being deflected), as the rock only scratches the tree with a high kinetic energy.

3.8 Terrain/Soil Material

The **soil material** has considerable influence on the simulation result. Shapefiles are used to delimit terrain areas with specific soil materials. 13 predefined soil categories are listed in Table 3.3. These are:

- River / Swamp
- Surface Soil (meadow/grassland)
- Subsoil (well vegetated moraine/scree)
- Alpine Spruce/Beech Forest
- Talus Vegetated
- Talus Fine (Q_{95} grain size ≤ 5cm, median grain ≤ 2cm)
- Talus Coarse (Q_{95}grain size ≤ 20 cm, median grain ≤ 10 cm)
- Talus Blocs (Q95 grain size ≤ 50 cm, median grain ≤ 30 cm)
- Boulder Field
- Mountain Road
- Asphalt
- Bedrock
- Snow

Selection of the appropriate terrain material model is the primary task of the hazard engineer when using RAMMS::ROCKFALL. If there is uncertainty about the specific terrain material, we recommend the user to compare the results of different terrain scenarios. Please consider the examples in Table 3.3 below as a preliminary suggestion.

Table 3.3: Terrain Categories in RAMMS::ROCKFALL

Category	Picture	Description	Example
River/Swamp		River or very wet ground. Cannot cross without deep sink-in. No high vegetation.	Moor, turf, gley, River
Surface Soil		Rocks penetrate meadow surface leaving impact scars. Soil is deep, few rock fragments. Rank vegetation. The proposed parameters apply only to regions where surface soil is deep (and followed by subsoil). Rock scars exclusively in soil.	Meadow/ grassland
Subsoil		Penetration depths are small. Ground is flat. Rocky debris is present. Shallow surface soil. Usually little (initial) vegetation. Well vegetated moraine/scree (10-20cm).	Non-paved mountain roads, mountain meadow

Alpine Spruce/Beech Forest		Forest soil, calibrated from rockfall tests in forests in Schiers, Switzerland	Forest
Vegetated Talus		In between pure fine talus and well vegetated moraine/scree (subsoil)	Vegetated talus scree

Talus Fine		Rocks jump over ground. Mostly small rocks. Usually without any vegetation. Q95 grain size <= 5cm, median grain <= 2cm	Rock scree, pebble
Talus Coarse		Rocks jump over ground. Mixture of large and small rocks. Usually without any vegetation. Q95 grain size <= 20 cm, median grain <= 10 cm.	Rock scree, pebble, coarse rock, paved roads

Talus Blocs		Rocks jump over ground. Can get stuck. Mostly large rocks. No vegetation. Q95 grain size <= 50 cm, median grain <= 30 cm.	Big rocks
Boulder Field		Tends to be composed of larger rocks and boulders. DEM should include this roughness. If not, increase Cd.	Rocks and boulders
Bedrock		Ground is very hard and is marginally deformed by rocks. No vegetation and no surface soil.	Bedrock, cliff

Based on the physical model of RAMMS::ROCKFALL described in the previous chapters, different soil types can be distinguished by the following properties:

- Scarring properties (see chapter 3.5)
    - Soil strength M_E
    - Drag coefficient C_d

The hard contact properties described in section 3.6 are the same for all soil types. This results from the model assumption that all soil types have similar properties when the soil is compacted to its maximum density. This also has practical reasons. The hard contact model has many degrees of freedom and friction parameters that are not intuitive in practice. Therefore, different soil types are distinguished entirely by their scarring properties and not during the hard contact. The hard contact properties are set to:

Table 3.4: Hard contact properties for all soil types used in the coulomb friction model (see equations (3.13), (3.15) and (3.16)).

μ_{min}	μ_{max}	β	κ	ϵ
0.55	2	185	3	0

3.8.1 Soil Strength M_E

The soil strength M_E is a geotechnical parameter that describes the amount of pressure that needs to be applied to achieve a certain amount of strain (or settlement over a certain soil thickness). The unit of M_E is therefore N/m^2 or Pa. Other terms for M_E are Oedometer modulus or compressibility modulus (in German: Steife-/Zusammendrückungsmodul). In the RAMMS::ROCKFALL model, M_E serves a similar purpose. It is used to describe the scar depth of a rock with given mass and velocity in a particular soil, according to the empirical formula introduced in chapter 3.5, equation 3.19:

$$d_{max} = 0.16\, M_r^{0.25}\, M_E^{-0.4}\, \left||V_\perp|\right|^{0.8}$$

The higher the M_E value is for a soil, the lower the scar depths of rocks and thus also the energy dissipation during soil interaction. In other words, the stiffness of the soil increases with the M_E value.

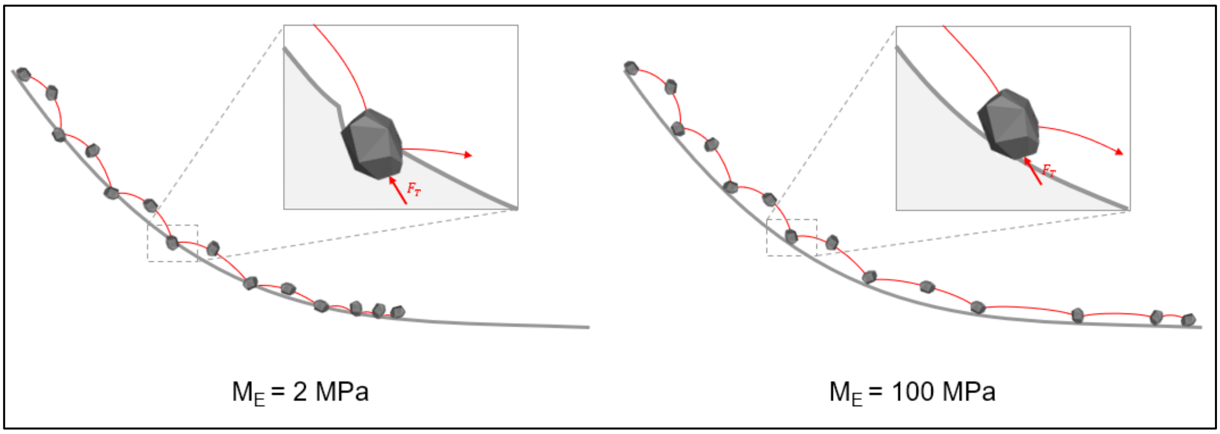


Figure 3-13: Changing M_E influences the scar depth (and thus the runout) of rocks.

The M_E value in RAMMS::ROCKFALL is closely related to the M_E value used in geotechnical engineering to increase the understanding of how it affects soil behaviour during rock-soil interaction. However, it should be noted that RAMMS::ROCKFALL uses this parameter in an empirical relationship that is part of a simplified model calibrated with real-scale rockfall experiments. We therefore do not recommend determining this parameter with oedometer tests in the laboratory, as is common in soil mechanic's practice. We strongly advise to use our recommended and calibrated standard parameters as a first approach (see Table 3.5), to perform plausibility checks by analysing the scar depths of the resulting simulations and to adjust the value accordingly. Realistic values in alpine terrain lie between 1 MPa and 200 MPa.

3.8.2 Drag Coefficient C_d

The drag coefficient influences the viscous drag force that the rock experiences during soil interaction (see chapter 3.5):

$$F_d(t) = \frac{1}{2}\, C_d\, \rho\, A(t)\, \left\|v(t)\right\|^2 \qquad (3.20)$$

The higher the drag coefficient C_d of a soil, the higher the resistance force and the higher the energy dissipation during ground contact. Note that C_d does not affect the scar depth.

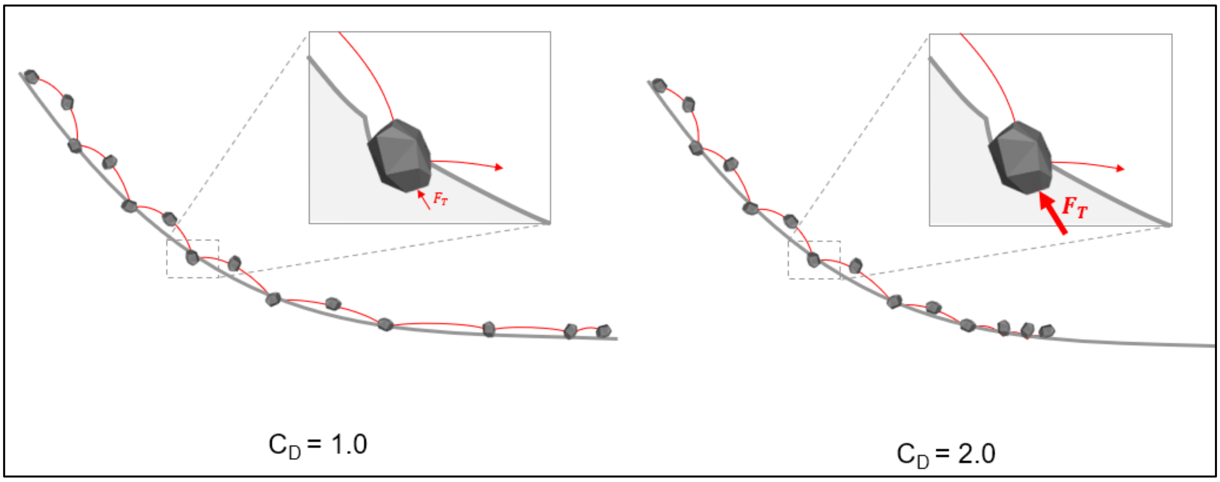


Figure 3-14: Changing C_D influences the resistance force during scarring and therefore the runout distance of rocks.

The coefficient originates from hydrodynamics for the calculation of a resistance force of an obstacle in a viscous fluid. It is a dimensionless, empirical coefficient that summarizes the effects of the object shape and material viscosity on the drag force. RAMMS::ROCKFALL adapts this concept with the modelling assumption that due to the high energy impact of rocks and the inelastic behaviour of soil, the soil particles behave like a fluid around the rock. Realistic values for the drag coefficient in alpine terrain are between 1 and 10.

RAMMS::ROCKFALL offers various default soil categories which are calibrated with real-scale experiments:

Table 3.5: Scarring properties of all default soil types.

Category	M_E [MPa]	C_d [-]
River / Swamp	0.2	1000
Surface Soil	3	1.55
Subsoil	4	1.8
Alpine Spruce/Beech Forest	5.5	1.2
Talus Vegetated	6	2.1
Talus Fine	7	2.3
Talus Coarse	10	2.7
Talus Blocs	15	3.5
Boulder Field	20	3.5
Mountain Road	50	2
Asphalt	75	2
Bedrock	100	4
Snow	0.1	1

3.8.3 Terrain conditions vs. selected terrain category vs. rock size

In previous versions of RAMMS::ROCKFALL, we suggested to change the ground categories depending on the rock size, to consider the additional energy dissipation when a large rock scars, compared to a the scarring of a small rock. With the new scarring model, this is now not necessary anymore because the scar depth is automatically determined from the rock mass, velocity, and soil strength (see equation (3.20). A larger rock will therefore automatically scar deeper and thus lose more energy.

3.8.4 Calibrating the ground parameters

While Table 3.5 provides good estimates for an initial simulation, the soil parameters may need to be adjusted for particular rockfall sites and scenarios. We recommend an iterative process of plausibility checks to tune the parameters accordingly. The more information that is known about the characteristics of the scenario, the easier this process will be.

Such information may include:

- previous events at the same location
- previous events at comparable locations
- silent witnesses of undocumented events

Example questions to be answered to check the plausibility of the results may include:

- Are the scar depths within a plausible range of soil type and rock size?
- Are the jump heights plausible? If possible, compare them to documented tree hits in forested areas.
- Where are the main deposition areas?

- Are rocks in the simulation reaching areas without any documented deposition points or silent witnesses?

If the plausibility check is negative, the following adjustments can be made:

Table 3.3.6: Actions to calibrate the ground parameters to a specific site.

Problem	**Possible Actions**
Scar depths are too high	Increase M_E Be aware that if you increase this value, you will also generate longer runouts and higher jump heights, as rock scarring and thus energy dissipation is reduced. If you wish to lower scar depths without effecting energy dissipation, you must increase C_d accordingly.
Runout distances are too short	Reduce C_d
	Increase M_E Be aware that this also affects scar depths.
Jump Heights are too low, but runout distances are fine	Increase M_E and increase C_d Be aware that this also affects scar depths

With this deterministic modeling approach, the influences of rock-shape on the dynamics and persistence of runout can be simulated. This is important because the model is highly sensitive to rock shape, which in the case of rebound approaches must be treated with stochastic methods (Bourrier et al., 2009). The role of rock-shape in runout dynamics is crucial in determining the rotational and rebound behavior. For specific rock-shapes, characteristic of geological zones, distinctive runout behavior such as extreme jump heights and runout distances are observed. Dynamics of this kind are decisive for hazard mapping and rockfall protection structures; and with full three-dimensional data of rock position, velocities, rotations, and energies (see Table 3.3.7 for a full list), rockfall management and the design of protection structures can be optimized. The listed data (Table 3.3.7) are available as *.log files which can be generated from simulations. The application of rigid-body theory to rockfall modeling has advanced the capacity to include detailed and hazard specific information on rock-shapes and sizes. This allows the inclusion of lithology and geological setting to establish realistic initial conditions for a hazard simulation.

Table 3.3.7: RAMMS::ROCKFALL output parameters

Data symbol	Description	Units
t	time	s
x	X coordinate CoM (CoM = Center of mass)	m
y	Y coordinate CoM	m
z	Z coordinate CoM	m
p0	Quaternion	
p1	Quaternion	
p2	Quaternion	
p3	Quaternion	
vx	Velocity (X) CoM	ms−1
vy	Velocity (Y) CoM	ms−1
vz	Velocity (Z) CoM	ms−1
wx	Angular velocity about inertial axis (X)	rot · s−1
wy	Angular velocity about inertial axis (Y)	rot · s−1
wz	Angular velocity about inertial axis (Z)	rot · s−1
E_{tot}	Total energy including potential energy with respects to the lowest point in simulation domain	kJ
E_{kin}	Total kinetic energy	kJ
$E_{kintrans}$	Translational kinetic energy	kJ
E_{kinrot}	Angular kinetic energy	kJ
z_t	Height position of lowest point on rock-body’s surface	M
Ground Drag	Translational viscous drag force	kN
Ground Torque	Rotational viscous drag torque	kNm
Scar Slippage	Scarring distance/length	m
Scar Depth	Scar depth	m
v_{res}	Absolute velocity	ms−1
w_{res}	Absolute angular velocity	rot · s−1
jumpH	Jump height, plumb-vertical distance of CoM to the terrain surface	m
projDist	Projected distance traced over ground from release point	m
J_c	Distance to the center of SD	m
J HJ c	Distance between SD at Jc to CoM	m
SD	Distance between two impacts	m

3.9 Terrain Model

The RAMMS::ROCKFALL model simulates the trajectories of falling rocks in three-dimensional terrain using a high-resolution digital elevation model. The terrain coordinate system is taken as the simulation frame O. Terrain elevation Z_m is specified for each coordinate pair (X_m, Y_m), for which four coordinate pairs define the vertices of planes constructing the tessellated terrain surface (Figure 3-15). The planes are flat, while their orientation is different because the Z_m- elevation of each coordinate pair can differ. The distance between coordinates (X_m, Y_m) defines the model terrain resolution and therefore the accuracy with which the terrain morphology is represented. Typically, a resolution between 0.5 m and 5 m is employed for simulations, as this accurately models important terrain features such as gullies and cliffs. The properties of each plane can be varied to consider variable surface properties, such as hardness and roughness. For example, forests are defined to be planes with enhanced drag.

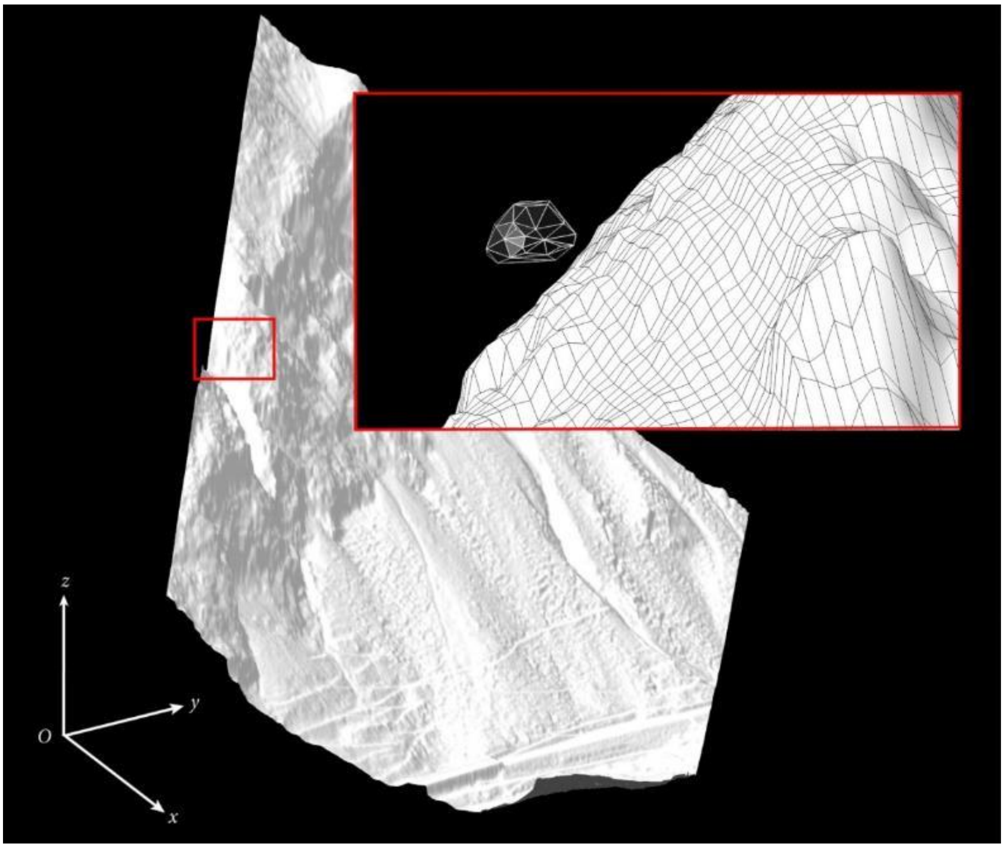


Figure 3-15: High resolution three dimensional terrain model forms simulation frame O in which the four sided planes form the tessellated terrain surface with which the rock-body can come into contact.

DEM resolution

A minimal cell size of 0.5-5m should be used to obtain realistic results. The cell size can be increased in case of long runout distances of > 2 km and scenarios with big block sizes (>10-50 m^3). If the project perimeter is rather small, corresponding runout distances short (<50m) and the variability of the terrain is high within a few meters, then the cell size of the DEM should be lower, e.g. 1.0 or even 0.5m.

4 Setting up a simulation

4.1 Preparations

To successfully start a new RAMMS project, a few important preparations are necessary. Topographic input data (DEM in ASCII- or GEOTIFF-format), project boundary coordinates and georeferenced maps or remote sensing imagery should be prepared in advance (.tif format and .tfw-file, maps and imagery are not mandatory, but nice to have). Georeferenced datasets must be in the same **Cartesian coordinate system** (e.g., UTM, Swiss CH1903 LV03, …) as the DEM. Polar coordinate systems in degree (e.g., WGS84 Longitude Latitude) **are not supported**. For more information about specific national coordinate systems please contact the national topographic agency in your country.

4.1.1 Topographic data - Digital Elevation Model (DEM)

The topographic data is the most important input requirement. How a rock moves (i.e. final runout distance, jump heights, translational and rotational velocities and total energy content of the rock) is strongly influenced by the interaction with the terrain. Therefore, the simulation results depend strongly on the resolution and accuracy of the topographic input data. We recommend a DEM resolution of **2-5 m or better** for meaningful rockfall simulations in complex terrain. However, if such high spatial resolution DEM data is not available, the user must keep in mind that important terrain features may not be correctly represented by the DEM. This can lead to unrealistic simulation results. Before you start a simulation make sure all important terrain features are represented in the input DEM. RAMMS can process the following topographic data:

- ESRI ASCII grid (Figure 4-1)
- GEOTIFF
- ASCII XYZ single space data (Figure 4-2)

The header of an ESRI ASCII grid must contain the information shown in Figure 4-1.

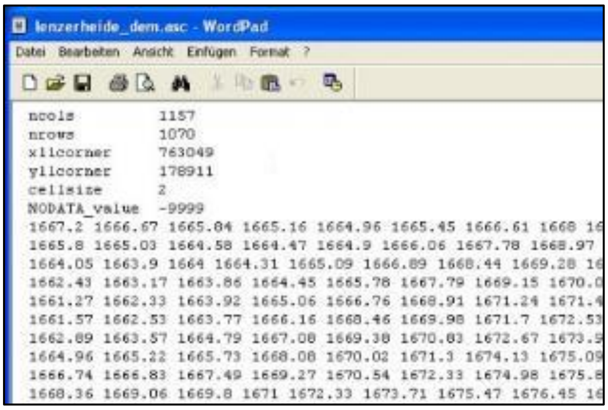


Figure 4-1: Example ESRI ASCII grid.

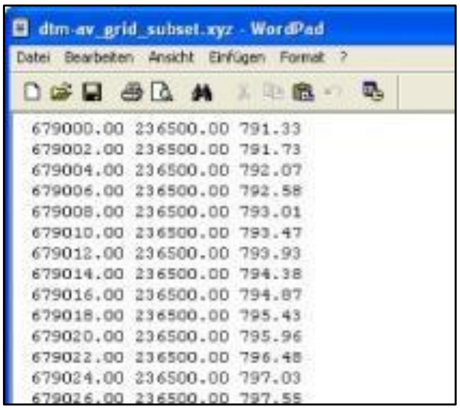


Figure 4-2: Example ASCII XYZ single space data.

ASCII XYZ data (regular and irregular) can be converted within RAMMS into an ASCII or GEOTIFF grid. A wizard will guide you through the conversion process, see below. The following interpolation methods are available: *LINEAR* or *INVERSE DISTANCE*.

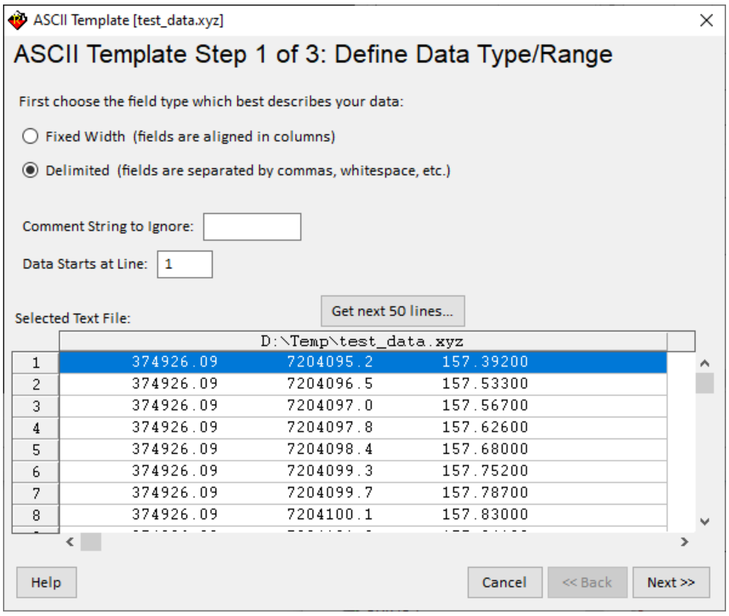


Figure 4-3: Convert XYZ to raster process, step 1 of 3.
Choose from which line number to start.

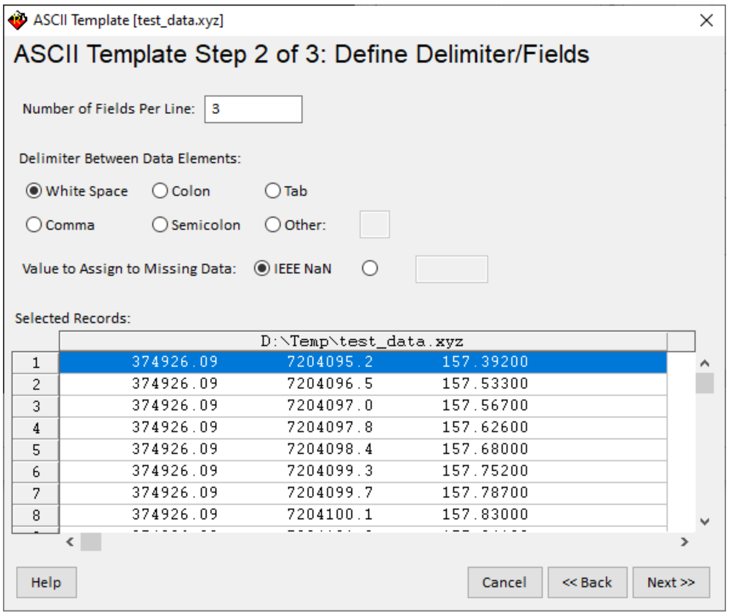


Figure 4-4: Convert XYZ to raster process, step 2 of 3. Choose nr of fields per line and delimiter to use (white space, comma, etc.)

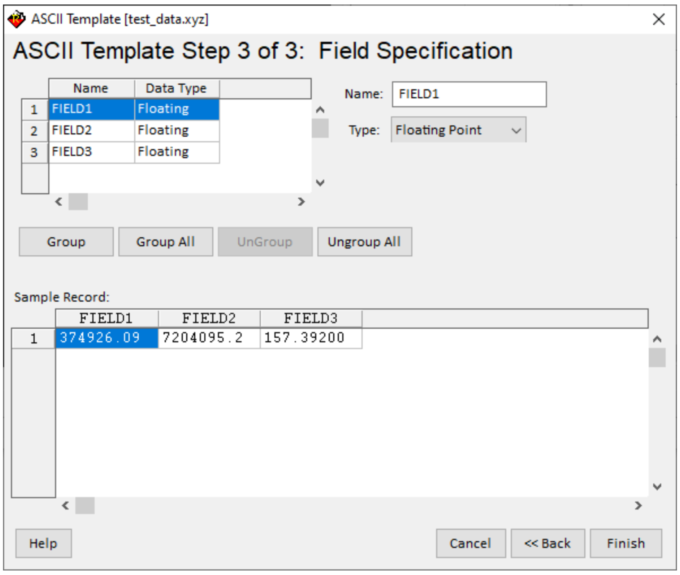


Figure 4-5: Convert XYZ to raster process, step 3 of 3.
Specify field types (Integer, float or double)

Click Finish to start the conversion process. RAMMS will suggest the interpolated grid resolution, which the user can change of course:

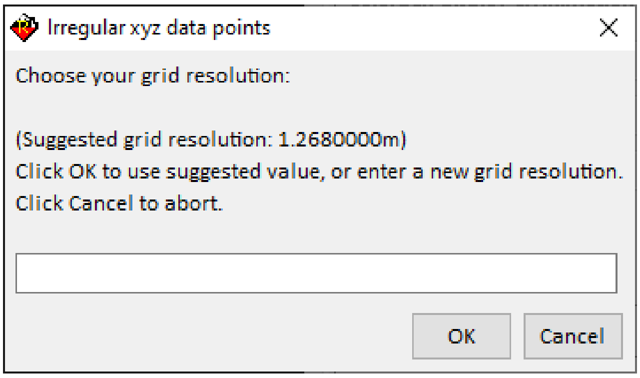


Figure 4-6: Grid resolution suggestion

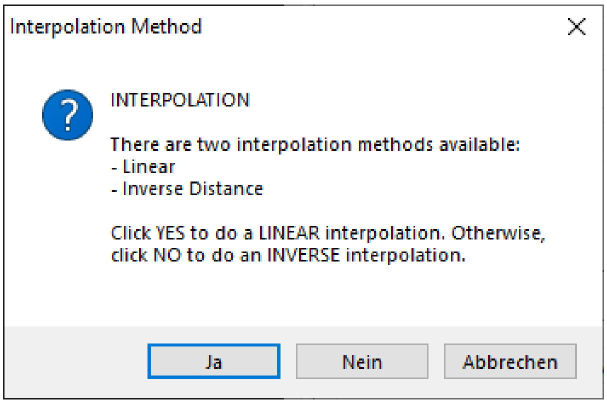


Figure 4-7: Select interpolation method

A tif-file with your raster-conversion will then be created in the same directory as your xyz-file. With this tif-file, you can then create a new project, see chapter 4.20 on page 55.

4.1.2 Project and Scenarios

A project is defined for a region of interest. Within a project, one or more scenarios can be specified and analyzed. For every scenario, a calculation can be executed. A project consists therefore of different scenarios (input files) with different input parameter files (release and friction files). The basic topographic input data is the same for every scenario. If you want to change the topographic input data (e.g., change the input DEM resolution or the project boundary coordinates) you must create a new project. Other input parameters (like rock shape, surface information, end time, time step etc.) can be changed for every scenario.

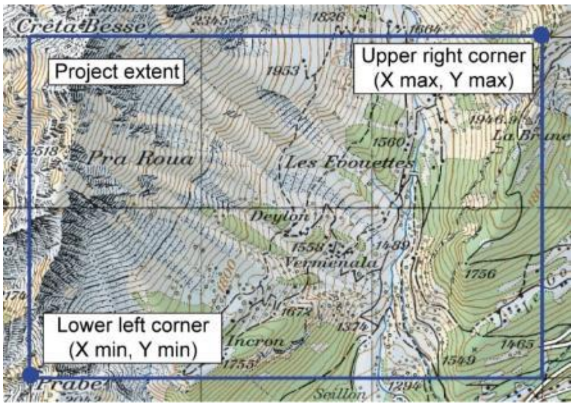


Figure 4-8: The same project extent (area of interest) can be used to calculate different scenarios with different input parameters.

4.1.3 Preferences

To ease the file handling, we recommend setting the preferences prior to start with simulations. The preferences set the path to the working directory and the necessary files such as DEM, maps, and ortho-imagery. If the path to the maps and the imagery files is set correctly in the preferences, RAMMS will automatically open the georeferenced data when you generate a project.

Use ***Track*** → ***Preferences*** to open the RAMMS preferences window or click the button . For resetting the general preferences use ***Help*** → ***Advanced…*** → ***Reset General Preferences***.

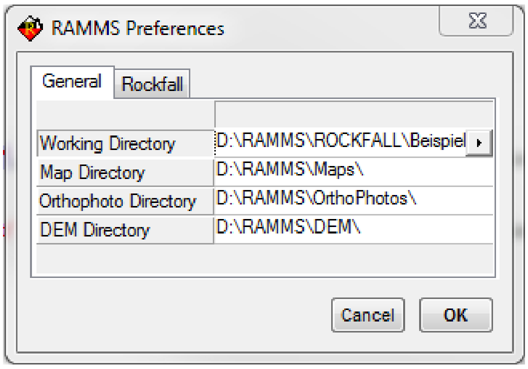


Figure 4-9: General tab of RAMMS preferences.

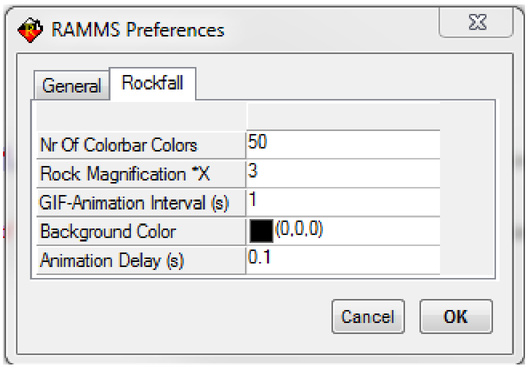


Figure 4-10: Rockfall tab of RAMMS preferences.

General Tab

Setting	Purpose
Working Directory	Set your working directory. VERY IMPORTANT: DO NOT USE BLANKS in the working directory path!
Map Directory	Set the folder where you place your georeferenced digital maps (consists of a .tif file and a corresponding .twf file (world-file).
Orthophoto Directory	Set the folder where you place your digital georeferenced orthophotos (aerial picture, consists of a .tif file and a corresponding .twf file (world-file).
DEM Directory	Set the folder where you place the Digital Elevation Models (format ASCII grid)

Rockfall Tab

Setting	Purpose
Nr of Colorbar Colors	Set default number of colorbar colors.
Rock Magnification *X	Set values between 1 and 100 for magnification of the rock size in the visualization.
GIF-Animation Interval [s]	Set interval for GIF animation images in seconds.
Background Color	Set background color.
Animation Delay [s]	Set animation delay to the animation speed.

The following exercise *Working directory* shows how to choose a new working directory. All further settings can be changed in a similar manner. The settings are saved, until they are changed again manually.

Exercise 4.1: Working directory

Choosing the right working directory is very useful and saves a lot of time searching for files and folders.

VERY IMPORTANT: Do NOT use blanks or special characters in the path names!

- Click  (or use ***Track*** → ***Preferences*** or ***Ctrl+P***) to open the RAMMS preferences window.
- Click into the field *Working directory*. A window pops up where you can choose your new working directory. Click *OK* in both windows. Do this also for other directories if necessary.

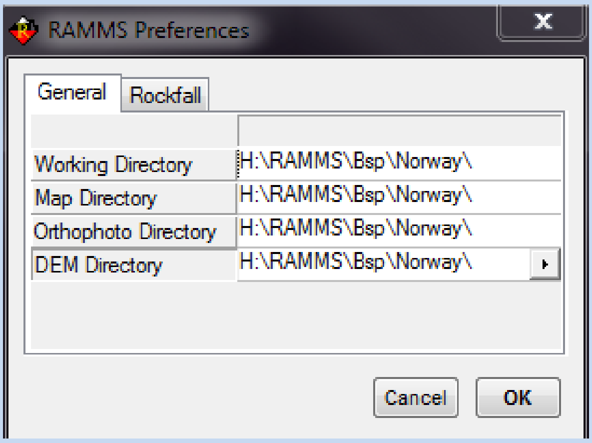


Figure 4-11: RAMMS preferences

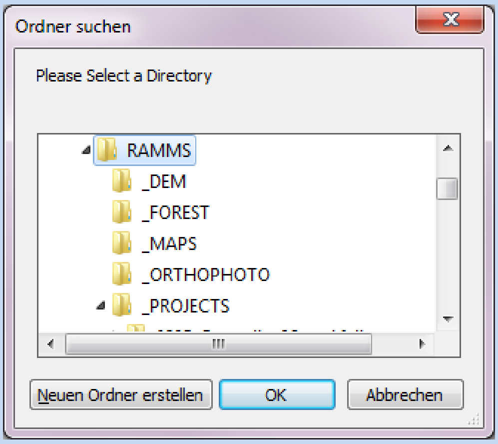


Figure 4-12: Browse for the correct folder.

4.1.4 Additional Preferences

There are many more settings that you can change. Unfortunately, there is no user-friendly widget for this yet. You must change these settings manually (explained below). Use this button in the vertical toolbar on the left

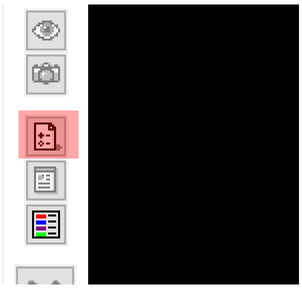
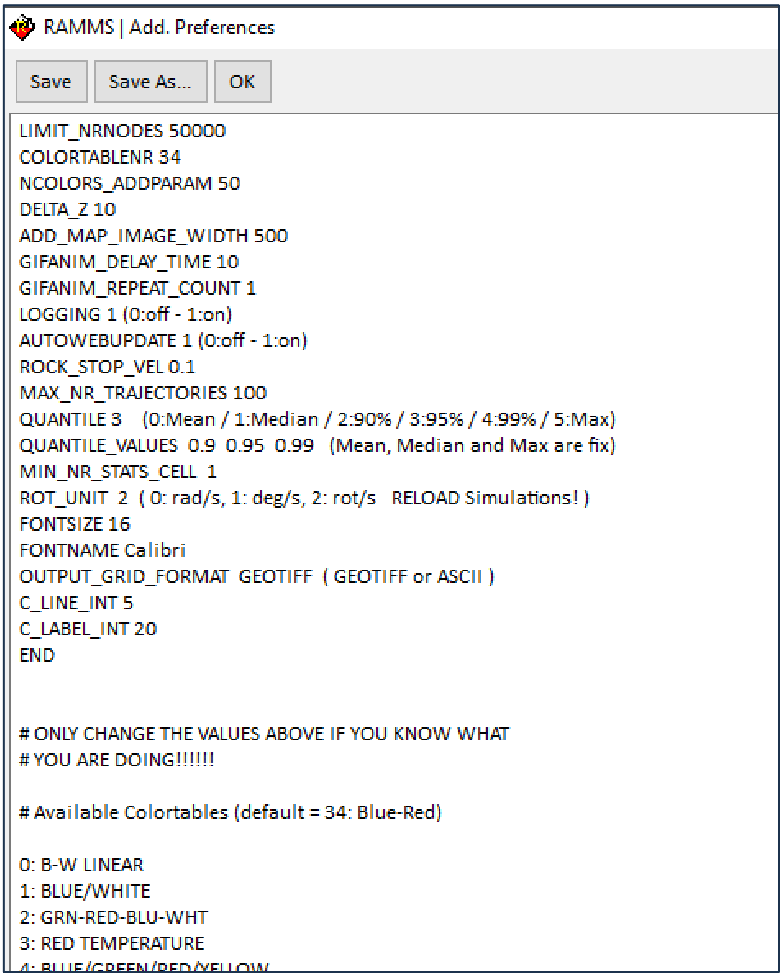


Figure 4-13: Additional preferences button in the vertical toolbar on the left

or the menu *Help* → *Advanced…* → *Additional Preferences…* → *Edit* to open the Additional Preferences in a text editor, see Figure below.




```
LIMIT_NRNODES 50000
COLORTABLENR 34
NCOLORS_ADDPARAM 50
DELTA_Z 10
ADD_MAP_IMAGE_WIDTH 500
GIFANIM_DELAY_TIME 10
GIFANIM_REPEAT_COUNT 1
LOGGING 1 (0:off - 1:on)
AUTOWEBUPDATE 1 (0:off - 1:on)
ROCK_STOP_VEL 0.1
MAX_NR_TRAJECTORIES 100
QUANTILE 3    (0:Mean / 1:Median / 2:90% / 3:95% / 4:99% / 5:Max)
QUANTILE_VALUES  0.9  0.95  0.99   (Mean, Median and Max are fix)
MIN_NR_STATS_CELL  1
ROT_UNIT  2  ( 0: rad/s, 1: deg/s, 2: rot/s   RELOAD Simulations! )
FONTSIZE 16
FONTNAME Calibri
OUTPUT_GRID_FORMAT  GEOTIFF  ( GEOTIFF or ASCII )
C_LINE_INT 5
C_LABEL_INT 20
END


# ONLY CHANGE THE VALUES ABOVE IF YOU KNOW WHAT
# YOU ARE DOING!!!!!!

# Available Colortables (default = 34: Blue-Red)

0: B-W LINEAR
1: BLUE/WHITE
2: GRN-RED-BLU-WHT
3: RED TEMPERATURE
4: BLUE/GREEN/RED/YELLOW
```

Details about above parameters and some more are listed below:

LIMIT_NRNODES	The DEM of the topography will be resampled to reduce the number of grid points for visualization purposes. This adjustment will not affect the simulation resolution. Default value is 50'000.
COLORTABLENR	Change the default colortable used in RAMMS. Available colortables are listed below, or can be visualized with *Help* → *Advanced…* → *ColorTables…* → *View Available ColorTables.* Default value is 34 (Rainbow).
NCOLORS_ADDPARAM	Nr of colors for second colorbar in Output-Mode. Default value is 50.
DELTA_Z	Lines of shapefiles are drawn slightly above the terrain. Default value is 10.0 (m). This is to prevent lines being drawn below the terrain, in case the topography is resamples (see LIMIT_NRNODES above).
ADD_MAP_IMAGE_WIDTH	Width (pixels) of window to select map/ortho images. If filenames are very long, it makes sense to increase this value. Default value is 500.
GIFANIM_DELAY_TIME	GIF-Animation parameter. Set this keyword to an integer giving the delay in hundredths (1/100) of a second after the decoder displays the current image. Default value is 20.
GIFANIM_REPEAT_COUNT	GIF-Animation parameter. Set this keyword to an integer giving the number of times that the decoder should repeat the animation. Set this keyword to zero to repeat an infinite number of times. This keyword is written using the Netscape application extension and may not be recognized by some decoders. Default value is 0.
LOGGING	0: no logging, 1: logging to file. Default is 1.
AUTOWEBUPDATE	0: no AutoWebUpdate, 1: do AutoWebUpdate. If enabled, RAMMS checks online for updates. Default value is 1.
ROCK_STOP_VEL	Stopping velocity of rocks. RAMMS uses this stopping velocity to calculate the min. kinetic energy for each rock. Default value is 0.1 m/s.
MAX_NR_TRAJECTORIES	Reading trajectories in Trajectory-Mode can use a lot of memory. If the user wants to read more trajectories than this threshold, RAMMS sends a warning to the user. Default value is 100.
QUANTILE	Default quantile visualization in Statistics-Mode is 3 (0:Mean / 1:Median / 2:90% / 3:95% / 4:99% / 5:Max)
QUANTILE_VALUES	Define three quantile values, default values are 0.9 0.95 0.99 (Mean, Median and Max are given)

MIN_NR_STATS_CELL	Users can specify e.g. a value of 5, meaning that statistics is only calculated for grid cell values containing at least 5 trajectories. Default value is 1.
ROT_UNIT	Definition of rotation unit (0: rad/s, 1: deg/s, 2: rot/s). After changing this parameter, users must RELOAD simulations. , Default value is 2.
FONTSIZE	Change font size of GUI. Default value is 16.
FONTNAME	Change font name of GUI. Default font name is *Helvetica.*
OUTPUT_GRID_FORMAT	
C_LINE_INT	Contour plot. Interval of contour lines in (m). Default value is 20m.
C_LABEL_INT	Contour plot. Interval of contour labels in (m). Default value is 100m.
RELP_SYM_NR	Symbol of visualized release point when defining the random distribution of release points with ***Set Release***, see section 4.5.3. Default value is 1. Possible symbols are: • 1: Plus sign (+) • 2: Asterisk (*) • 3: Period (.) • 4: Diamond • 5: Triangle • 6: Square • 7: X
RELP_SYM_SIZE	Size of symbol from above. Default value is 1.
RELP_SYM_THICK	Thickness of symbol from above. Default value is 1.

4.2 Creating a new project

A new project is created by selecting the Geotiff- or ASCII-DEM-file, from which you want to create a new RAMMS project. The exercise below shows how this works:

Exercise 4.2: How to create a new project

- Click or ***Track*** → ***New...*** → ***Project Wizard*** and select your DEM-file, e.g. *dhm.tif*.
- The following window pops up.

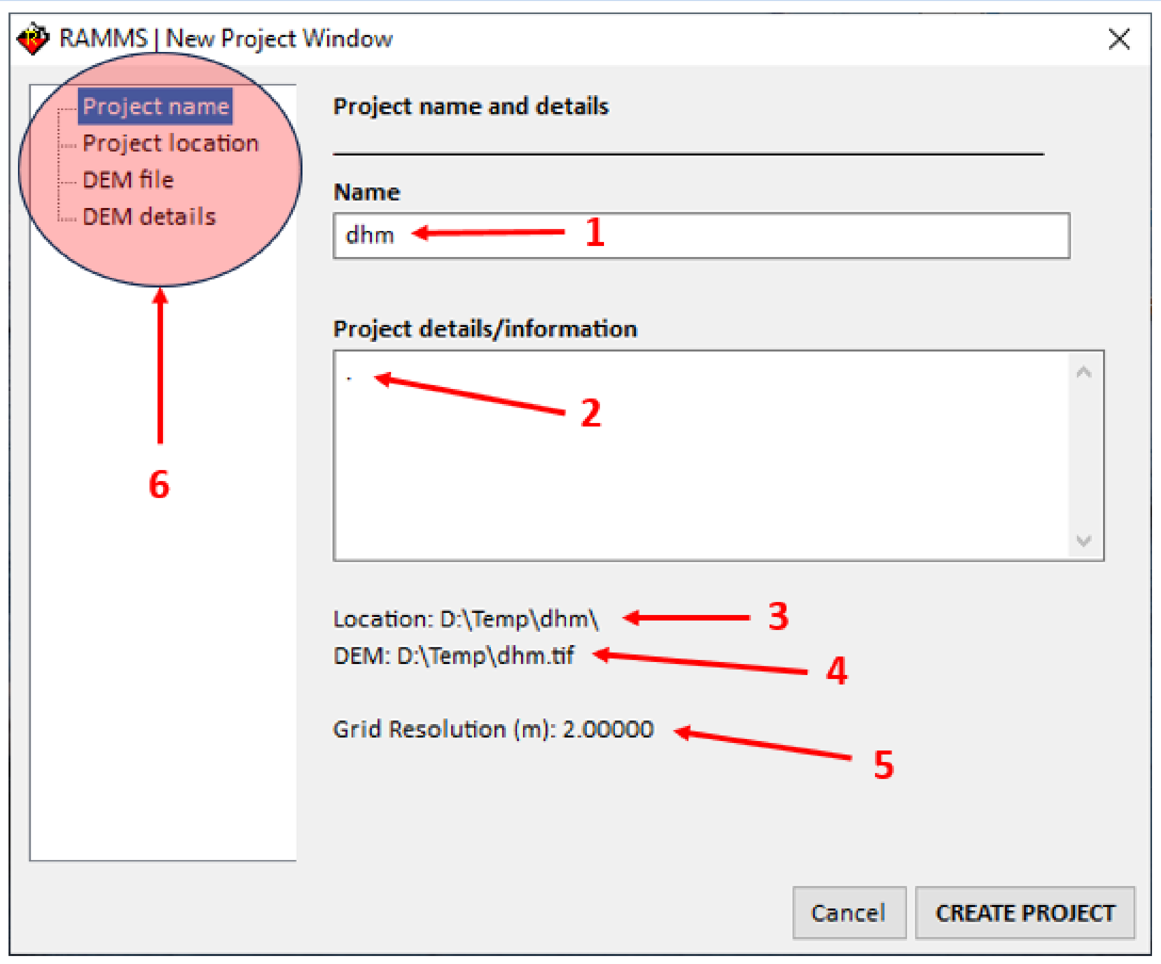


Figure 4-14: RAMMS Rockfall Project Wizard

Continuation of Exercise 4.2: How to create a new project

The ***New Project Windows*** contains:

- 1) Project name suggestion (derived from the tif-filename)
- 2) Possibility to enter project details
- 3) The project directory is composed of the directory of the tif-file and the suggested project name. To change the location, click the *Project Location* tab on the left.
- 4) The name and path of the tif-file.
- 5) The grid resolution of the tif-file.
- 6) Tab to change project name, project location, DEM file or DEM details

To check out the DEM-details (e.g. clipping the DEM, changing grid resolution), click *DEM details* on the left. The window will change to the following:

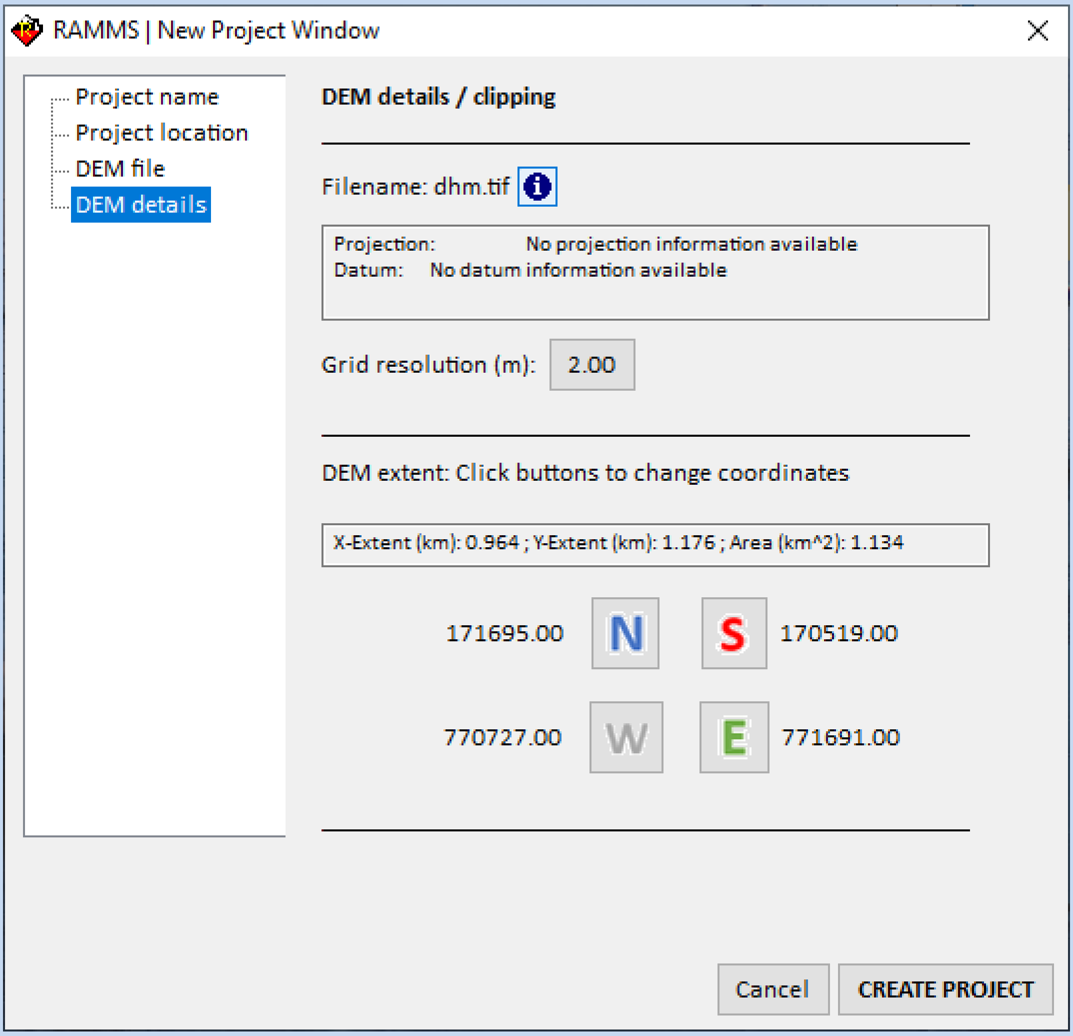


Figure 4-15: DEM details window

Continuation of Exercise 4.2: How to create a new project

Clipping the DEM:

Click the appropriate button (N for North, S for South, etc.) to change coordinates, according to your project region, as it is shown below for the Vallée de la Sionne area.

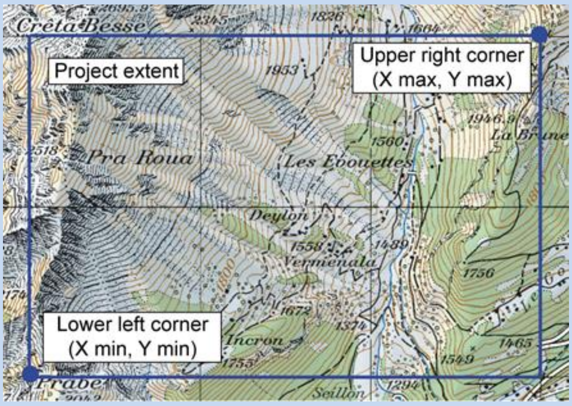


Figure 4-16: Project coordinates: lower left and upper right corner of project area.

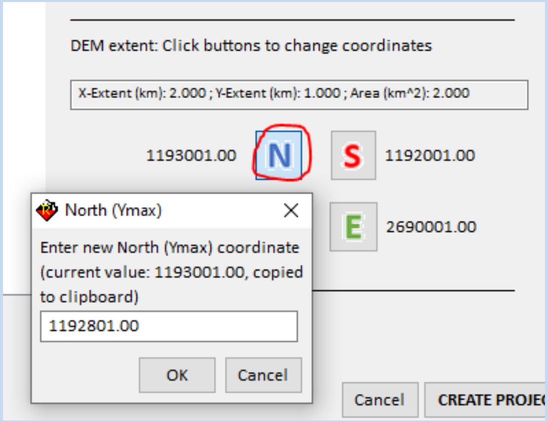


Figure 4-17: Clipping DEM coordinates.

Changing DEM resolution:

- Click the button next to *Grid resolution* (2.00 in this example).
- Enter a new grid resolution and click OK.
- RAMMS will then do a bilinear interpolation from the DEM resolution to the new grid resolution.

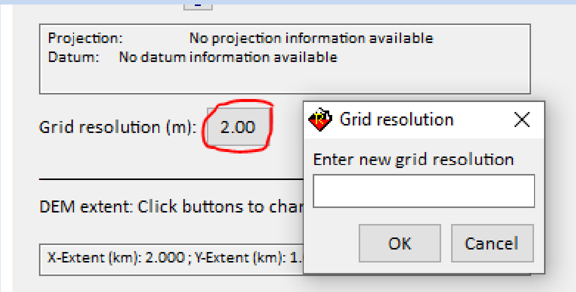


Figure 4-18: Changing grid resolution.

Project creation:

If you specified all information, click ***CREATE PROJECT***. The creation process can take a while. Different status bars will pop up and show the progress of the project creation process. Slope angles and aspects are calculated and saved as tif-files.

The following files will be created in the project folder.

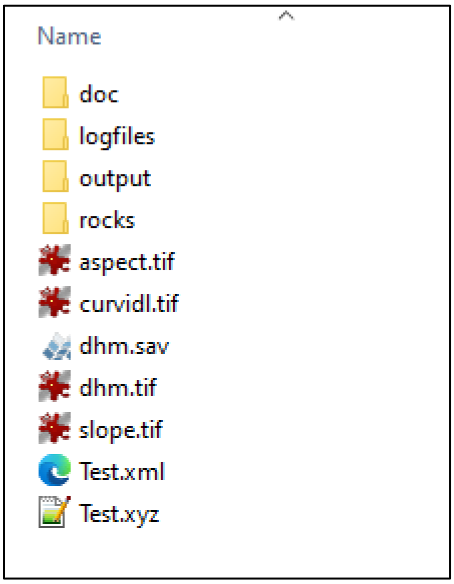


Figure 4-19: Files and directories created with a new RAMMS::ROCKFALL project.

Table 4.1: Listing of files and directories created with a new RAMMS::ROCKFALL project.

File / Folder	Purpose
doc (folder)	Folder containing input and output log files
logfiles (folder)	Project creation and calculation log files
output (folder)	Folder containing calculated scenarios
rocks (folder)	Folder to save rock files (.pts)
aspect.tif	Aspect raster tif-file
curvidl.tif	Calculated planar curvatures of DEM
dhm.sav	Internal binary file containing DEM information
dhm.tif	GEOTIFF raster file with altitude values
Test.xml	Input file
Test.xyz	Topographic data used in RAMMS
slope.tif	Calculated slope angles of DEM

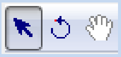
4.3 Working with the interface

Once the project is created, there are several useful tools which can be helpful when working with RAMMS. They are explained in the exercises below.

4.3.1 Moving, resizing, rotating, viewing

Exercise 4.3a: Moving and resizing the model

a. Terrain model has a dimension of 100% or smaller:

- By clicking on the *arrow*  the model can be moved and resized.

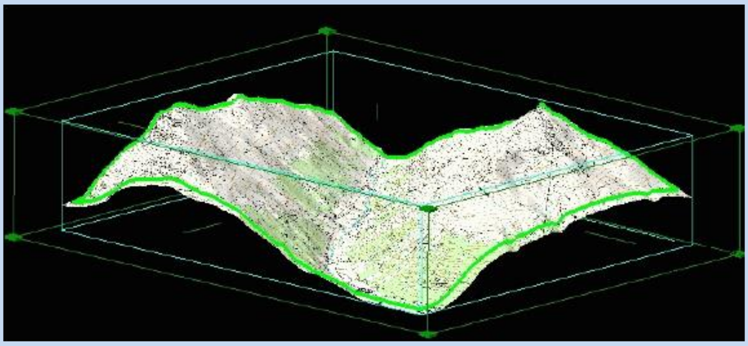


Figure 4-20: *Active* project with lines and corners for resizing.

- To move the model without changing size or aspect ratio, move the cursor to the model and check if the cursor turns to . Then click and hold the left mouse button and drag the model to the desired position.
- To resize the model without changing the aspect ratio, use the mouse wheel to zoom in or out. Alternatively, you can resize the model by changing the percentage value in the horizontal toolbar 

.

b. Terrain model has a dimension > 100%:

- All steps explained above are still possible.
- In addition to this, the white hand right next to the rotation button becomes active as well. After clicking on this so-called *view pan* button , it is also possible to move the model.

Exercise 4.3b: Rotating the model

After activating the rotation button, the model can be rotated along the rotation axis', by moving the cursor directly on one of the axis until the cursor changes from to . Otherwise, a freehand rotation in any direction is possible.

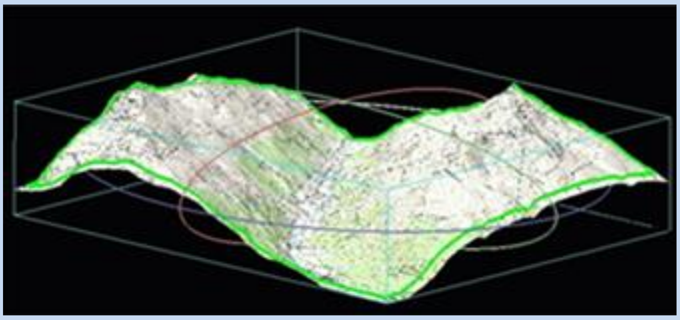


Figure 4-21: *Active* project with rotation axes.

Exercise 4.3c: How to switch between 2D and 3D mode

Click to switch from 3D to 2D view. This button then changes to and by clicking again, you will return to 3D view.

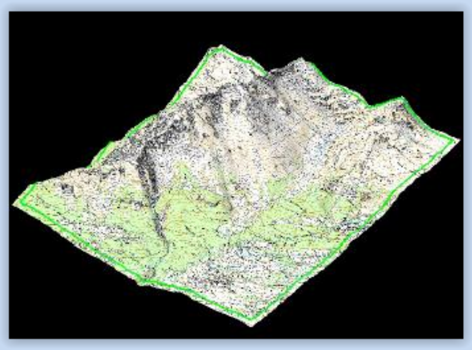


Figure 4-22: 3D view of example model.

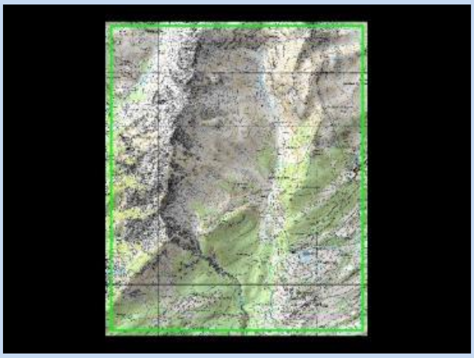


Figure 4-23: 2D view of example model.

In 2D mode you have all possibilities that work for the 3D mode. It works for input files as well as for simulations. **For the following functions of RAMMS it is necessary to switch from 3D to 2D view:**

INPUT:

Draw New Release Points

Draw New Release Line

Draw New Polygon Shapefile

Edit Forest Parameters

Edit Soil Parameters

Release On-Off

OUTPUT:

Draw Line Profile

4.3.2 Colorbar

As soon as a parameter is shown in the project, the colorbar appears on the right side of the main window. It can be turned on and off by clicking on . The colorbar can be moved anywhere in the screen (and can get lost). Use ***Edit*** → ***Get Colorbar*** to find a lost colorbar.

Exercise 4.3d: Editing the colorbar

Changing the minimum and maximum values of the colorbar as well as changing the number of colors used is done in the panel *ROCKFALL* (right of the map window) in the *Display* section at the top.

- Simply type a new value into the respective field and hit the **return key** on the keyboard. The display will be refreshed.
- To view the underlying topography or image, you can change the **transparency**.

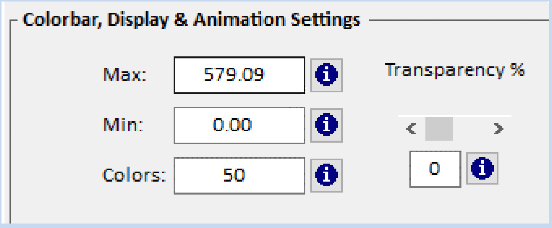


Figure 4-24: Colorbar and Display Options.

- Open the editing window by either choosing ***Edit*** → ***Colorbar Properties***.
- To change the colorbar properties simply click into the field you want to change, then click *OK*.

→ Using ***Edit*** → ***Colorbar White Color*** the text-color of the colorbar can be changed to white. This can be useful when changing the background color of your project to black or white ***Track*** → ***Preferences*** → ***Rockfall Tab*** → ***Background Color***.

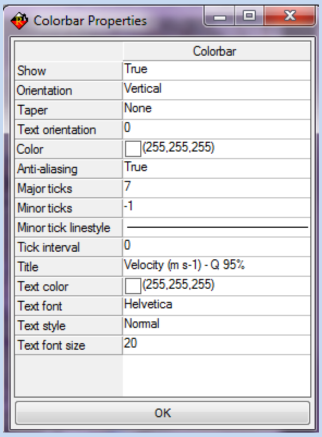


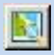
Figure 4-25: The Colorbar Properties window.

4.3.3 Changing maps and remote sensing imagery

It is possible to change the map or imagery of a project anytime. Be aware, that the corresponding .tfw-file (world-file) has to be in the same folder as the actual map (.tif). If this is not the case, the map will not be found!

Exercise 4.3e : How to add or change maps

a. Add or change a map:

- Go to ***Extras*** → ***Map…*** → ***Add/Change Map*** or click .
- If more than one map is found, the following window pops up, listing the maps found:

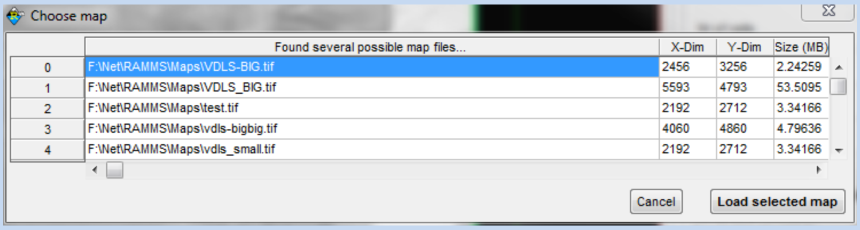


Figure 4-26: Window to choose map image.

- Information on the image dimensions (x-Dim and y-Dim, pixel) and size (in MB) are provided and might be a selection criterion.
- Select the map you wish to add and click ***Load selected map***.

b. Map not found:

- If the question "No map found, continue search?" appears, you either don't have an appropriate map, the map-folder directory is set wrong, or the map is saved in a different folder. In the second case click ***Yes*** and choose the correct folder. A window pops up to browse for the correct map location and file.
- Or click ***No*** to cancel search.

c. Change remote sensing imagery:

- Go to ***Extras*** → ***Image…*** → ***Add/Change Image*** or click .

4.3.4 Hillshade visualization

Use *Extras* → *Create Hillshade Image* to create a hillshade visualization. For this RAMMS follows the instructions from ArcGIS at

https://desktop.arcgis.com/en/arcmap/10.3/tools/spatial-analyst-toolbox/how-hillshade-works.htm

to calculate the hillshade representation of your DEM, see Figures below.

Go **to Extras → Image… → Add/Change Image** or click to load a newly generated hillshade image into the project.

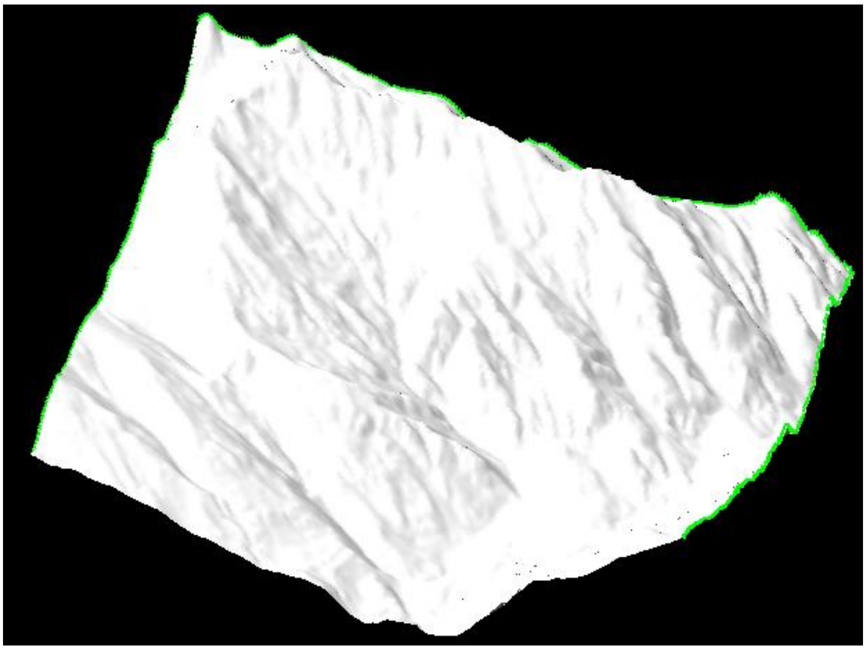


Figure 4-27 DEM surface visualization (with shadows) after creating a new project in RAMMS.

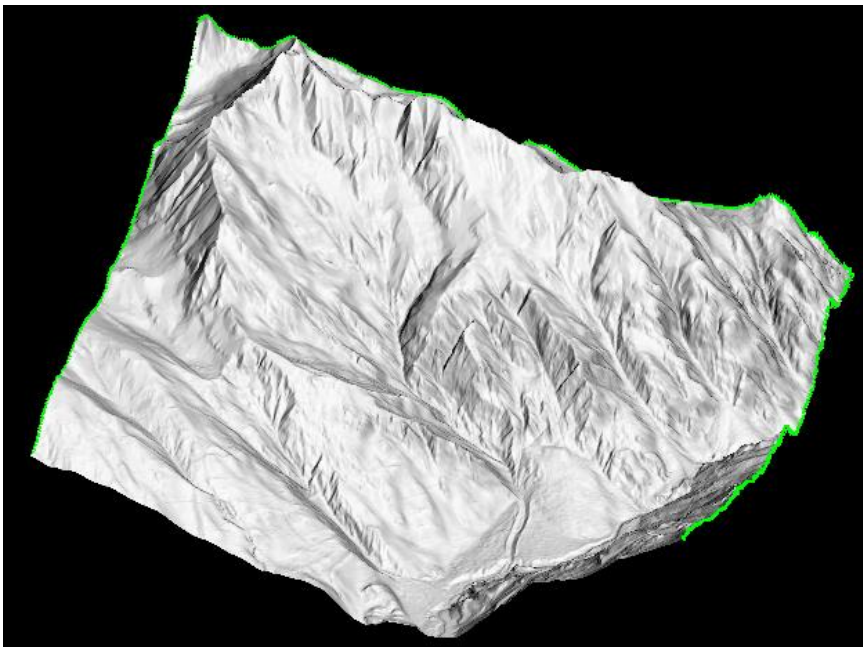


Figure 4-28 Visualization after creating and adding the hillshade image to RAMMS.

4.3.5 Show Slope Angles, Terrain Curvature or Contour Lines

With these three buttons in the horizontal toolbar, slope angles, curvatures and contour lines can be visualized.

-  Slope angle
-  Curvature (planar)
-  Contour lines

By again clicking on the same symbol, the visualization is removed.

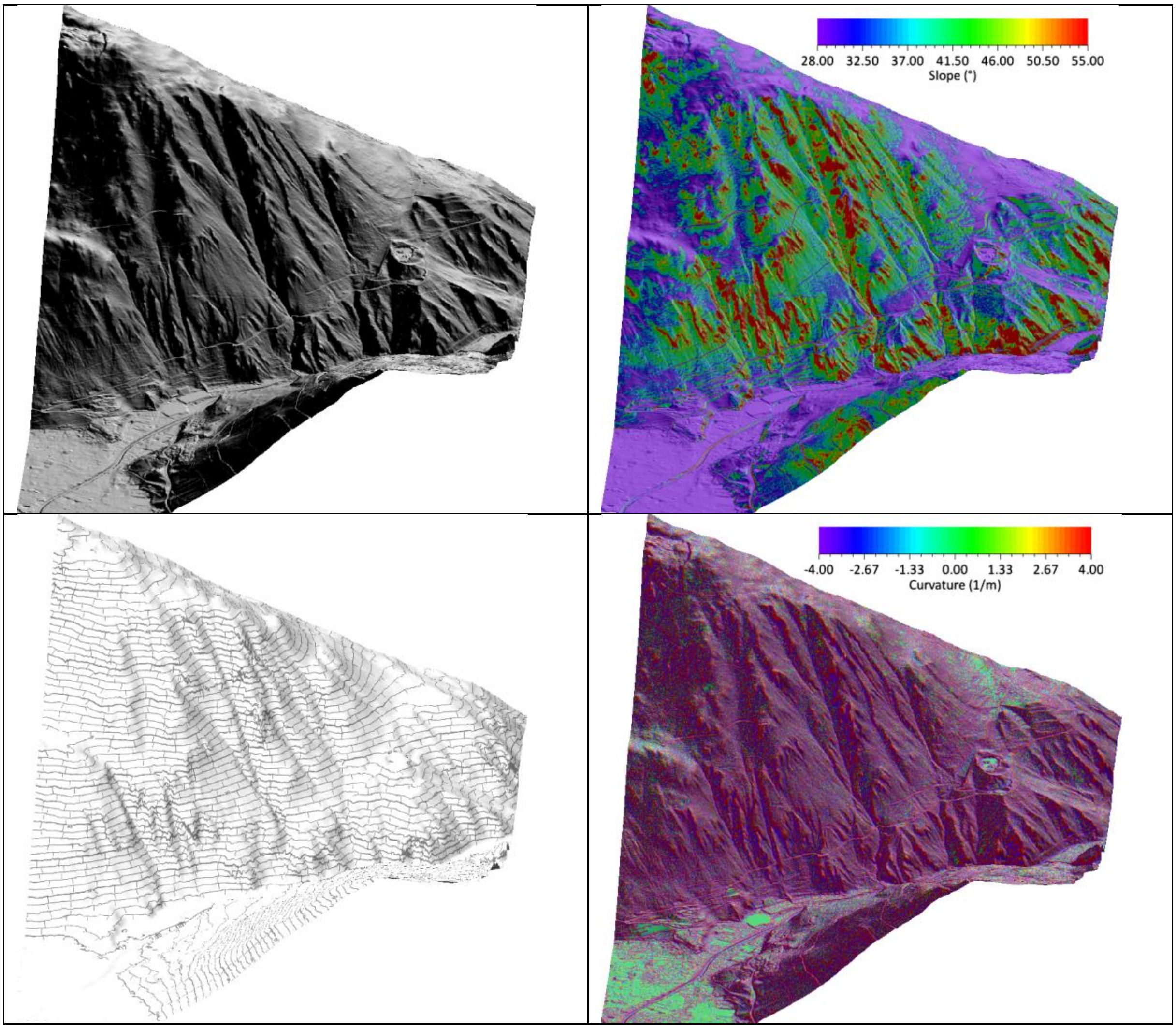


Figure 4-29: Top left: Hillshade image, top right: slope angle
bottom left: contour lines, bottom right: curvature

Line and label intervals of the contour plot can be set in the Additional Preferences, see section 4.1.4 on page 52.

4.3.6 How to save input files and program settings

Once a project is created, it is saved under the name and location you entered in the RAMMS Project Wizard (Figure 4-14). The created input file has the ending .xml. The second situation, in which the input file is saved automatically, is when a simulation is started. The saved input file has the same name as the created output file.

Exercise 4.3f : How to save input files and program settings manually

a. Input file:

- In case you want to save the input file manually before running a simulation, go to ***Track*** → ***Save***. This is helpful, when for example a release line was loaded but you wish to close the project before doing the simulation.
- If you wish to save a copy of your file under a new name, go to ***Track*** → ***Save Copy As*** or click .
- A window pops up to choose an old file which should be overwritten or to type in a new name, then click ***Save.***
- Continue working on the original file, not the just saved one.

b. Position settings

- If you have moved and/or rotated your project for a better view, you can save this position by going on ***Extras*** → ***Save Active Position***. There is also a button in the horizontal toolbar for this operation → .
- You can now get back to this position anytime by choosing ***Extras*** → ***Reload Position***.

Exercise 4.3g : How to open an input file

Close any active project file .

- Go to ***Track*** → ***Open*** → ***Input File*** or click .
- A window opens to browse for a rockfall input file (.xml).
- Click ***Open*** after the file name was selected.
- The project will be opened.
- You can access recent input files by choosing ***Track*** → ***Recent…***

Exercise 4.3h : How to load an optional shapefile

- To load a shapefile, go to ***GIS*** → ***Import Shapefile*** or click .
- A window opens to browse for a shapefile (.shp).
- Click ***Open*** after the file was selected.

Exercise 4.3i : How to open an output file/rockfall simulation

Close any active project file .

How to open a scenario in Statistics-Mode:

- Go to ***Track*** → ***Open...*** → ***Rockfall Scenario*** or click .
  Scenarios are located in the *output* folder of your project directory. Choose a scenario folder and click ***OK***.
- If you want to open several scenarios (from the same project) together, click ***Track*** → ***Open...*** → ***Rockfall Scenario (Filter/Multi)***, and then choose more scenarios, or use a filter to open only specific output results (e.g. with the same rock-name).

How to open trajectories from a scenario in Trajectory-Mode:

- Go to ***Track*** → ***Open...*** → ***Rockfall Trajectories (Ctrl+T)*** or click
- A window opens to browse for rockfall simulation files (.rts). Click ***OK***.
- The simulation(s) will then be opened.

- If you want to open trajectories from different scenarios (from the same project) together, click ***Track*** → ***Open...*** → ***Rockfall Trajectories (Filter/Multi) (Ctrl+F)***, and then choose more trajectories from a different scenario folder, and/or use a filter to open only specific trajectories (e.g. with the same rock-name).

Or use the recent menu to open recently opened input files or scenarios (***Track*** → ***Recent…***).

4.3.7 About RAMMS

Some information about the RAMMS installation on your computer is found here: ***Help*** → ***About RAMMS***.

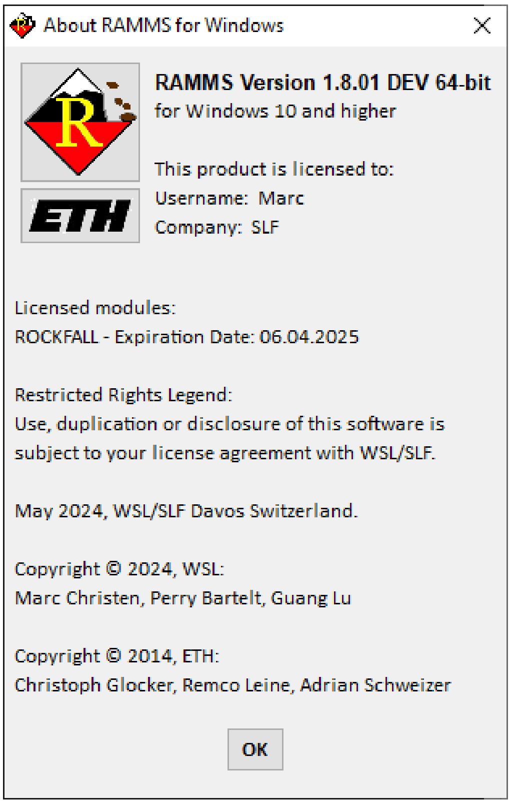


Figure 4-30: About RAMMS::ROCKFALL

4.4 Shapefiles

Shapefiles are used for all spatially variable input data, such as the definition of rockfall release zones (see section 4.5, definition of areas with specific terrain material (see section 4.6), definition of forested areas (see section 4.7). The workflow is always the same. First, the user creates or imports shapefiles and then assigns terrain parameters, forest or release zones. All shapefiles of a project are shown in the file tree in the right panel under the **Files** tab.

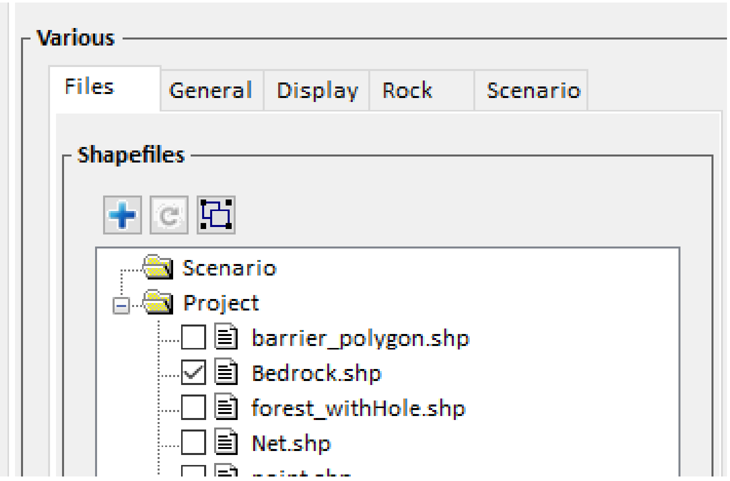


Figure 4-31: File tree with all shapefiles of a project.

The checkbox to the left of a shapefile in the file tree can be used to activate or deactivate a specific shapefile. This will hide the shapefile visualization from the view. The shapefile will not be considered during a simulation, meaning that if a deactivated shapefile has an assigned ground category, forest or release property, this information is ignored. Shapefiles can only be drawn in 2D mode.

4.4.1 Drawing Shapefiles

Create Point Shapefile

Click  or use ***Input → Point → Draw New Release Point(s)***, move the cursor to the desired position and click with the left mouse button to create as many points as you want. Finish the process with the right mouse button and enter a name for your point shapefile.

Alternatively, you can create a point shapefile by entering its X/Y coordinates. Go to ***Input → Point→ Enter Point Coordinates (X/Y)*** and enter the coordinates with a space delimiter in the reference system of the DEM. Click **OK** and optionally define additional points for the same shapefile.

Create Line Shapefile

Draw a new line shapefile by clicking  or use ***Input → Line/Area → Draw New Release Line(s)***. Draw the line by clicking points with your left mouse button. If you want to delete the last drawn point of the line, click the middle mouse button. Finish the line by a click on your right mouse button. You can then optionally choose to define additional lines within the same shapefile. Enter a name for the line shapefile.

Create Polygon Shapefile

Draw a new polygon shapefile by clicking  or use ***Input → Line/Area → Draw New Polygon Shapefile***. Draw the polygon in clockwise direction with left mouse clicks. If you want to delete the last drawn point of the polygon, click the middle mouse button. Finish and automatically close the polygon with a right-click. You can then optionally choose to define additional polygons within the same shapefile. It is possible to define holes within polygons. For this, draw the outer polygon in clockwise direction, then in the dialog **Add more polygon areas?** Click **Yes** and draw the hole with left mouse clicks in **counter-clockwise** direction. Confirm with a right mouse click and confirm that the polygon is a hole. Enter a name for the release shapefile.

4.4.2 Import Shapefiles

If you would like to import shapefiles from other projects or from GIS, there are two options.

1. To import a **single** shapefile, click in the left toolbar or choose ***GIS*** → ***Import Shapefile***, select the shapefile in the file browser and click **Open.** The selected shapefile is then added to the file tree in the right panel. Please make sure that the shapefile is in the same reference system as the DEM of the project.

2. Figure 4-31). Navigate to the desired directory, select it, and click **OK.** All shapefiles inside the selected folder are then added to the file tree in the right panel. Please make sure that the shapefiles are in the same reference system as the DEM of the project.

4.5 Assign Release Zones

A rockfall starting zone can be specified by setting a release point, drawing release line(s) (containing many release points) or defining release area(s) (polygon). The definition and localization of a rockfall starting zone has a strong impact on the results of RAMMS simulations. Therefore, we recommend using reference information such as photography, GPS measurements or field maps to define release points, release lines and release areas. This should be done by persons with experience concerning the topographic, geological, and meteorological situation of the investigation area.

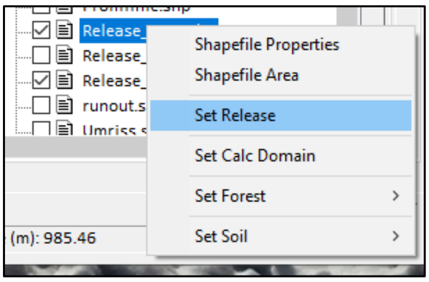


Figure 4-32: Setting a shapefile as a release.

To flag a shapefile as a release shapefile, right-click the specific shapefile (point, line or polygon) in the file tree and select **Set Release** (or select the *Release On-Off* tool in the top toolbar and click into a polygon).

You can flag as many shapefiles as you want as release zones simultaneously. Release shapefiles are always marked with a ***blue color.*** Depending on the shapefile type, you need to enter additional information, see below. To visualize randomly distributed release points in release polygons, it makes sense to zoom closely to your release polygon.

4.5.1 Release Point

You do not need to provide more information. A dialog opens that shows the number of points within the shapefile. Click **OK** to confirm. See Exercise 4.4a below for more details.

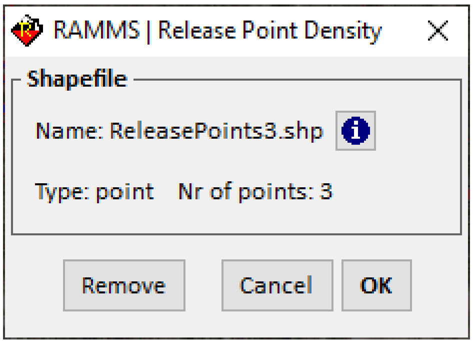


Figure 4-33: Release Point – Set Release

4.5.2 Release Line

Enter the amount of release points that will be evenly distributed along the defined line (don’t forget to hit **ENTER**!!) and click **OK**. See Exercise 4.4b below for more details.

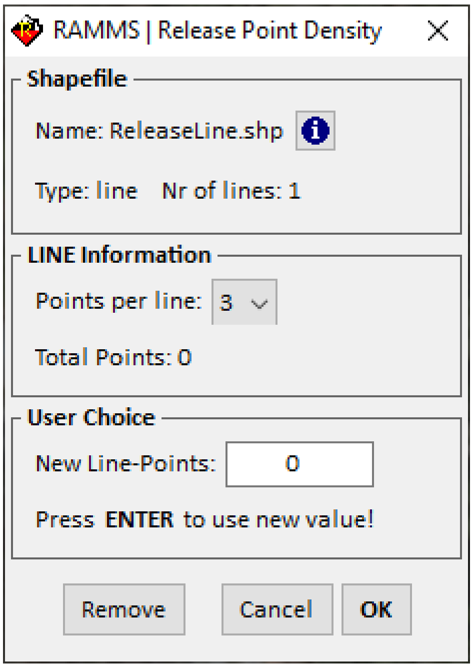


Figure 4-34: Release Line - Set Release

4.5.3 Release Area

A dialog opens, where a ***Release Point Density*** needs to be defined.

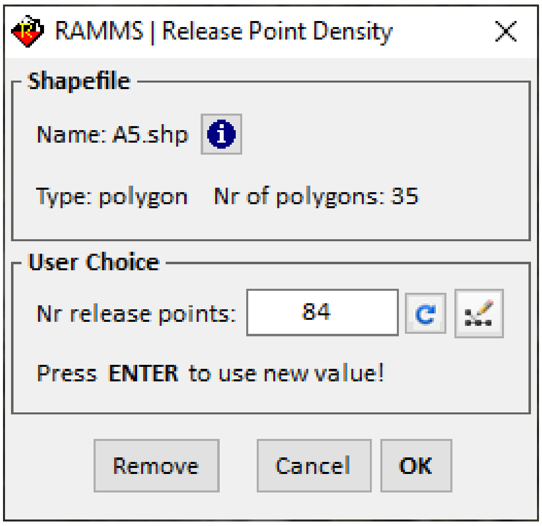


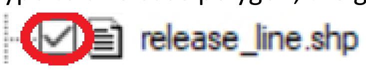
Figure 4-35: Release Point Density Dialog for Polygon Shapefiles.

Enter the amount of release points that will be randomly distributed within all the polygons of your release shapefile (or only in one selected polygon, depending on how you selected this dialog; either by right-clicking on a shapefile in the file tree, or by using the Release On/Off button in the horizontal toolbar, and selecting one of the polygons). Don't forget to hit **ENTER** after you entered the number of release points.

4.5.4 Delete Release Zones

To delete release zones, there are two different ways:

- Deactivate the shapefile by removing the checkmark left of it in the file tree. Be aware that this deactivates all properties of the shapefile. Meaning, if you have also assigned a ground type to a release polygon, the ground type information will be ignored as well.



- Right-click on the shapefile in the file tree, select **Set Release** and then click on **Remove** (see Figure above).

Exercise 4.4a: How to define a release point

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once.
- Click to start drawing a point shapefile.

- Left-click into the project where you want to define your rockfall release point. You can draw as many points as you want. If you would like to delete the last point, click the *middle* mouse button.
- Finish by clicking with the right mouse button and enter a name for the shapefile. You will see red plus signs at the location of your release points.

Figure 4-36: Defining 4 release points.

- Color, thickness and point symbol of your release points can be changed by right-clicking the shapefile in the file tree and selecting **Shapefile Properties**.

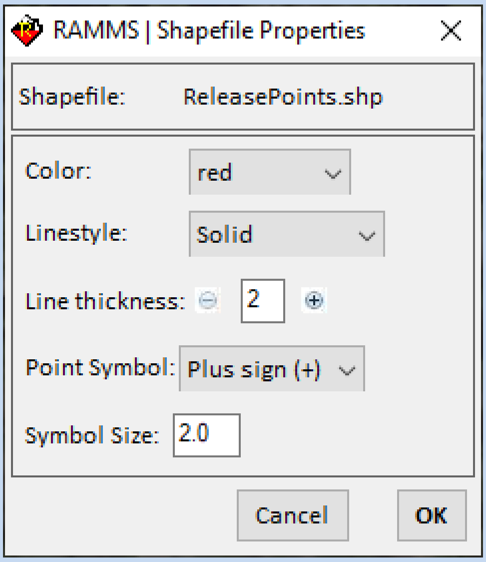
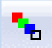


Figure 4-37: Shapefile Properties of release points

- To flag the release point shapefile as a release file, right-click the shapefile in the file tree and select **Set as Release** and then **OK.**
- The point(s) should then change the color from red to blue.

Exercise 4.4b: How to create a new release line

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once.
- Click  to start drawing a new line shapefile.
- Click into the project where you want to start drawing the outline of the release line.
- Continue drawing the release line by moving the cursor and clicking *the left mouse button.* If you would like to delete one step of the drawing, click the *middle* mouse button.
- Finish by clicking the ***right*** mouse button***.*** Optionally draw additional release lines in the same shapefile. Enter a name for the shapefile after drawing the last line.

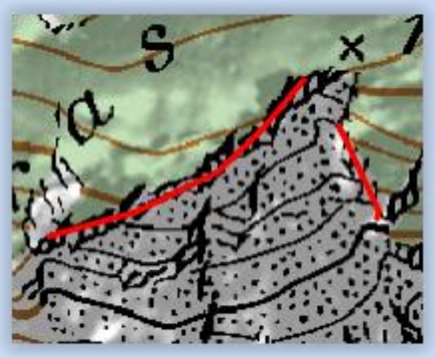


Figure 4-38: Project with emerging release lines.

- Right-click the shapefile in the file tree and select **Set as Release.**
- Enter the amount of release points that will be evenly distributed along the defined line(s) and click OK. The line should then turn from red to blue.

Exercise 4.4c: How to create a new release polygon

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once.
- Click  to start drawing a new polygon shapefile.
- Click into the project where you want to start drawing the outline of the release polygon.
- Continue drawing the release polygon by moving the cursor and clicking *the left mouse button.* If you would like to delete one step of the drawing, click the *middle mouse button*.
- To end the release polygon, click the ***right mouse button.*** Optionally, draw additional release polygons in the same shapefile. Enter a name for the shapefile after drawing the last polygon.

Figure 4-39: Example of release polygon area.

- Right-click the shapefile in the file tree and select **Set as Release.**
- Enter the amount of release points that will be randomly distributed within the defined polygon and click OK. The polygon should then turn from red to blue.

Exercise 4.4d: How to load an existing release point/line/area

- Import a **single** shapefile by clicking [icon] in the left toolbar or import a folder with **multiple** shapefiles by clicking [icon] above the file tree.
- Uncheck all checked (and visualized) shapefiles by clicking the *Uncheck All* button [icon].

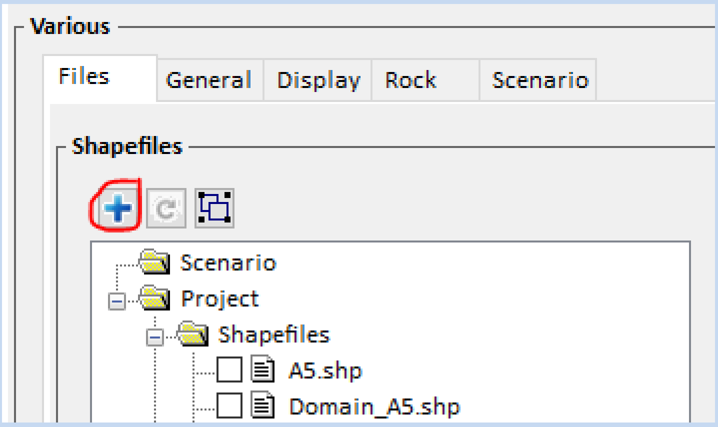


Figure 4-40: Import all shapefiles from a folder

- Right-click on the imported shapefiles in the file tree and select **Set Release**
- Depending on the shapefile type, define the amount of release points along a line shapefile or the release point density within a polygon shapefile.

4.6 Assign Ground Categories

If you want to use more than just one global soil/ground category, you must define polygon areas and assign soil types to them. You can either draw new polygon shapefiles directly in RAMMS (see section 0) or import already existing shapefiles from previous projects or from GIS (see section 4.4.2). Choose appropriate filenames for the different shapefiles while generating them so there is no confusion which shapefile belongs to which terrain type. To assign a soil category to a polygon shapefile you can either:

- 1) Select the **Edit Soil Parameters tool** in the top toolbar and click into the polygon. With this tool, you can assign different ground categories to polygons of the same shapefile. Only the selected polygon will be assigned to the ground category.
- 2) Right-click on the shapefile in the file tree in the right panel and select **Set Soil.** If a shapefile consists of several polygons, all polygons will be assigned to the chosen soil type.

This shows a list where you can either choose a default soil type or enter custom values for M_E and C_d by choosing **Edit Soil.**

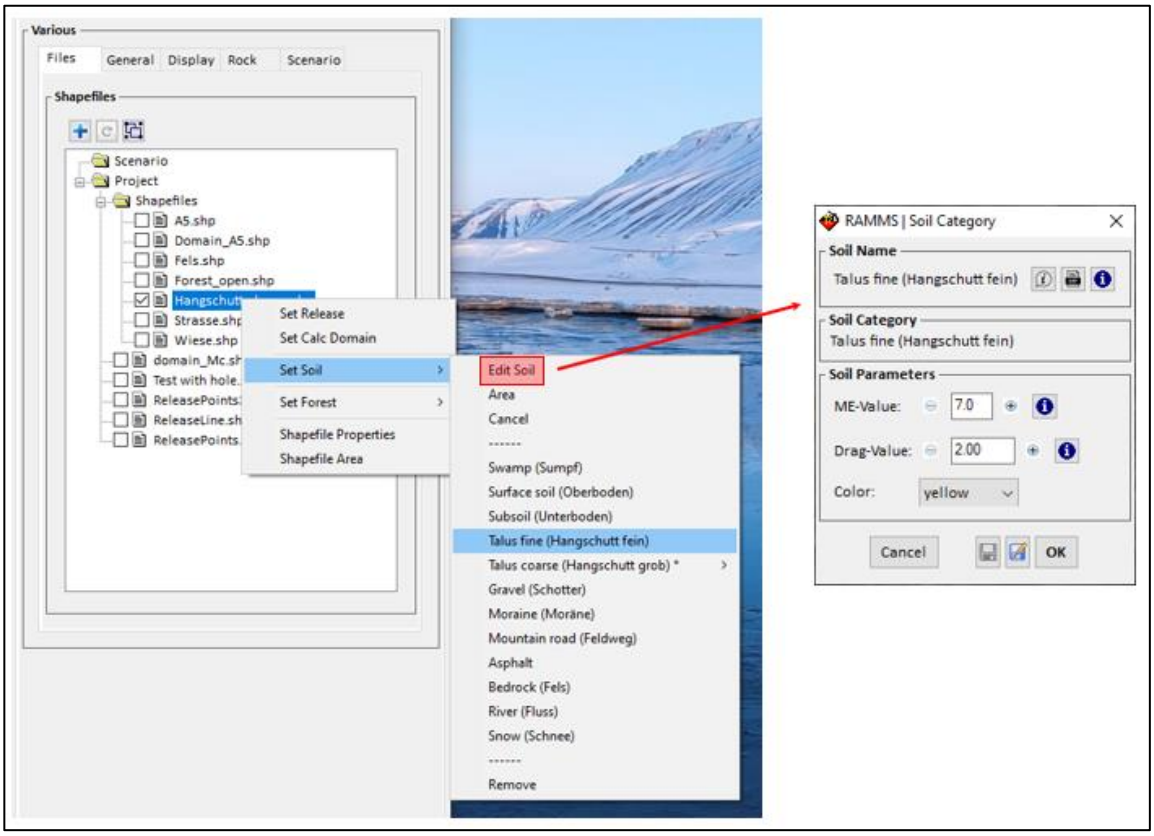


Figure 4-41: Assigning a soil type to a polygon shapefile from the file tree (left) and dialog to enter custom values for ME and Cd (right).

Each soil/ground category defines the parameters of the soil compressibility as well as a ground-drag value. The ground-drag value accounts for the viscoplastic drag due to terrain deformation during ground-contact and -scarring. The two input parameters are explained in more detail in chapters 3.8.1 and 3.8.2. The default ground parameters provided by RAMMS are described in Table 3.3. Please use these parameters with the awareness that they are currently based on case studies and real-scale experiments. It remains an ongoing research task to reassure these parameters rigorously.

The soil compressibility and drag coefficients should be defined for every terrain material shapefile. The list below gives an overview on some possible terrain materials. You can choose between the categories: Swamp, Surface Soil, Subsoil, Talus fine, Talus coarse, Gravel, Moraine, Mountain Road, Asphalt, Bedrock, River and Snow. The used values have a large impact on the simulation results and therefore it is important to critically think about the chosen parameters. Please also consider chapter 3.8.4 to check for plausibility of results and how to adjust ground parameters accordingly.

Exercise 4.5a shows how to define these terrain material parameters.

ASCII-raster-files will be created for both terrain parameters M_E and C_d, if specific ground parameters are assigned to shapefiles. If only the overall soil/ground material is specified, no ASCII-files will be created and used.

Exercise 4.5a: How to create a shapefile with specific terrain characterization

- Switch to 2D mode by clicking .
- Activate the project by clicking on the map once.
- Click *Draw New Polygon Shapefile* .
- Click into the project where you want to start drawing the outline of the shapefile.
- Continue drawing the shapefile in clockwise direction by moving the cursor and clicking the ***left mouse button***. Finish the polygon by clicking the ***right mouse button***. The polygon will be closed automatically.

Figure 4-42: Project with emerging polygon shapefile.

Before the polygon shapefile is created, you must answer the following questions:

- **Add more polygons?**
  You can either answer with ***Yes*** and create a second polygon as explained above or answer with ***No*** and continue with the next step.
- **Is this polygon a hole?**
  This dialog appears if you have drawn the polygon in counterclockwise direction. If this is a mistake and you want it to be an ordinary polygon, click **No** and the drawing direction is

inverted. If you want to cut a hole into a polygon, first draw the outer polygon in clockwise direction, then select **Yes** when asked **Add more polygons?**, draw the hole in counterclockwise direction and select **Yes** when asked **Is this polygon a hole?**

- **Choose a new polygon file name:**
  Enter a new name according to the terrain material represented by the polygon(s) (e.g. bedrock). The ending *.shp is added automatically. The polygon shapefile will now be created and added to the project directly.
- Alternatively, you can draw the polygon shapefiles in a GIS software and load them directly with ***GIS*** -> ***Import Shapefile*** or by clicking
- Assign a soil category to a specific shapefile by right clicking on its name in the file tree and choosing ***Set Soil*** followed by choosing either a default soil type or ***Edit Soil,*** where custom combinations of M_E and C_d can be entered. This soil category will be applied to all polygons of the shapefile. If you want to choose individual soil categories for the polygons in the shapefile, use the **pencil tool** in the top toolbar and click into the specific polygons.

4.6.1 Creating Custom Soil Types

After choosing a soil type, users can change ME-, Cd-values and colors (with **Edit Soil**) and then save the changes as a new custom soil, within the original soil category.

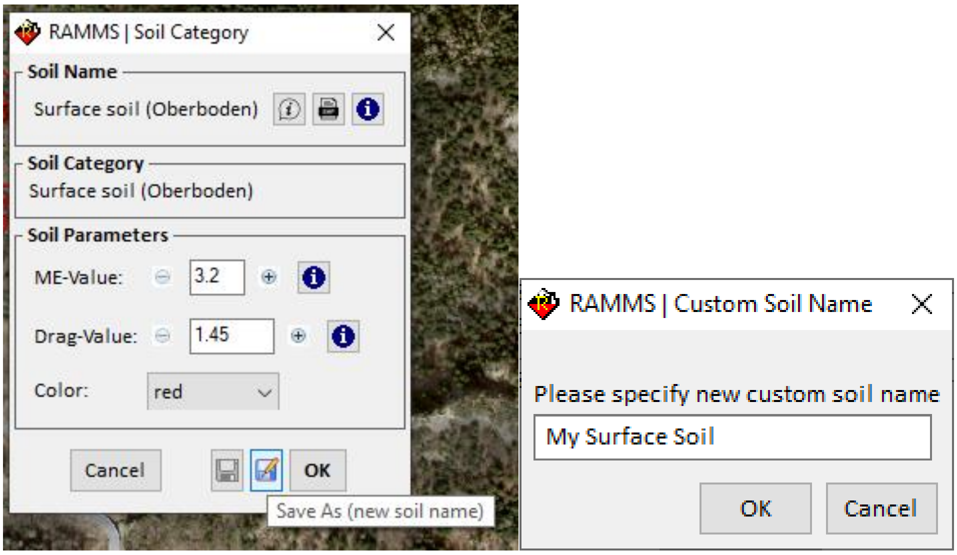


Figure 4-43: Save new custom soil type

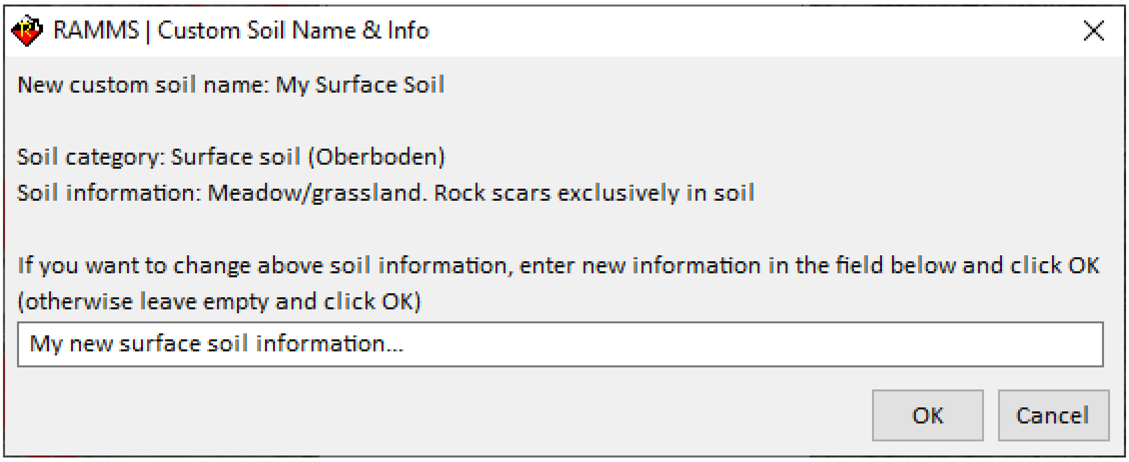


Figure 4-44: Updating custom soil information

Your custom soil types are then saved as a xml-file in your userprofile-directory. If you want to delete a custom soil type, choose *'Input → Soil/Forest Parameters... → Edit my Custom Soil Types'* .

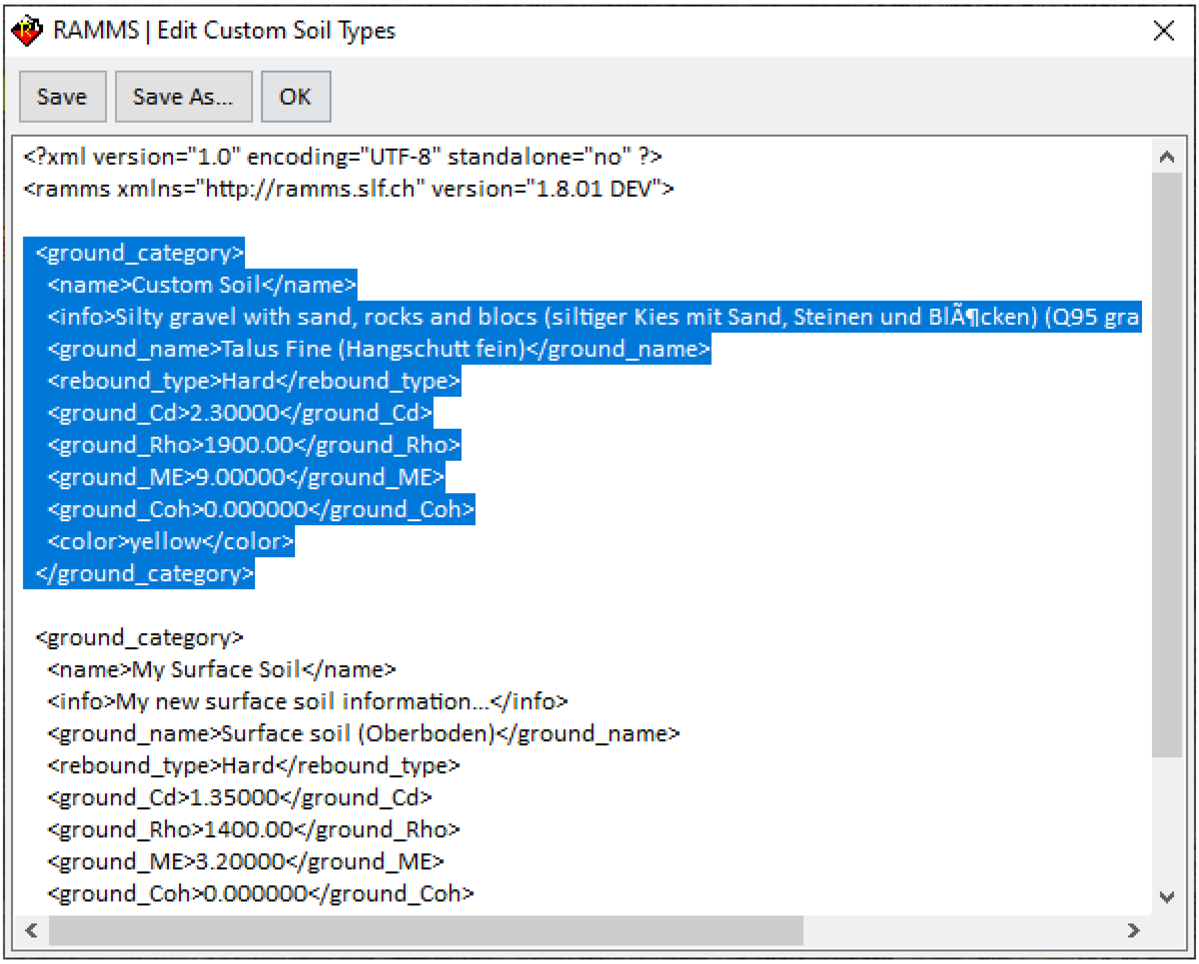


Figure 4-45: Delete custom soil types by removing one or all <ground_category> blocks as highlighted above. Click **Save** and **OK**.

4.7 Forested area

Forest has a major impact on runout and velocities of rockfalls. To include forested areas into a RAMMS simulation you need to specify the areas as polygon shapefiles as described in Exercise 4.5a. Create a polygon shapefile (see chapter 0) or import it from other projects or from GIS (see chapter 4.4.2). Choose appropriate filenames for the different shapefiles while generating them so there is no confusion which shapefile belongs to which terrain type or forest. To assign a forest to a polygon shapefile you can either:

- Select the **edit forest parameters tool** in the top toolbar and click into a polygon. With this tool, you can assign different forest parameters to polygons of the same shapefile. Only the selected polygon will be assigned to the forest parameters.
- Right-click on the shapefile in the file tree in the right panel and select **Set Forest.** If a shapefile consists of several polygons, all polygons will be assigned to the chosen forest type.

This shows a list where you can either choose a default forest type or enter custom tree densities and BHD distributions by choosing **Edit Forest.**

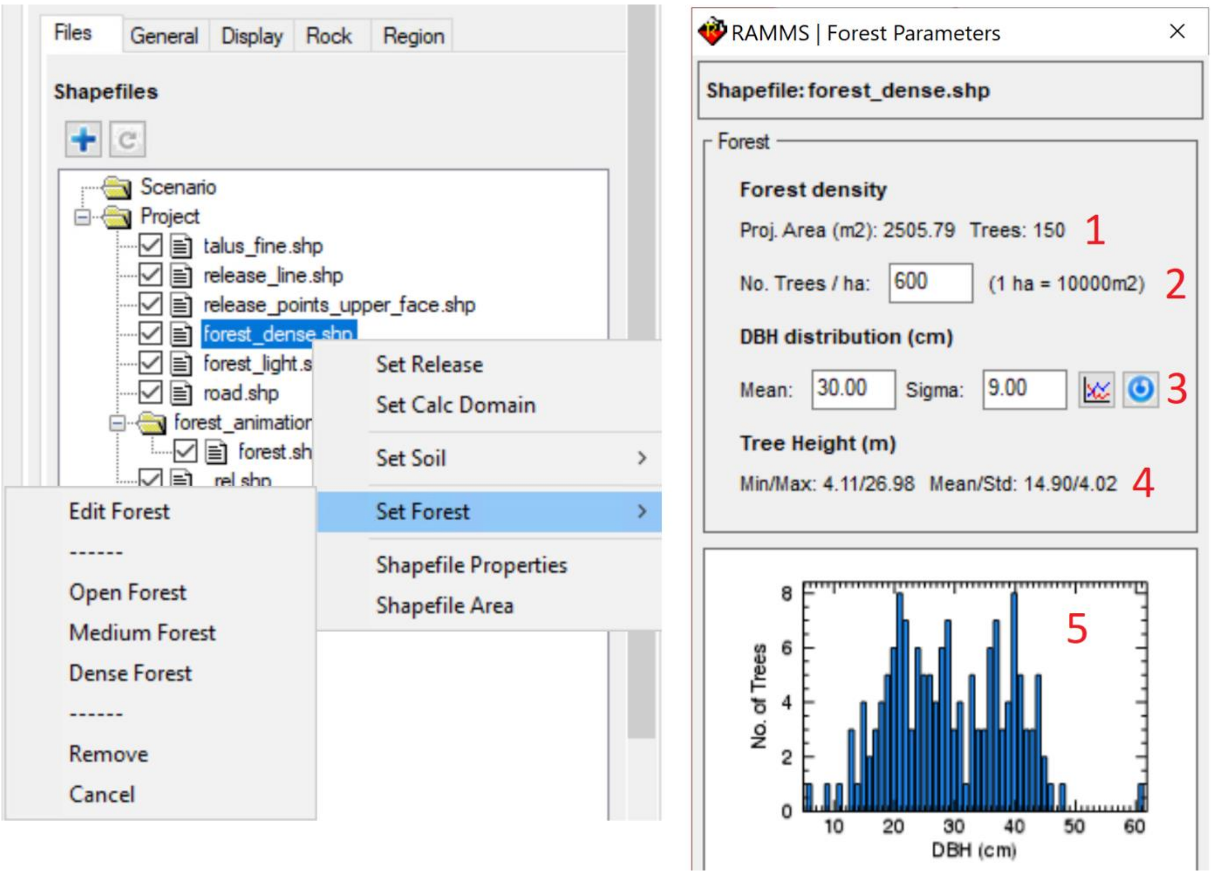


Figure 4-46: Assigning a forest type to a polygon shapefile from the file tree (left) and dialog to enter custom forest densities and DBH distributions (right).

The **Forest Parameters** dialog (see Figure 4-46) shows:

1. The area of the selected polygon and the number of generated trees according to the entered tree density (2).
2. The tree density [trees/ha]
3. Mean diameter at breast height (DBH) and standard derivation for the Gaussian distribution. If one of the parameters is changed, a new distribution is generated automatically and shown in (5). Click to generate a new random distribution without changing any parameters.
4. Statistical values of the calculated tree heights based on the generated DBHs. The tree height of a generated tree is (see chapter 0):

$$H_{Tree}\,[m] = DBH\,[cm]^{0.8}$$

5. Histogram of the DBH of the generated trees based on the parameters defined in (3).

RAMMS::ROCKFALL will generate the forest according to the defined tree density and DBH distribution. Detailed information about forest modelling can be found in Chapter 0. Note that creating a forest does not influence the soil properties within the shapefile. This means that if you do not specifically assign a terrain material to a forest shapefile (see section **Error! Reference source not found.**), the g lobal soil property is taken.

Forests can be visualized in two ways. In the default visualization, the forest polygons are filled with a dotted pattern. The density of the pattern indicates the density of the forest. If you want to visualize the single trees, choose in the top navigation bar **Show -> Show Trees.** Be aware that this may take some time, depending on the number of trees that need to be visualized.

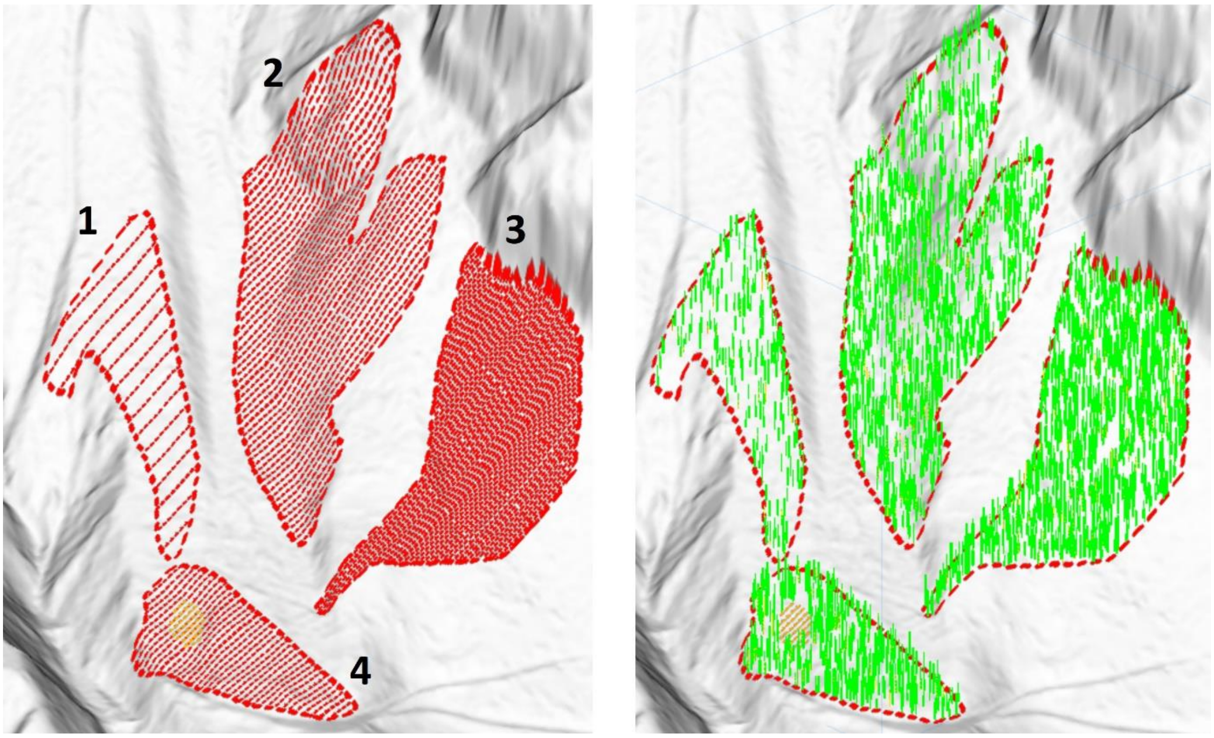


Figure 4-47: Default forest visualisation (left) and visualisation with single trees (right). The forest types in this example are (1) Open forest, (2) Medium forest, (3) Dense forest and (4) Medium forest with a clearing/hole shown with yellow dotted pattern.

Exercise 4.6b: How to create a forested area

- Switch to 2D mode by clicking .
- Activate the project by clicking on the map once.
- Click *Draw New Polygon Shapefile* .
- Click into the project where you want to start drawing the outline of the shapefile.
- Continue drawing the shapefile in clockwise direction by moving the cursor and clicking the ***left mouse button***. Finish the polygon by clicking the ***right mouse button***. The polygon will be closed automatically.

Figure 4-48: Project with emerging polygon shapefile (left, middle) and assigned dense forest (right).

Before the polygon shapefile is created, you must answer the following questions:

- **Add more polygons?**
  You can either answer with ***Yes*** and create a second polygon as explained above or answer with ***No*** and continue with the next step.
- **Is this polygon a hole?**
  This dialog appears if you have drawn the polygon in counterclockwise direction. If this is a mistake and you want it to be an ordinary polygon, click **No** and the drawing direction is inverted. If you want to cut a hole into a polygon, first draw the outer polygon in clockwise direction, then select **Yes** when asked **Add more polygons?**, draw the hole in counterclockwise direction and select **Yes** when asked **Is this polygon a hole?**
- **Choose a new polygon file name:**
  Enter a new name according to the forest represented by the polygon(s) (e.g. dense forest). The ending *.shp is added automatically. The polygon shapefile will now be created and added to the project directly.
- Alternatively, you can draw the polygon shapefiles in a GIS software and load them directly with ***GIS*** -> ***Import Shapefile*** or by clicking 
- Assign a forest category to a specific shapefile by right clicking on its name in the file tree and choosing ***Set Forest*** followed by choosing either a default forest type or ***Edit Forest,*** where custom tree densities and BHD distributions can be entered. The trees will be

generated for all polygons of the shapefile. If you want to choose individual forest properties for the polygons in the shapefile, use the **pencil tool** in the top toolbar and click into the specific polygons. Choose a default forest type or enter custom forest parameters (see section 4.7 above).

- Optionally you can assign a **soil type** to the newly generated forest according to **Exercise 4.5**a. If no soil type is defined, the global soil properties are taken.

4.8 Rock builder

RAMMS offers the *Rock Builder* to create realistic point cloud files from predefined rock shapes. We strongly recommend using the *Rock Builder* instead of using spheres or cuboids for rockfall simulations as the rock shape has major impact on the output of the rockfall simulations with RAMMS. There are already several realistic rock shapes included in the library. Exercise 4.7 demonstrates how to create a realistic rock shape with the Rock Builder tool. The rock mass and volume for realistic rocks have to be defined in the *Rock Builder* and have to be saved in the rock .pts file. You cannot change the rock volume or mass afterwards.

Exercise 4.7: How to create a rock with the Rock Builder

- Click to open the ***Rock Builder***.

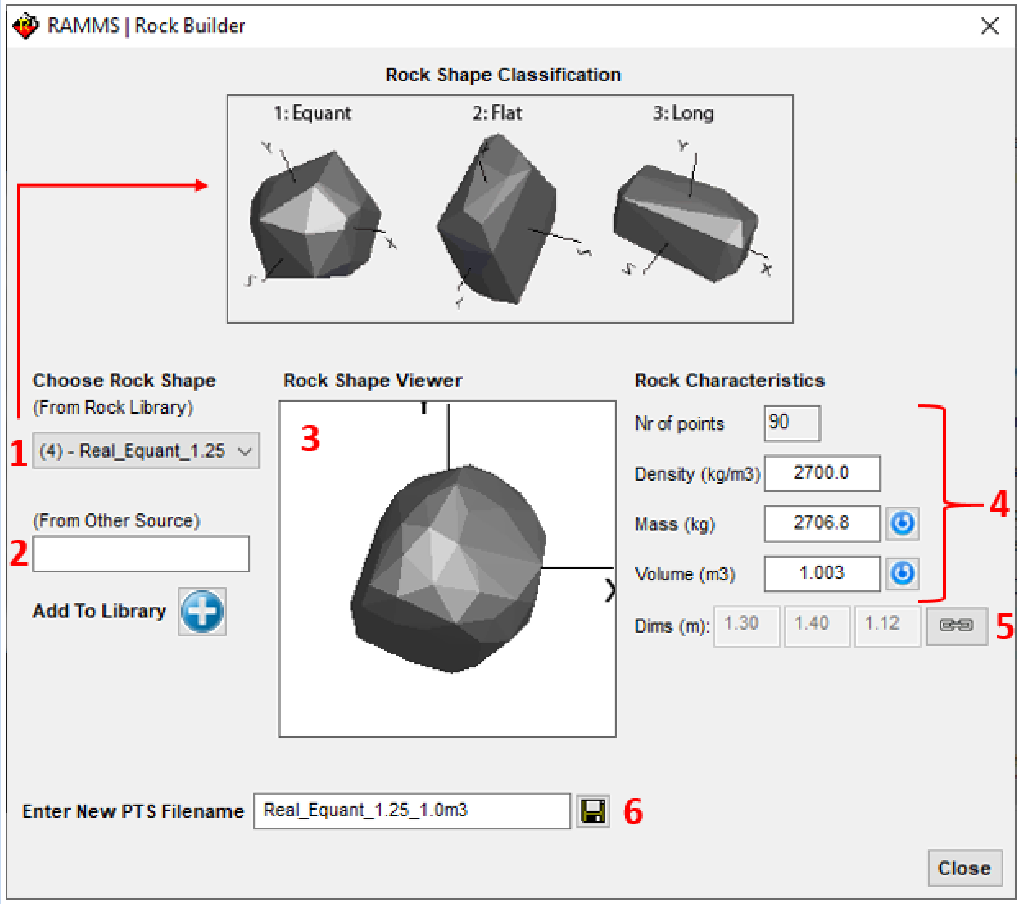


Figure 4-49: Rock Builder

- Select a predefined rock shape from the rock library (1) or select a .pts-file of a rock shape from another source (2). You can then add this rock to your rock-library by clicking **Add To Library**. This rock-library is then saved in your Windows-Userprofile.

- By pressing the left mouse button and moving the mouse you can move the 3D visualization of the rock interactively and look at it from any direction (3).

- The rock has predefined initial rock characteristics (4).
  When changing the rock density, the *Rock Builder* automatically calculates the new mass of the rock. After changing the mass of the rock, click to adjust the volume and the dimensions (X/Y/Z) of the rock. Enter a new rock volume and click to adjust the rock mass as well as the rock dimensions (X/Y/Z). Be aware that the *.pts file format only saves the rock vertices. Mass and density information are therefore not saved after constructing the rock with the rock builder. The density and mass fields are therefore only a help to calculate the preferred volume of the rock. If you want to use a different density than the default for your simulation, you must adjust it in the “Run Simulation” dialog (see Figure 4-71)

- Change axes of rock (5)
  Click on the button next to the rock dimensions (unlock aspect). Now you can change the

rock's axes. Press ENTER after changing an axis, such that the view of the rock is updated, and volume and mass are calculated accordingly.

- Enter a file name or use the suggested name and click  to save the new .pts-file (6). RAMMS automatically creates a ***rocks*** folder in your project directory. It's strongly recommended to save your new rocks in this directory.

- Click ***Close*** to close the *Rock Builder* window.

Once a rockfall simulation has been finished and opened in RAMMS, you can find additional information on the rock for every trajectory in the *ROCKFALL* panel, tab *Rock*, see Figure 4-50. Use the left mouse to move the visualization rock in any direction.

Please consider that you must be in the trajectory mode and activate a specific trajectory to get information about the rock.

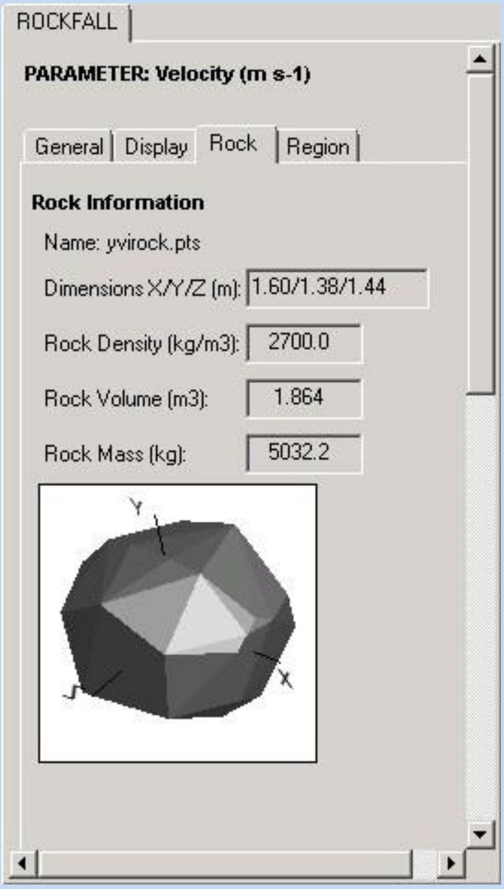


Figure 4-50: Rock Information

Edit custom rock library

For now, you can edit your custom rock library manually by using this feature:

Extras → Edit my Rock Library

Your rock library (xml-file) will then be shown in a text editor, see Figure below. You can remove <rock>-sections, **save** it, click **OK** and then restart RAMMS, for changes to take effect. Please make sure that you do not delete </ramms> at the end of the document, or any other line (otherwise the xml-file will be corrupted).

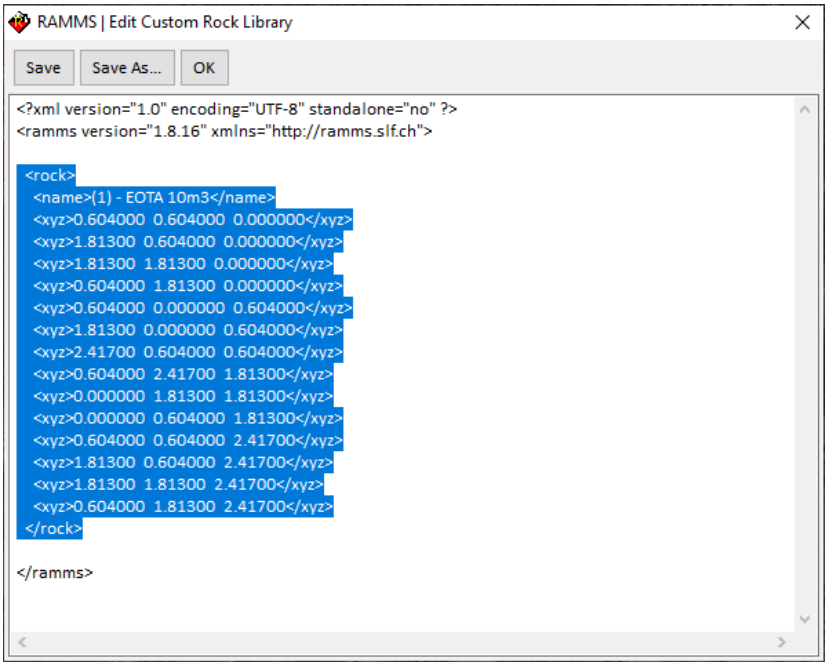


Figure 4-51: Edit your custom rock library. Remove <rock>-sections if needed, as highlighted above.

4.9 Barrier objects (nets)

Figure 4-52: Example of rockfall net

RAMMS models nets as “thin wall” objects (see Figure above), as rigid obstacles. These “thin wall” objects are modeled as convex hulls (point clouds). A separate barrier object is created for each net field, from support post to support post, see Figure below.

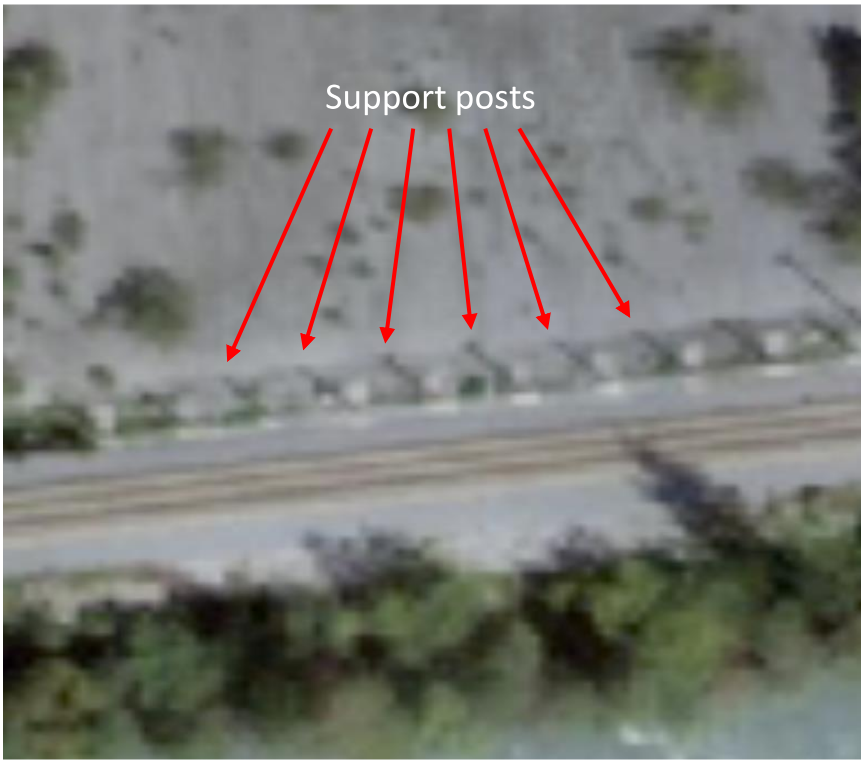


Figure 4-53: Rockfall net support posts

The angle (α) between the support and the terrain can be defined according to this sketch from Geobrugg.

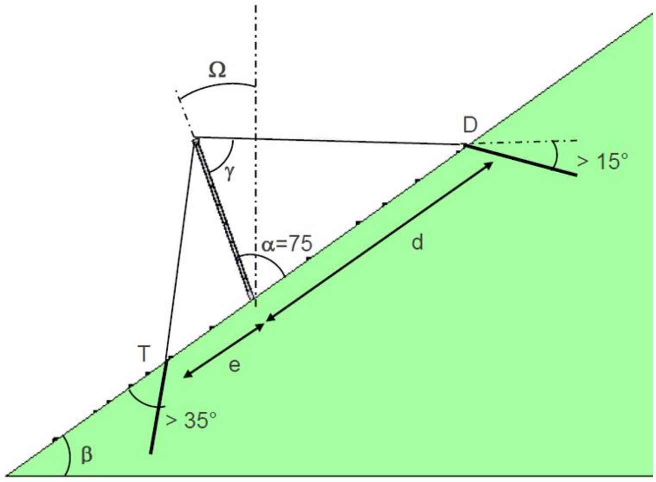


Figure 4-54: The default angle between the terrain and the post is 75° (sketch provided by Geobrugg).

Energy Absorption Capacity

For each line shapefile (and its corresponding net objects), an energy absorption capacity can be specified (in kJ), see Figure below:

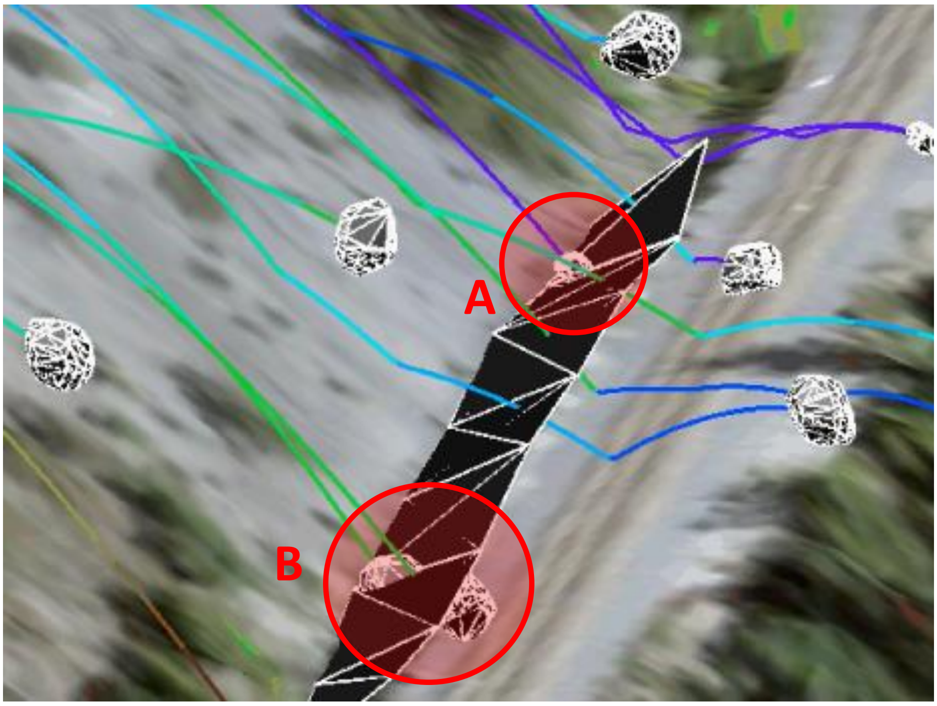


Figure 4-55: Rockfall nets with an energy absorption capacity of 1'000 kJ. Small rocks are stopped (**A**), but larger ones pass through (**B**).

If the kinetic energy of the rock is lower than this limit, the rock is stopped (**A**). If this limit value is exceeded by the rock, the net has no influence on the rock's trajectory, and the rock passes through the net (**B**).

There are two possibilities to create new barrier (net) objects:

a) Draw a new line shapefile in RAMMS, and subsequently create net objects from there, or
b) Use “Input → Barriers… → Create Barriers from Line-Shapefiles” to create net objects from already existing line-shapefiles.

Create new net object: Step-by-step

- (Option a): Draw a new line shapefile at the location of barriers (net) directly in RAMMS. While drawing the line shapefile, RAMMS indicates the distance from the mouse position to the selected support post, see Figure below.

Figure 4-56: Distance measure between support posts.

- (Option a): RAMMS will then ask you if a barrier object should be created from this line shapefile.

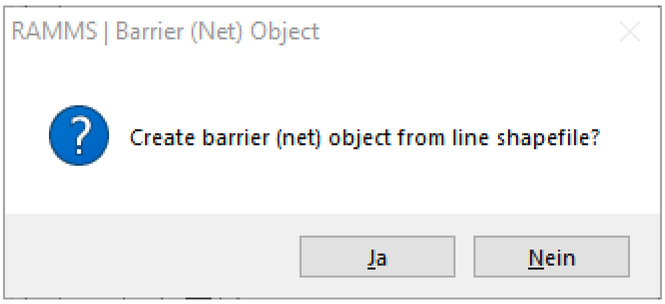


Figure 4-57: Create barrier net object from line-shapefile.

- Click **Yes**, and then enter barrier height (m), the angle between terrain and post (°) and the energy absorption capacity (in kJ), see Figure below.

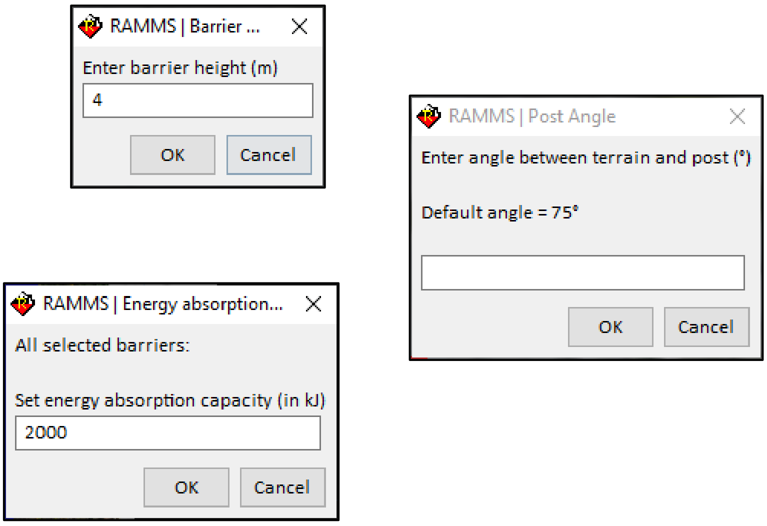


Figure 4-58: Enter barrier height, angle and energy absorption capacity.

- For every net field (from support post to support post), RAMMS creates a single convex hull (point cloud) object. The filename from the line-shapefile is used, added by an ID-number, and the file extension .pts .
- The net objects are then visualized in RAMMS, see Figure below. Visualized net objects are always considered in a new simulation.

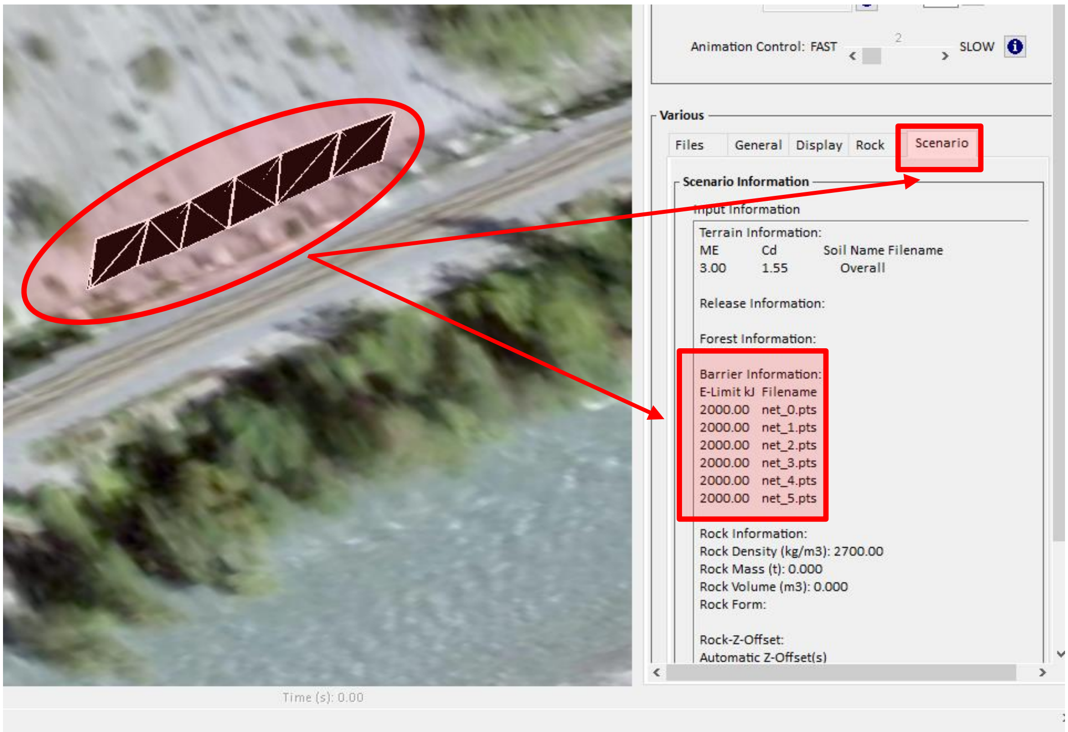


Figure 4-59: Net objects visualized in RAMMS.

- If you do not want to use net objects for a simulation, remove all barrier objects with «Input → Remove Barriers/Dams».

- Net objects (*.pts) can be added later to a project by using "Input → Barriers… → Add Barriers". You can then specify an energy absorption capacity to the net object(s). Select multiple pts-files (by holding the Shift-Key) to assign the same energy absorption capacity to multiple nets.

4.10 Dam/Gallery objects

Dams and galleries are rigid, artificial obstacles and modelled as convex hulls (point clouds). The maximum kinetic energy that an obstacle can absorb when a rock impacts, is limited by an upper energy limit (energy absorption capacity in kJ). For simplicity, it is assumed that an obstacle whose limit value is exceeded by a rock cannot have any influence on it. This means that collisions with these obstacles are registered during the simulation, but they have no influence on the rock's trajectory.

To create both dam and gallery objects in RAMMS, you need polygon-shapefiles. Use existing polygon-shapefiles (e.g., from GIS), or create them directly in RAMMS ("Input → Line / Area… → Draw New Polygon Shapefile"). On the other hand, you can also create a point-cloud file for a dam object, and use it directly in RAMMS, see section below.

4.10.1 Dam objects

For a dam object, two polygon-shapefiles are needed. One for the dam foot, and one for the dam crest, see Figure below:

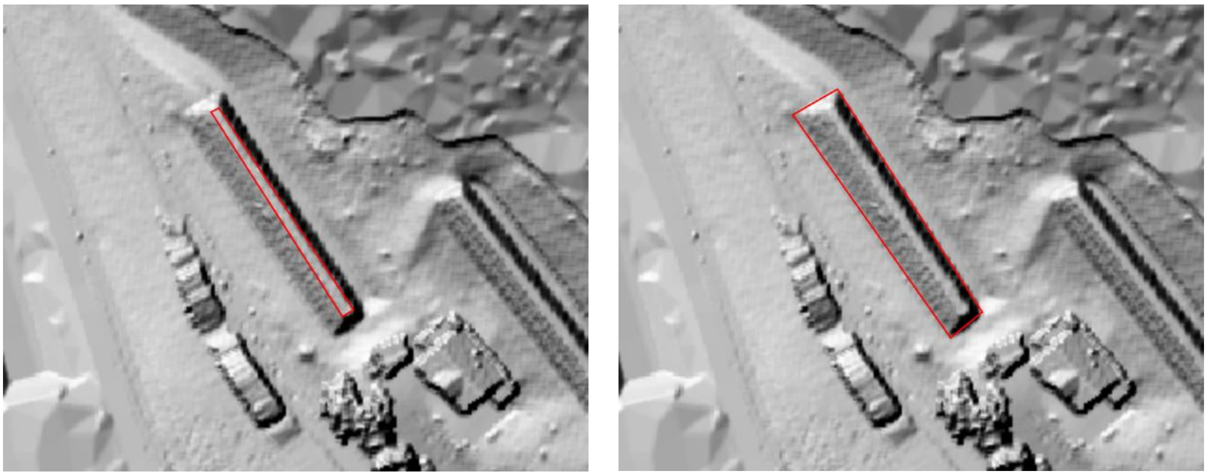


Figure 4-60: **Dam crest** polygon-shapefile (left), and **dam foot** polygon-shapefile (right)

There are two possibilities to create a new dam object:

a) "Input → Dams… → Create Dam from Shapefiles (Elevation)", where you specify the horizontal elevation (in m a.s.l.) of the dam crest, or
b) "Input → Dams… → Create Dam from Shapefiles (Relative Height)", where you specify the constant difference in height (in meters) between dam foot and dam crest.

Create new dam object: Step-by-step

- Use option a) or b) from above. Then select dam foot polygon-shapefile, and afterwards the dam crest polygon-shapefile.

- Then enter dam crest elevation, or relative height, see Figure below:

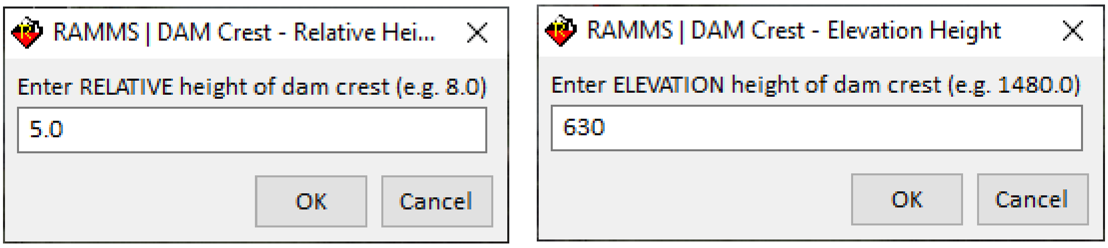


Figure 4-61: Enter dam crest elevation or relative height.

In the next steps, a dam name as well as energy absorption capacity (in kJ) and a cd-value (drag, energy dissipation) for the dam obstacle must be specified:

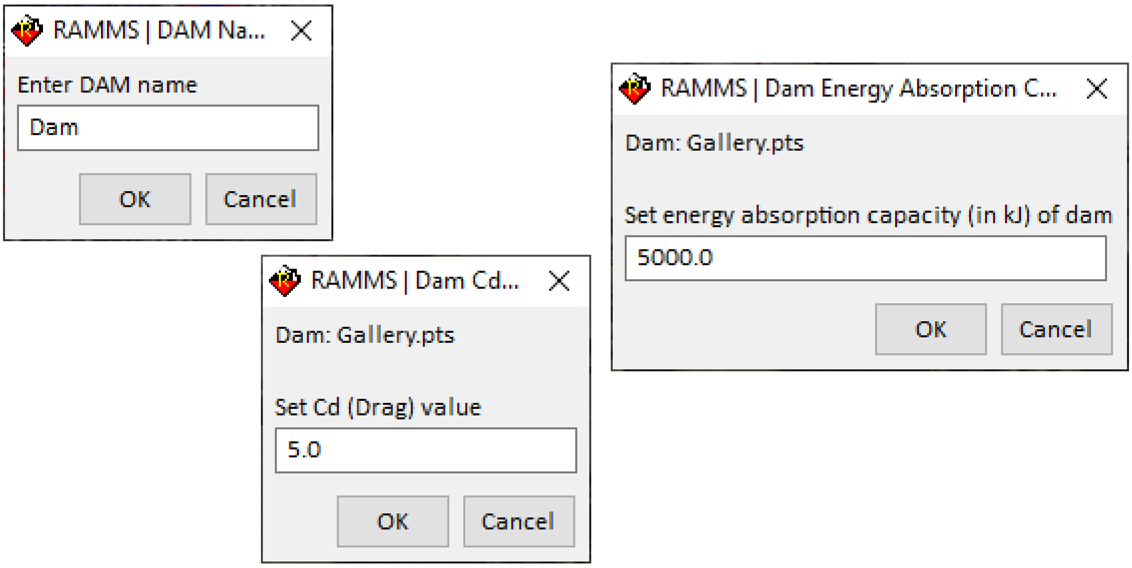


Figure 4-62: Dam name, energy absorption capacity and cd-value.

RAMMS then creates the convex hull (point cloud) dam object file, with the name specified above, and the file extension .pts.

Figure 4-63: Dam-visualization in RAMMS - Dam.pts

4.10.1 Gallery objects

Gallery objects are treated in the same way as dams or nets, as convex hull (point cloud) rigid obstacles.

The procedure to create gallery objects in RAMMS is optimized for galleries with a horizontal gallery top surface. On the other hand, you can also create a point-cloud file for a gallery object outside of RAMMS, and use it directly in RAMMS, see section ***Format of point-cloud-object*** below.

Creating a (horizontal) gallery object in RAMMS

The following procedure describes, how to create a gallery object in RAMMS. Because the roof of the gallery must be **horizontal** (for now), it is best to look at the contour plot. You can then use the contour lines to draw the basic shapefile (at least for the line on the mountain side), as shown in the images below.

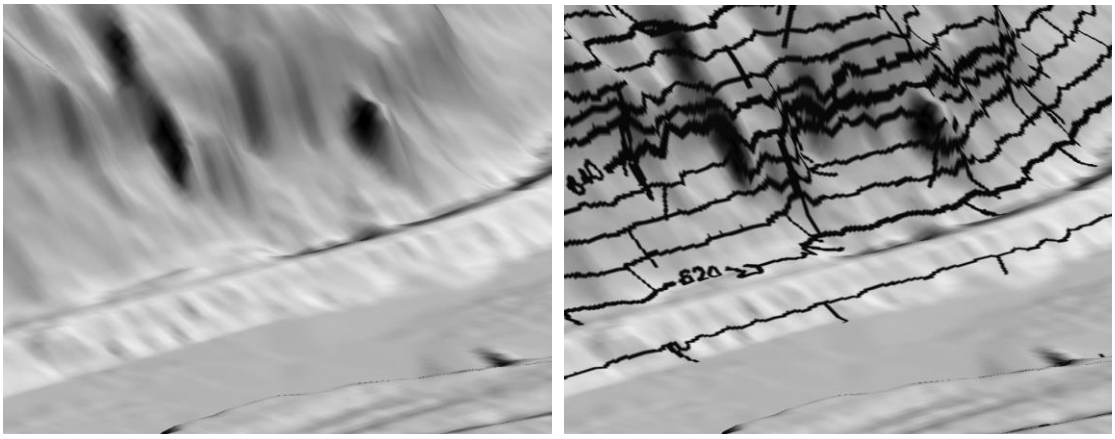


Figure 4-64: Planned gallery with (right) and without (left) contour lines.

Change into 2D-mode and draw the footprint of the planned gallery object (new polygon shapefile). Use the contour line of 625m for the boundary on the hill-side, see Figure 4-65 below.

Now use the feature "*Input → Dams… → Create Dam from Shapefiles (Elevation)*". Proceed as explained in the dam-chapter above and select **twice** your created footprint-shapefile for both foot- and crest-shapefile. When asked for the elevation, use your chosen hill-side elevation (625m in this example). Equally choose a gallery name, energy absorption capacity and a drag value (see dam chapter above). RAMMS::ROCKFALL will then create and display your gallery object, see Figure 4-65 below.

- Remember: Visualized objects are always considered in a new simulation.
- If you do not want to use objects for a simulation, remove all objects with «*Input → Remove Barriers/Dams*».
- Point-cloud objects (*.pts) can be added later to a project by using "Input → Dams… → Add Dams". You can then specify an energy absorption capacity as well as a cd-value for the object(s). Select multiple pts-files (by holding the Shift-Key) to assign the same energy absorption capacity and cd-value to multiple objects.

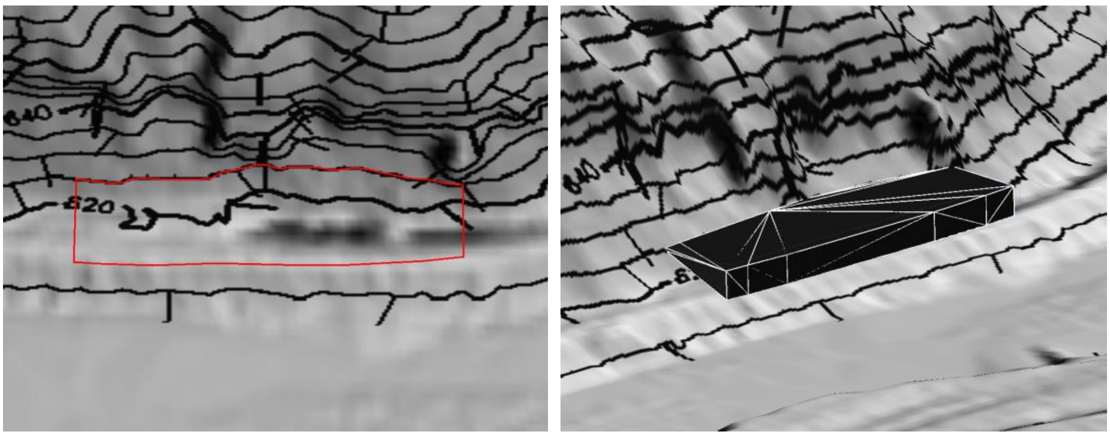


Figure 4-65: Footprint of planned gallery object (left) and gallery-point-cloud-object (right)

Format of point-cloud-object

An obstacle point-cloud object consists of two files:

- *<gallery_name>.pts*: Point-cloud coordinates (x, y, z), relative to the reference point. Any point of the point-cloud-points can be the reference point.
- *<gallery_name>.txt*: Coordinates of reference point (x, y, z), in cartesian coordinate system.

Gallery_625_0.pts

0.00000000	0.00000000	0.00000000
2.5088603	-0.25088345	-1.3889771
3.8887340	-0.50176686	0.47198486
5.8958223	-0.62721460	-1.2570190
7.2756960	-0.87809802	-1.2570190
9.4082268	-0.87809808	-1.1119995
10.913543	-0.75265643	-1.0570068

Gallery_625_0.txt

2744897.5	1185775.6	625.63800

Figure 4-66: Point-cloud file (.pts) and reference point file (.txt)

With this information, object point-cloud files can also be created outside of RAMMS.

Section 5.1.11 on page 121 explains how to analyze gallery impacts.

4.11 Running a simulation

To run a simulation, you must complete the steps described in the chapters above. If you wish to consider different terrain materials and surface covers the corresponding shapefiles must be created in advance as described in Exercise 4.5. Release lines and release shapefiles must be generated in advance too as shown in Exercise 4.5. Exercise 4.8: *How to run a simulation* leads you through the required steps to run a rockfall simulation.

The following tabs must be completed subsequently:

4.11.1 General

In this tab you specify the **name** of the output folder and the **dump step** (time interval between different dumps saved to disk).

4.11.2 Terrain

Here you specify the overall **terrain type** for all surfaces which are not assigned to a category with shapefiles (see section 4.6). Additionally, you can see a summary of the ground parameters of all shapefiles in your project. The available default terrain types are:

- Swamp
- Surface Soil
- Subsoil
- Talus Fine
- Talus Coarse
- Gravel
- Moraine
- Mountain Road
- Asphalt

- Bedrock
- River
- Snow

A detailed description of the terrain types is given in Table 3.3 and Table 3.5. Please make sure that the selected shapes are depicted in the list otherwise they will not be considered in the simulation.

4.11.3 Forest

This tab is purely informative. You can see a summary of all defined forest parameters (see section 4.7 on how to assign a forest) and the shapefiles these parameters are assigned to.

A detailed description of default forest types is given in Table 3.3. Please make sure that the selected shapes are depicted in the list otherwise they will not be considered in the simulation.

4.11.4 Release

Here you specify the **random start orientations** of the rocks and additional **initial conditions.**

To introduce variability into the rockfall simulation you must specify the number of **random initial orientations** of the rocks. This number multiplied with the number of release points and number of rock shapes. As an example: If you have a release polygon shapefile with a density of 20 release points, 3 additional release points from point shapefiles, 2 rock shapes and 30 random orientations, you will end up doing (20 + 3) * 2 * 30 = 1'380 Simulations (see Figure 4-74). This number is automatically updated and displayed in the *Run 'XXX' Simulations* button in the bottom right of the window.

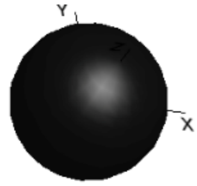
You can optionally set the rocks **initial velocities** and **initial rotation velocities** along all three axes (x, y, z).

To set the **rock offset** (initial fall height of the rocks measured from the center of mass) you have two options. RAMMS can automatically calculate the minimal offset that is necessary to start the rock (Automatic). Alternatively, you can set the rock offset manually. Be aware that this offset is measured from the center of mass of the rock, so it should be high enough such that the rock is not sticking in the terrain and cannot start.

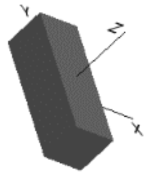
4.11.5 Rock

In the *Rock* tab you can choose between three different types of rocks:

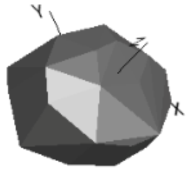
- Artificial **sphere** (defined by the radius)



- Artificial **cuboid** (defined by the x, y and z dimension)



- **Real rocks** (defined in the *Rock Builder*)



For real rocks, you can either directly launch the rock builder from this window or select a ROCK file (*.pts) that you previously created with the rock builder.

You can also choose a **folder** containing different rocks. You must fill the folder with rocks generated with the *Rock Builder* in advance (*.pts files). All rocks in the specified folder will be calculated.

We strongly suggest o use *Real Rocks*, and for sure no *Sphere* rocks.

4.11.6 Exercise how to run a simulation

Exercise 4.8: How to run a simulation

- To run a simulation choose ***Run*** → ***Run Rockfall Simulation***, hit the F8 button or click
- The **RAMMS|Run Simulation** window opens. Before clicking ***Run Simulation***, you should check the input parameters.

General Tab:

(1) Enter a specific output filename. This filename corresponds to the basic scenario name.

(2) Dump step(s) is preset by RAMMS to a default value of 0.02. This value is ten times the time step. This means the data of every tenth time step is saved in the output. If you want the data of every fifth time step you need to set the dump step to 0.01. If you want to save storage capacity you can set the dump step higher.

(3) The **Stop criterion** is set automatically and depends on rock mass and rock stop velocity. The rock stop velocity ROCK_STOP_VEL may be set in RAMMS via ***Help*** → ***Advanced...*** → ***Additional Preferences...*** → ***Edit***. Additionally, you may choose an **End time (s)** to stop your simulation after a given time. The simulation stops at the first stop criterion to reach.

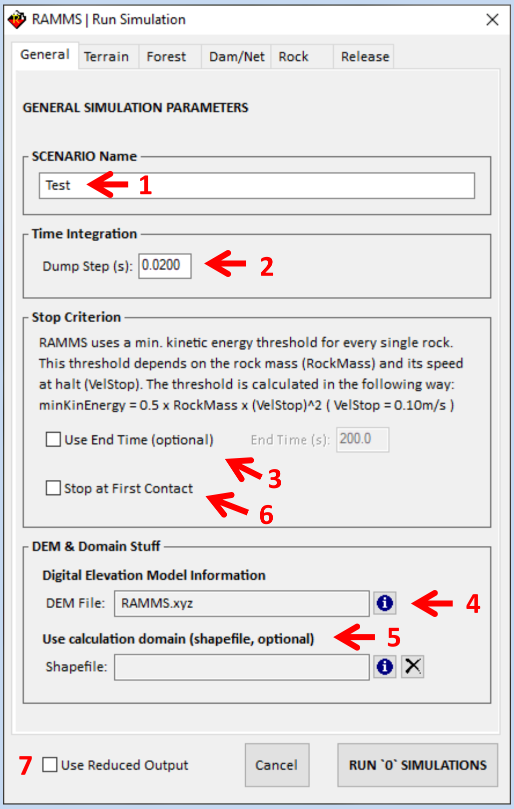


Figure 4-67: Tab General

(4) **Digital Elevation Model Information** shows you which DEM is used for the simulation.

(5) **Calculation Domain (optional):** Narrow down your calculation area by using a polygon shapefile.

(6) Activate the box ***Stop at first contact*** only if you wish to stop your simulation as soon as the rock reaches the terrain for the first time.

(7) **Use Reduced Output**: Check this box to only save reduced output values. This will reduce the disk size of the output files, but also speeds up the reading of the output files. Values saved are: Kin. Energy, Jump Height, Velocity and Scar Depth.

Terrain Tab

(1) Choose the category of the **overall terrain material** of your simulation area by either choosing a default type or manually entering M_E and C_D.

(2) All defined terrain types assigned to certain shapefiles are listed here.

(3) Click on **Cd/ME Plot** for a graphical representation of all assigned ground categories

Please note: When loading multiple shapefiles for different terrain materials, be aware that the order of specification in the "*Terrain SUMMARY*" window matters: the last shapefile dominates the others. This is relevant if you have overlapping shapefiles.

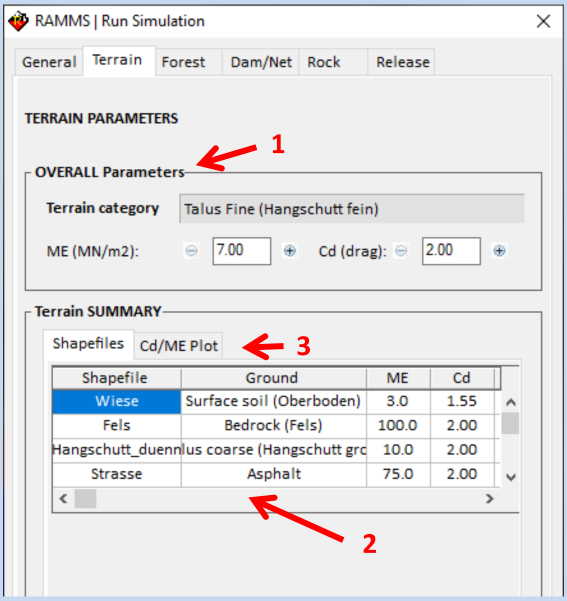


Figure 4-68: Tab Terrain

Forest Tab

(1) All defined forest types assigned to certain shapefiles are listed here with tree density, area of shapefile, mean DBH and standard derivation σ of the DBH distribution

(2) The sum of all generated trees in all shapefiles is shown here.

Make sure, that forest regions do not overlap, as trees of overlapping regions will be added to each other, resulting in denser forests than selected.

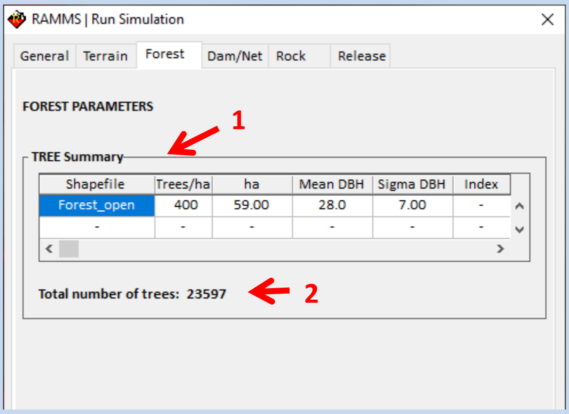


Figure 4-69: Tab Forest

Dam/Net Tab

(1) All specified and added dams or net are shown in this list. Objects can be removed (*Delete*) or the whole list can be deleted (*Clear List*).

(2) It's also possible to add dam/net objects here (*Add Dam/Net pts-file*), by selecting pts-files, and assigning the energy-threshold value. If you want to add a dam, then please check the *This a Dam* checkbox, and add ME- and Cd-values.

(3) If you specify pts-files here, click the *PLUS*-button to add the pts-file to the list below.

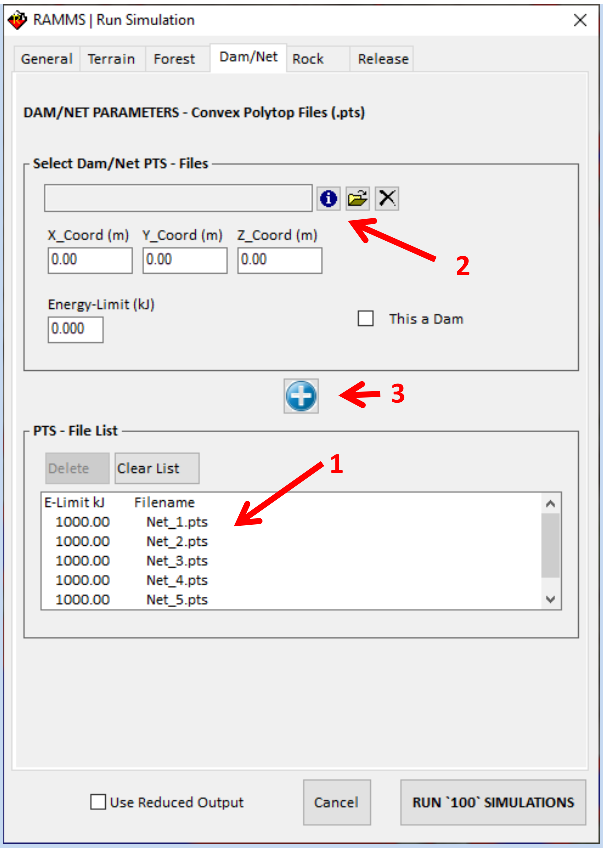


Figure 4-70: Tab Dam/Net

Rock Tab → Rock

(1) You can directly open the *Rock Builder* from here, and change your rocks.

(2) Choose **rock type**: Click **Rock** to run a simulation with a real rock shape which you produced before in the *Rock Builder* (Exercise 4.7).

(3) Select the .pts file of the rock you wish to simulate. A visualization of the selected rock is then shown in the rock window. Use your mouse to move the rock in any direction. The rock's characteristics and dimensions are shown on the right side.

(4) Optionally adjust the rock density

(5) You can select the **rocks** folder in your scenario folder (or any folder containing multiple rocks). The number of .pts files in the folder will be shown. On the right side

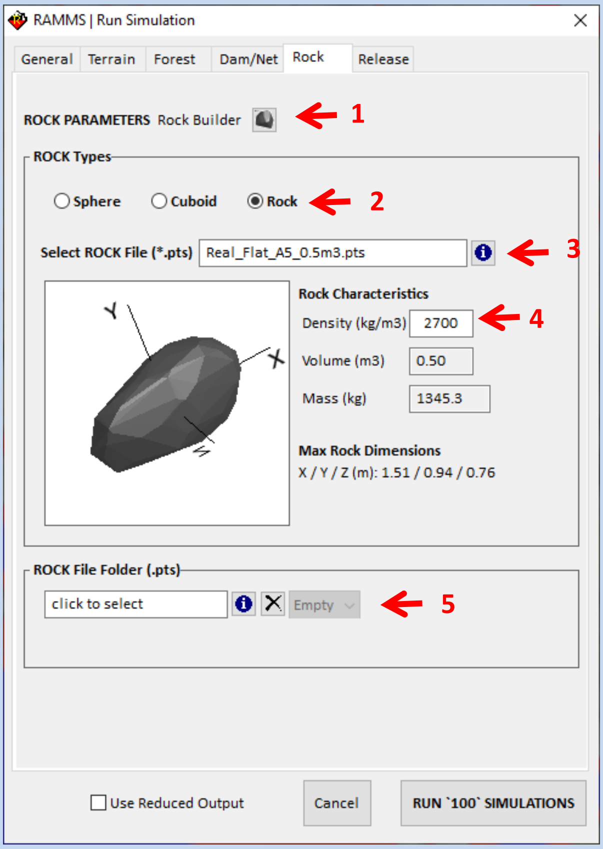


Figure 4-71: Tab Rock → Rock

you can check which rocks the folder includes. Select a file from the list to look at the rock in the window. All the rocks within this folder will be used for the simulations.

Rock Tab → Cuboid / Sphere

(1) Choose **rock type**: Click **Cuboid / Sphere** to run a RAMMS simulation with a cuboid / sphere. **Using a sphere is not recommended!**

(2) Specify the volume of the cuboid by defining the length of the three axes X, Y and Z (m). Specify the *Rock Radius* of your rock sphere. Use your mouse to move the cuboid / sphere interactively in any direction. You find the rock characteristics and dimensions on the right side of the *Rock* tab.

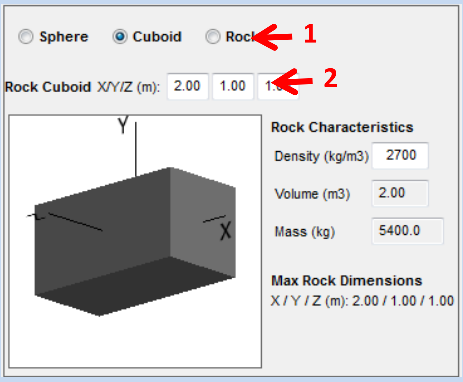


Figure 4-72: Tab Rock → Cuboid

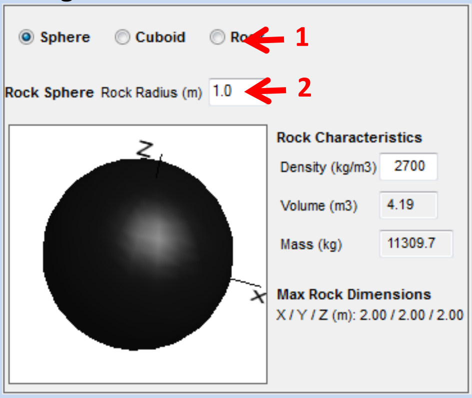


Figure 4-73: Tab Rock → Sphere

Release Tab

(1) Enter the **number of random orientations** per release point and rock shape. It is highly recommended to use high numbers of random orientations. Suggested values are between 20-30. **Do not use values below 5!**

(2) Summary of all release points. In this case, there is a polygon shapefile with a density of 50 points. See exercise 4.5.3 on how to create release points.

(3) Define the **Initial Velocity (m/s)** and the **Initial Rotational Velocity (rad/s)** of the rock-body at release time. This can be useful for cases where the values are known, or specific situations should be simulated.

(4) Select **Rock Z-Offset Automatic**: RAMMS defines the Z-offset such that the starting of the rock is guaranteed. This is the **default** setting, use Automatic Offset if possible!

Select Rock Z-Offset **Manual**: Type in a value (m) to define the release height of a rock above the terrain. Select **Use Multi** to release several rocks at the same point but different release heights. **Delta** specifies the heights (m) and **Steps** defines how often Delta is applied.

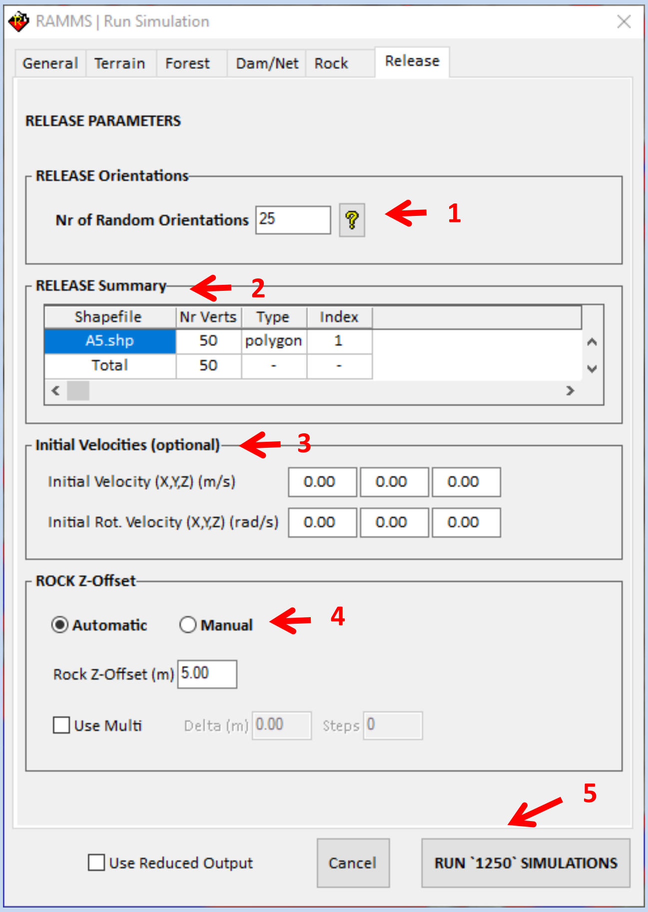


Figure 4-74: Tab Release

(5) ***RUN "XXX" SIMULATIONS*** **shows how many rocks will be simulated in the defined scenario. Click on the button and the simulations will start. The number of simulations is the product of:**

- Number of release points
- Number of rock shapes
- Number of random orientations
- Number of z-offset steps if a manual rock offset is chosen with the "Multi"-option.

Nr Simulations - Nr Random Orientations

In order to achieve statistical relevant results at the object of interest (e.g. village, road, endangered object), after a first test with low numbers of released rocks and short calculation times, some main model runs should be undertaken. The first main model runs should start with

- 10-15 **Nr Random Orientations**
- **Release Locations**: There should be a release location every 10-20m within your release polygon or line.
- Create a polygon shapefile at the object of interest, and then do a **barrier plot** for this shapefile (e.g. kin. Energy)

Then do a next model run, with

- 20-25 **Nr Random Orientations**

and compare the new **barrier plot** for above polygon shapefile with the one from the first model run with 10-15 **Nr Random Orientations**.

If the statistical results differ significantly, then increase your **Nr Random Orientation** and/or **Release Locations**, until the statistical results for the barrier plot do not differ significantly anymore.

4.11.7 Scenario Preparation and Simulation Process

If the scenario already exists, RAMMS will ask you if you want to overwrite the scenario:

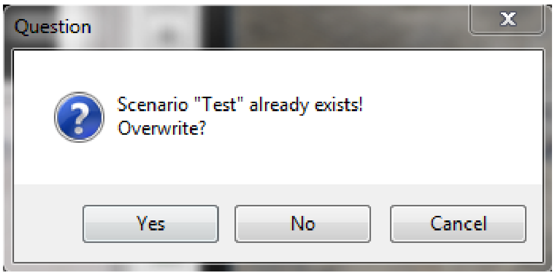


Figure 4-75: Scenario already exists dialogue.

If you click *No* or *Cancel*, you will be able to rename your scenario in the *General* tab. Click *Yes*, and the old scenario is deleted (all the files and subdirectories within the scenario folder).

In the next step, RAMMS asks you if you want to use existing random orientations. Generally, these orientations are randomized for every simulation in a project. This means that if you make 2 simulations with exactly the same input parameters, the results will be slightly different because of this randomness in the initial conditions.

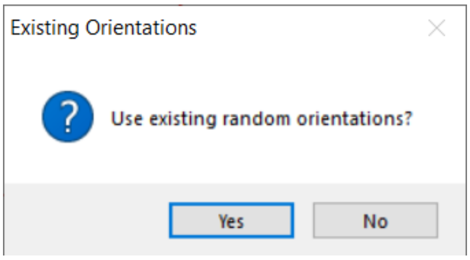


Figure 4-76: Use existing random orienations dialogue.

If you wish to reproduce a simulation precisely, you can therefore load these initial random orientations from a previous simulation. Click “yes”, move to the folder ../**ProjectName/output/ScenarioName** and select the **.random.sav** file.

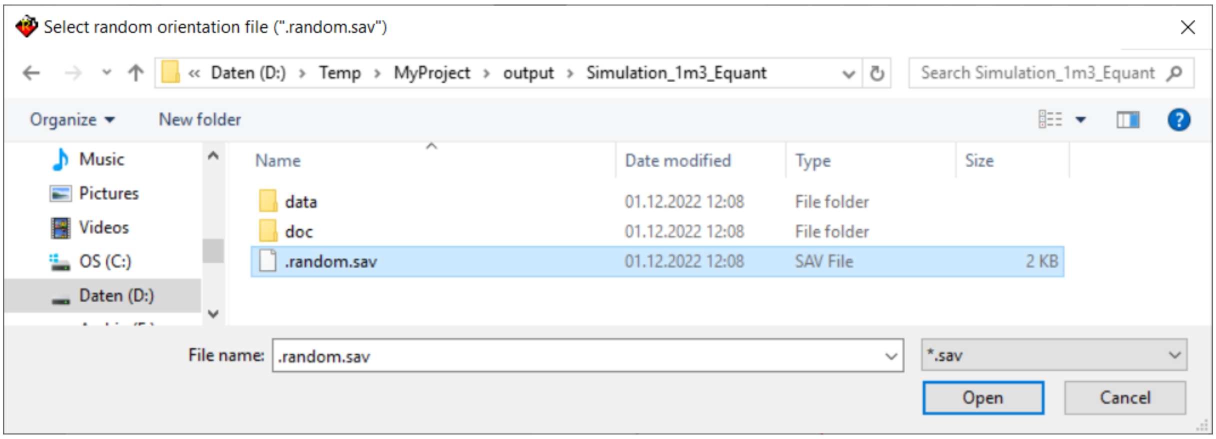


Figure 4-77: Choosing the initial rotations of a previous simulation (Simulation_1m3_Equant).

If you click “no” in the dialogue (Figure 4-76), RAMMS will generate new random orientations for the simulation and create a new **.random.sav** file in the scenario folder.

The rockfall simulations are parallelised over several CPUs. RAMMS splits the simulations with a certain number of CPU’s (chosen by the user) either by the number of release points or by random orientations. The larger of these two numbers is chosen. In the example below, we want to run a simulation with 50 release points and 25 random orientations (1250 simulations in total) on 5 CPU’s. Then the release points will be divided between the CPU’s. This means that each CPU will calculate 10 release points for all 25 random orientations (in total 250 simulations per CPU). It is therefore advised that the number of CPUs that you choose for the simulation is a divisor of this higher number. RAMMS will suggest possible nr of CPU’s, see Figure below.

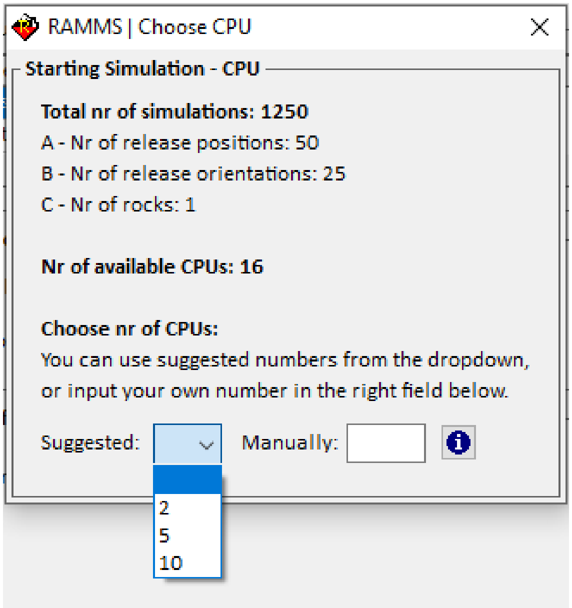


Figure 4-78: Available CPUs dialogue.

In the dialogue you will see a summary of your scenario, and how many CPU's your PC/laptop owns. In general, the more you specify, the faster your scenario will be calculated. Please note, that if you specified a very large forest (large = many trees), then it could be faster to calculate the scenario with less CPU's, because reading large forest files could take a while. Note also, that if you use all available CPU's for your scenario calculation, your computer may be blocked for all parallel activities during the simulation. In the case above, 2, 5 and 10 are possible divisors for the number of orientations. If another number is chosen (in the field *Manually*), the last CPU takes all remainders, which slows down the calculation.

Scenario Preparation

If you specified terrain and/or forest shapefiles, RAMMS will gather the data and saving the appropriate friction parameters *ASCII* files, showing messages like the one below in the lower left status bar:

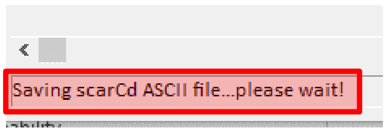


Figure 4-79: Saving friction parameter ascii files.

After that, RAMMS starts the simulation process:

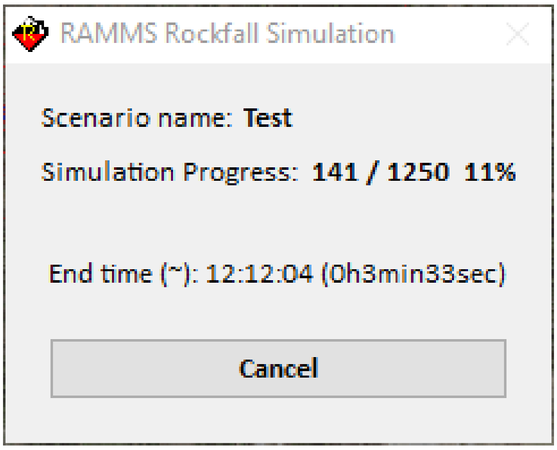


Figure 4-80: Rockfall simulation information window.

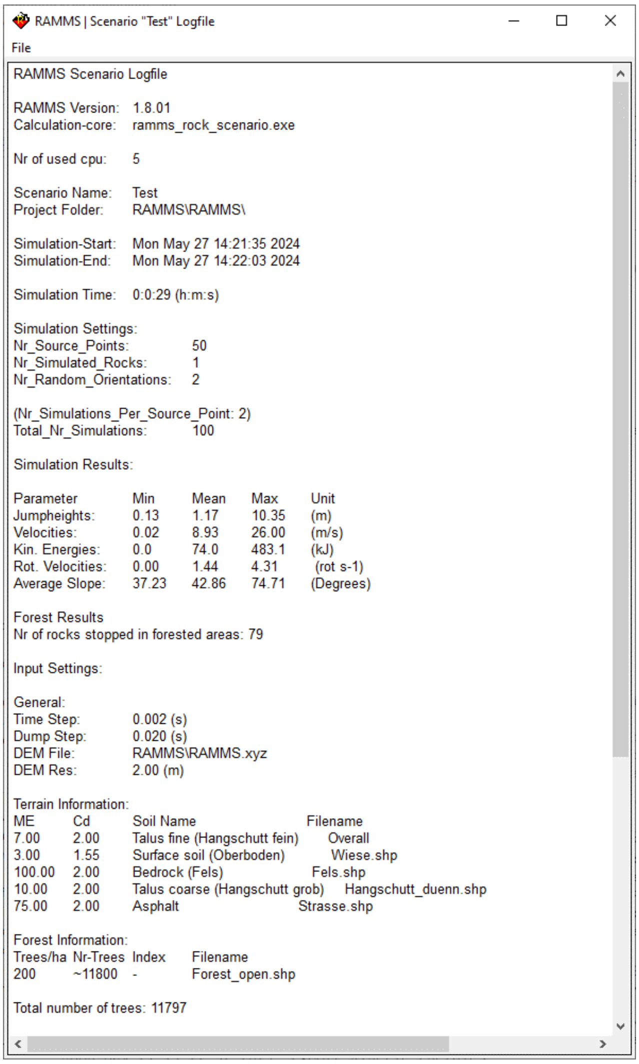
This window (Simulation Progress) shows important information concerning your scenario-simulation:

- **Scenario name:** the scenario name.
- **Simulation Progress:** Number and percentage of finished trajectory simulations
- **End time:** Showing estimated end time (10:58:32) as well as the duration (0h1min2sec).
- **Cancel button:** Click the Cancel button to cancel the scenario. All the simulations calculated up to now are then opened in Scenario-Mode.

After the completion of all simulations or if the user clicks *Cancel*, RAMMS will create the following output files:

- *<scenario_name>_Trajectories.shp:* Shapefile containing all the trajectories as polylines. Attributes of these polylines are corresponding trajectory filename as well as the rock name.
- *<scenario_name>_StartPositions.shp: Shapefile containing all start point positions.*
- *<scenario_name>_Nr of Rocks.tif:* TIFF-raster of output result “Nr of Rocks”. This result shows how many rocks passed the grid cells.
- *<scenario_name>_Jump Height (m) - Q 95%.tif:* TIFF-raster of output result “Jump Height (m) - Q 95%”.
- *<scenario_name>_Velocity (m s-1) - Q 95%.tif:* TIFF-raster of output result “Velocity (m s-1) - Q 95%”.
- *<scenario_name>_Kinetic Rock Energy (kJ) - Q 95%.tif:* TIFF-raster of output result “Kinetic Rock Energy (kJ) - Q 95%”.
- *<scenario_name>_Source Reach Probability (%).tif:* TIFF-raster of output result “Source Reach Probability (%)”.
- *<scenario_name>_endpoints.txt:* A simple txt-file with all X/Y coordinates of the deposition points.

The *Scenario-Logfile* will then appear:



RAMMS Scenario Logfile

RAMMS Version: 1.8.01
Calculation-core: ramms_rock_scenario.exe

Nr of used cpu: 5

Scenario Name: Test
Project Folder: RAMMS\RAMMS\

Simulation-Start: Mon May 27 14:21:35 2024
Simulation-End: Mon May 27 14:22:03 2024

Simulation Time: 0:0:29 (h:m:s)

Simulation Settings:
Nr_Source_Points: 50
Nr_Simulated_Rocks: 1
Nr_Random_Orientations: 2

(Nr_Simulations_Per_Source_Point: 2)
Total_Nr_Simulations: 100

Simulation Results:

Parameter	Min	Mean	Max	Unit
Jumpheights:	0.13	1.17	10.35	(m)
Velocities:	0.02	8.93	26.00	(m/s)
Kin. Energies:	0.0	74.0	483.1	(kJ)
Rot. Velocities:	0.00	1.44	4.31	(rot s-1)
Average Slope:	37.23	42.86	74.71	(Degrees)

Forest Results
Nr of rocks stopped in forested areas: 79

Input Settings:

General:
Time Step: 0.002 (s)
Dump Step: 0.020 (s)
DEM File: RAMMS\RAMMS.xyz
DEM Res: 2.00 (m)

Terrain Information:

ME	Cd	Soil Name	Filename
7.00	2.00	Talus fine (Hangschutt fein)	Overall
3.00	1.55	Surface soil (Oberboden)	Wiese.shp
100.00	2.00	Bedrock (Fels)	Fels.shp
10.00	2.00	Talus coarse (Hangschutt grob)	Hangschutt_duenn.shp
75.00	2.00	Asphalt	Strasse.shp

Forest Information:

Trees/ha	Nr-Trees	Index	Filename
200	~11800	-	Forest_open.shp

Total number of trees: 11797

Figure 4-81: RAMMS Scenario Logfile

5 Results

RAMMS offers a variety of tools and visualizations to interpret the simulation results. There are two different modes to open simulation results: a) *Statistic Mode* to visualize a large number of simulations (> 100) and b) *Trajectory Mode* to analyze single trajectories in detail. The two modes are described in this chapter.

5.1 Statistic Mode

In *Statistic Mode*, we try to answer the following questions:

- Which cells are affected by which trajectories?
- How many trajectories fly over a given cell?
- What are velocity, kinetic energy, jump height and rotational velocity values in a given cell?
- What is the probability that a rock reaches a given cell?

RAMMS analyses every trajectory and then saves jump height, velocity, kinetic energy and rotational velocity values in the cells affected by the trajectories.

Example:
We assume that RAMMS has saved 42 values (42 values of jump height, 42 values of velocity, etc.) in a given cell, see figure below (showing only part of the 42 values):

All 42 Data Values (+ Output File Name):

JumpH	Vel	KinE	RotV	Filename
2.70	14.87	174.65	2.50	Test_Pos10_PTSReal_Flat_A5_0.5m3_O2.rts
0.73	7.57	43.85	1.19	Test_Pos12_PTSReal_Flat_A5_0.5m3_O1.rts
0.61	6.64	33.64	0.99	Test_Pos12_PTSReal_Flat_A5_0.5m3_O2.rts
1.10	11.64	104.25	1.80	Test_Pos15_PTSReal_Flat_A5_0.5m3_O2.rts
0.92	6.98	36.96	1.08	Test_Pos16_PTSReal_Flat_A5_0.5m3_O1.rts
0.96	7.80	47.35	1.47	Test_Pos16_PTSReal_Flat_A5_0.5m3_O2.rts
0.53	7.47	44.66	1.32	Test_Pos17_PTSReal_Flat_A5_0.5m3_O2.rts
0.69	6.11	30.65	1.31	Test_Pos21_PTSReal_Flat_A5_0.5m3_O2.rts
0.65	6.10	27.71	1.06	Test_Pos22_PTSReal_Flat_A5_0.5m3_O1.rts
0.75	10.34	87.90	1.91	Test_Pos23_PTSReal_Flat_A5_0.5m3_O1.rts
0.98	15.99	183.86	1.70	Test_Pos23_PTSReal_Flat_A5_0.5m3_O2.rts
0.99	5.32	22.69	0.96	Test_Pos26_PTSReal_Flat_A5_0.5m3_O1.rts
0.76	4.86	19.22	1.04	Test_Pos27_PTSReal_Flat_A5_0.5m3_O2.rts

Figure 5-1: Trajectory values in a given cell

RAMMS then calculates the following statistic values for this given cell out of the 63 values (e.g. Jump Height):

- Mean value (mean) → 1.01 m
- Median value (50%) → 0.89 m
- 90% Quantile value (90%) → 1.81 m
- 95% Quantile value (95%) → 2.70 m
- 99% Quantile value (99%) → 2.75 m
- Maximum value (max) → 2.75 m

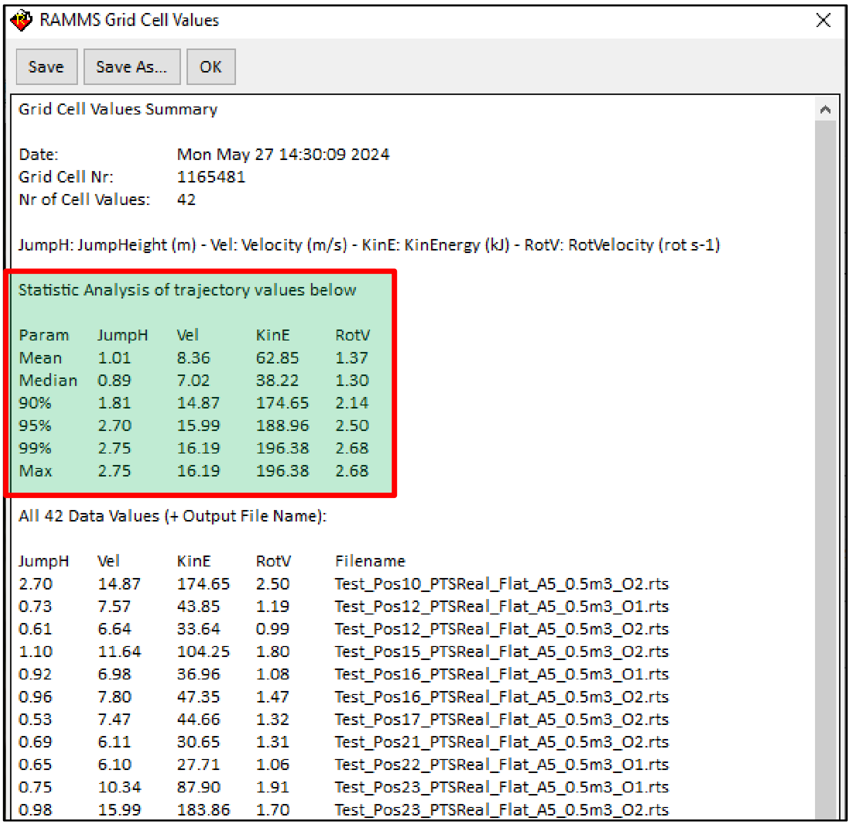


Figure 5-2: Statistic values of a given cell

5.1.1 Quantile Values

The *default quantile values* in RAMMS::ROCKFALL are *90%*, *95%* and *99%*. These three values can be changed by the user, see details below. The *Mean*, *Median* and *Max* values are fixed and cannot be changed.

How to change the Quantile Values

Use ***Help*** → ***Advanced…*** → ***Additional Preferences…*** → ***Edit*** or use the button  *(Additional Preferences)* in the lower left toolbar.

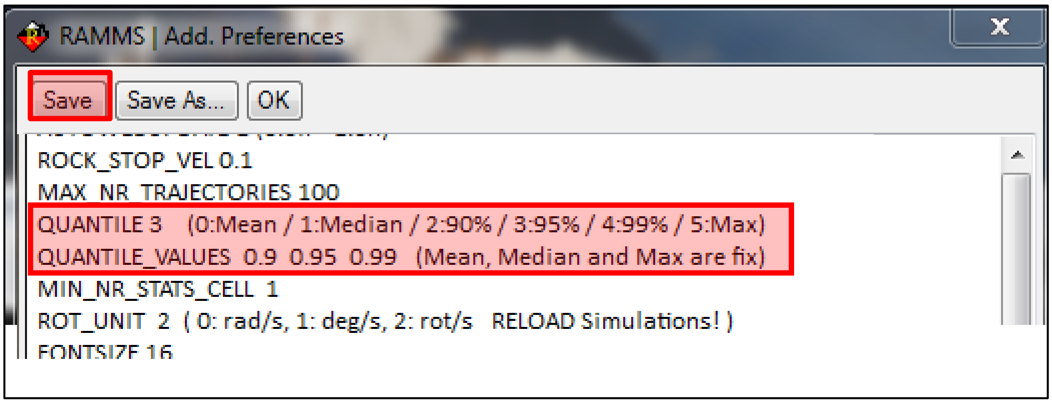


Figure 5-3: Additional Preferences: Quantile Values

Find the keyword *QUANTILE_VALUES*, change the values accordingly and press the *Save* button. Changing these values results in adjusted statistical analyses and dropdown menus, according to the values the user entered (and saved!).

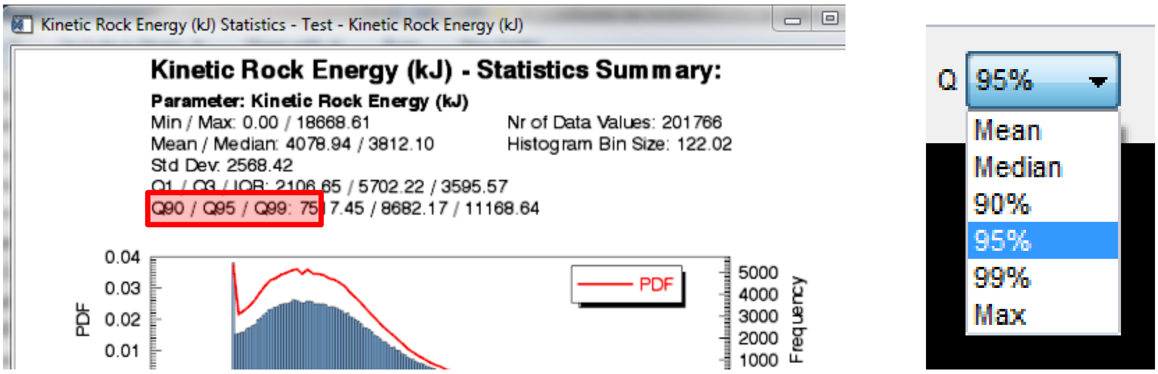


Figure 5-4: Adjusted quantile values in *Statistic Mode*; Left: Statistic Summary Plot, Right: Quantile dropdown menu in upper right toolbar of GUI.

5.1.2 Statistic Vocabulary

Probability Density Function (PDF):

Wikipedia: "*The probability density function (PDF), or density of a continuous random variable, is a function that describes the relative likelihood for this random variable to take on a given value. The probability of the random variable falling within a particular range of values is given by the integral of this variable's density over that range—that is, it is given by the area under the density function but above the horizontal axis and between the lowest and greatest values of the range. The probability density function is non-negative everywhere, and its integral over the entire space is equal to one.*"

Cumulative Distribution Function (CDF):

Wikipedia: "*In probability theory and statistics, the cumulative distribution function (CDF), or just distribution function, describes the probability that a real-valued random variable X with a given probability distribution will be found to have a value less than or equal to x.*"

Empirical Distribution Function (EDF):

Wikipedia: "*In statistics, the empirical distribution function is the distribution function associated with the empirical measure of the sample. This cumulative distribution function is a step function that jumps up by 1/n at each of the n data points. The empirical distribution function estimates the cumulative distribution function underlying of the points in the sample and converges with probability 1 according to the Glivenko–Cantelli theorem.*"

Boxplot:

Wikipedia: "*In descriptive statistics, a box plot or boxplot is a convenient way of graphically depicting groups of numerical data through their quartiles. Box plots are non-parametric: they display variation in samples of a statistical population without making any assumptions of the underlying statistical distribution. The spacings between the different parts of the box indicate the degree of dispersion (spread) and skewness in the data, and show outliers.*"

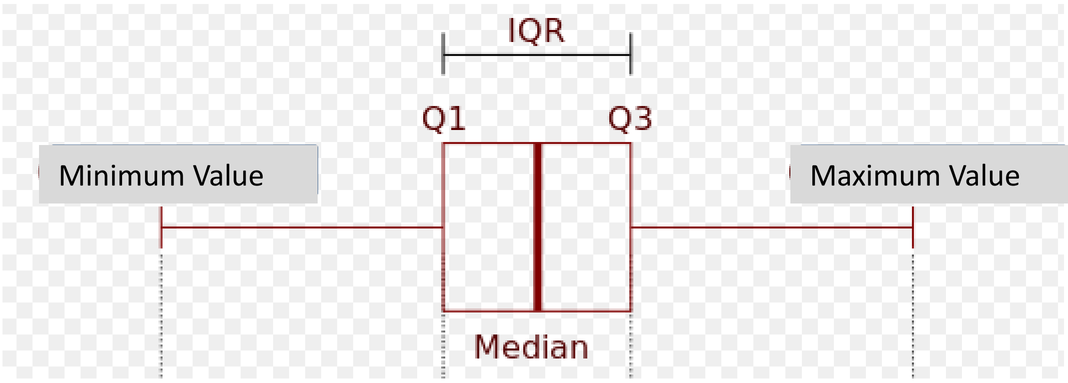


Figure 5-5: Boxplot Explanations (Q1: lower quartile = 25 %, Q3: upper quartile = 75 %, IQR: interquartile range).

5.1.3 Open a Scenario

Open a simulation scenario with ***Track*** → ***Open…*** → ***Rockfall Scenario*** or click  in the toolbar and then choose a scenario in a project's output folder.

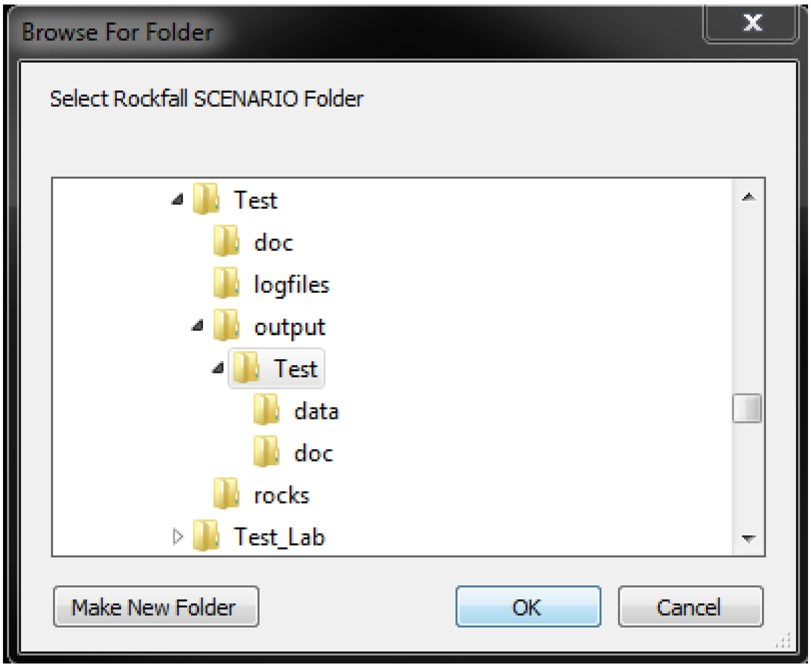


Figure 5-6: Browse for Scenario Folder.

Click *OK* to choose the selected scenario. RAMMS will then open the scenario.

If you would like to open several scenarios, or you want to filter results, then use ***Track*** → ***Open…*** → ***Rockfall Scenario (Filter/Multi).***

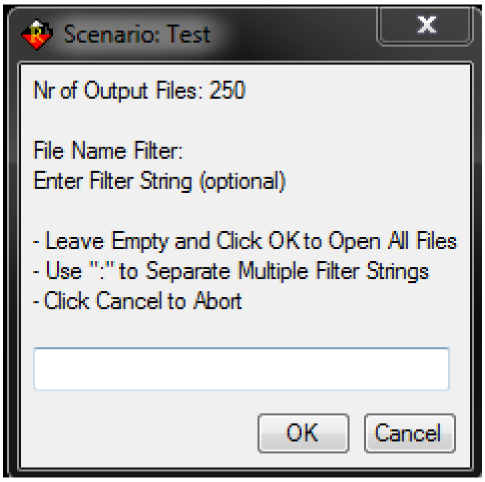


Figure 5-7: The file name filter shows information about the scenario that you are opening. You can enter a file string or click *OK* to open all files.

Enter a file name filter for the specific results (use a colon to use more than one filter string) or click *OK*, if you are interested in all the simulations in the scenario folder. Click *OK* to proceed.

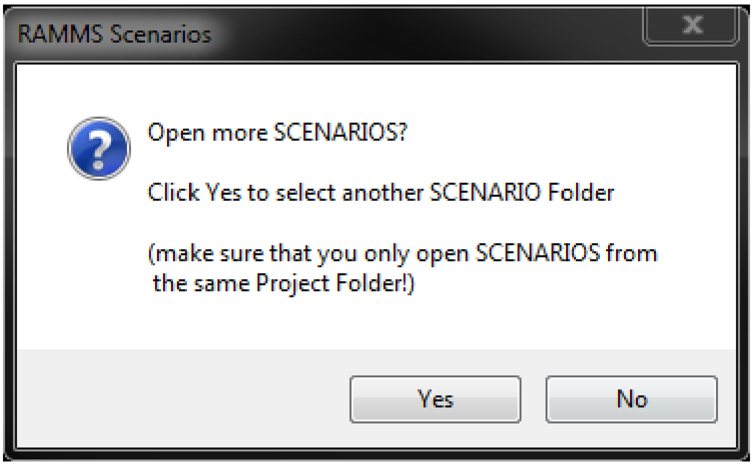


Figure 5-8: Open more Scenarios?

Click *Yes* to choose another scenario from the output folder. It is important that the scenarios are saved in the same project folder. Click *No* if you want to analyze only the results from one scenario.

RAMMS will open the scenario and show the 95%-Quantile of the kinetic Rock Energy (kJ). The 95%-Quantile is the default selection of the quantile dropdown menu in the upper right toolbar. You can change the default selection in the *Additional Preferences* (Keyword: *QUANTILE*, values between 0 - 5 correspond to the position of the quantile in the dropdown menu, see Figure 5-4).

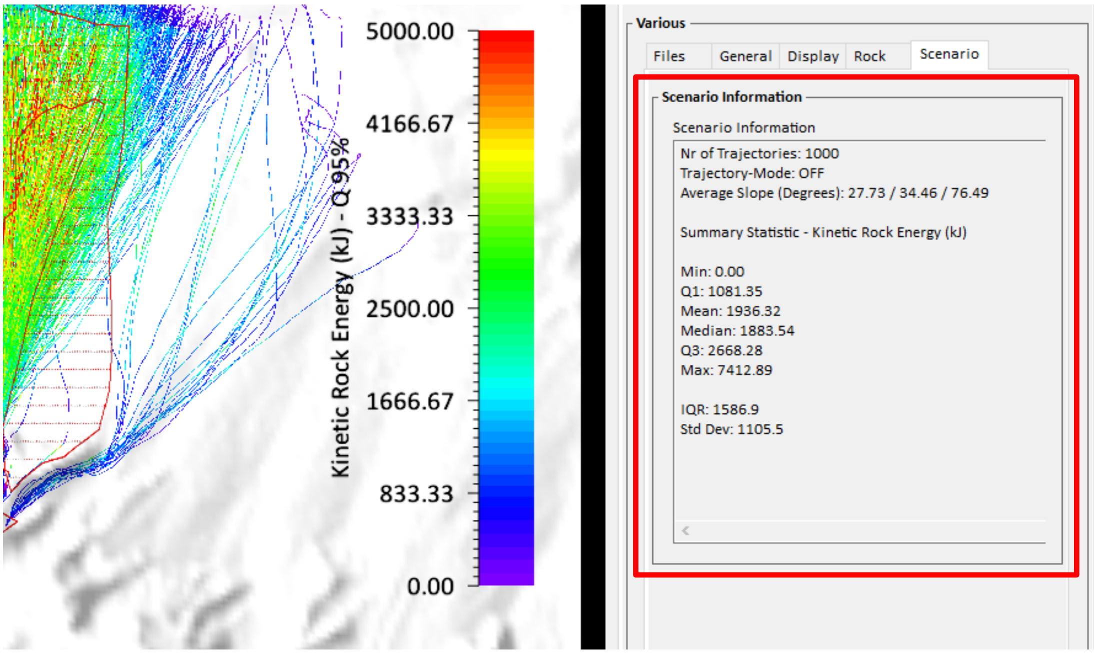


Figure 5-9: *Statistic Mode* information is shown in the right panel in the **Scenario** tab. (Min, Q1, Mean, Median, Q3, Max, IQR, StdDev).

The *Scenario tab* on the right shows useful *Statistic Mode* information. The trajectory mode should be OFF – you are in the statistic mode. You find general information about the selected scenario:

- Nr of Trajectories and Average Slope over all trajectories (=Pauschalgefälle: min, mean, max). The average slope of a trajectory is the slope of the line drawn between start and deposition point of the rock.
- 8-Point Statistic information of the selected parameter

In *Statistic Mode*, Jump Height (**H**), Rock Velocity (**V**), Resultant Rotational Rock Velocity, Kinetic Rock Energy (**E**), Scar Length and Scar Depth results are available (

).

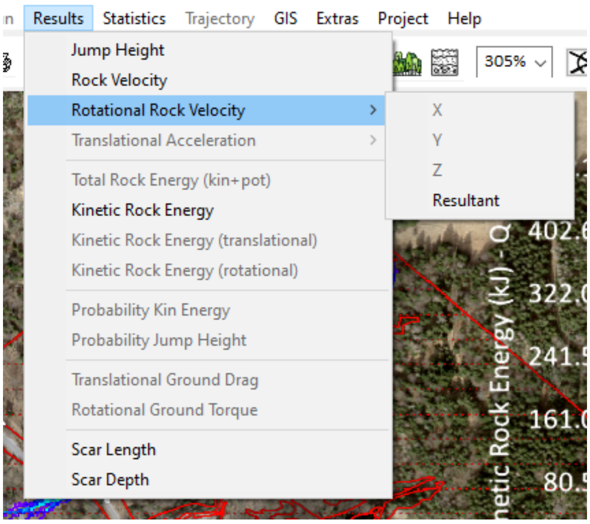
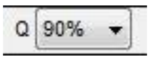


Figure 5-10: Statistics Mode: Dropdown menu Results

All other results are available in *Trajectory Mode* only. For the visualization of the parameters, you can choose between the values Mean, Median, 90%, 95%, 99% or Max values. The dropdown is in the upper toolbar 

 .

The menu *Statistics* offers the following functions:

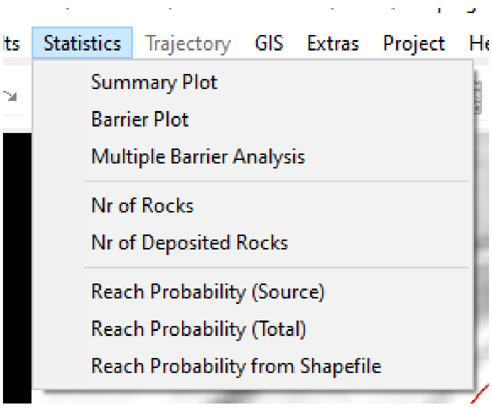


Figure 5-11: Statistics Mode: Menu *Statistics*.

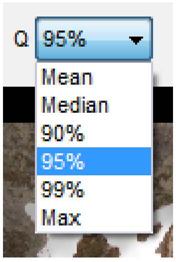
- Summary Plot (statistics summary of the selected parameter)
- Barrier Plot (statistics of line profile or polygon area of selected parameter)

- Multiple Barrier Analysis (do a statistical analysis of several barrier areas, but without a barrier plot. Results are written into a log-file.

- Nr of Rocks
- Nr of Deposited Rocks

- Reach Probability (Source)
- Reach Probability (Total)
- Reach Probability from Shapefile

In the horizontal toolbar you can find the following functions:

- Barrier Plot 
- Line Profile 
- Cell Info File 
- Quantile dropdown menu 

5.1.4 Summary Plot

Choose the result parameter that you are interested in (e.g. Jump Height, Rock Velocity, Kinetic Rock Energy or Resultant Rotational Rock Velocity). The results appear in the main window. Exercise 5.1 shows how to produce and analyze a *Summary Plot*.

Exercise 5.1: How to analyze the Statistics Summary Plot.

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once. Be sure that you are in the *Statistics Mode* (*Trajectory Mode = OFF* in the right toolbar).
- Choose the result parameter that you are interested in.

- Go to ***Statistics*** → ***Summary Plot***.
- A window opens, displaying the **Statistics Summary Plot**. You can save, print or edit the plot by clicking one of the buttons on the lower left corner. .

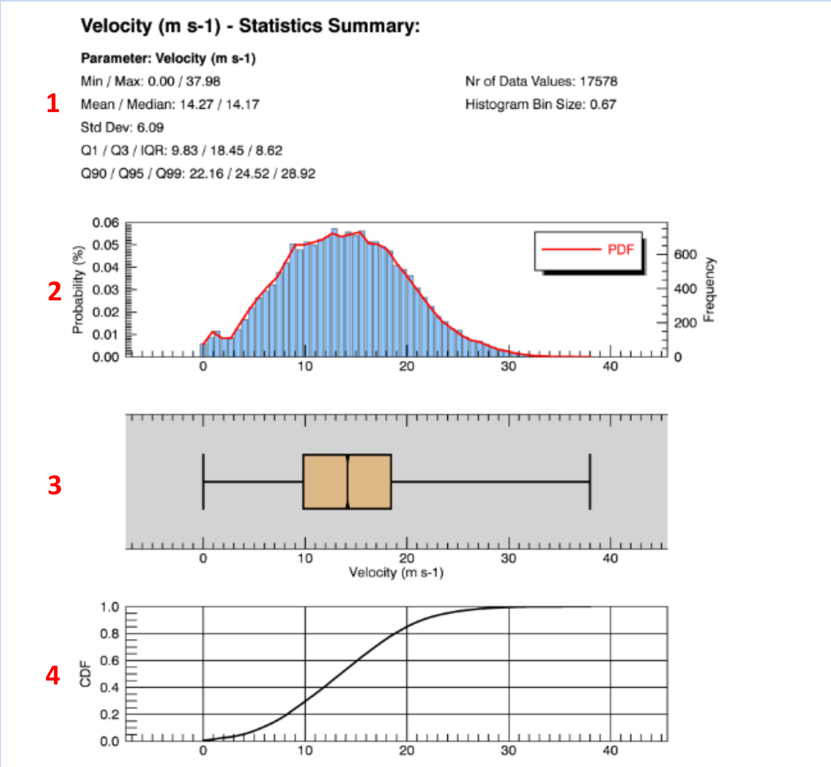


Figure 5-12: Statistics Summary Plot.

(1) Data information
(2) Probability Density Function PDF
(3) Boxplot
(4) Cumulative Distribution Function CDF

5.1.5 Barrier Plot

If you need to analyze special areas (region of a planned dam or realized rockfall nets, etc.) then the *Barrier Plot* is a good choice. Use a line profile (polyline shapefile) or a polygon region (polygon shapefile) to create a *Barrier Plot*.

A *Barrier Plot* contains the same statistical information as a *Summary Plot*, but for a certain region of interest (line or polygon). Additionally, for smaller datasets (< 10000 data values), an empirical distribution function plot (EDF) is added to the CDF plot. For small datasets, the EDF plot (red line in lower plot, see Figure 5-14) can deviate from the CDF plot. For large datasets, the EDF plot is not shown, as the two plots are then identical.

It is important to note, that the analysis and interpretation of the barrier plot should be carefully undertaken. The number of trajectories passing through certain grid cells (from a polyline or polygon region) is crucial to establish a confidential statistic with reliable results. For this, a third axis has been added to the line profile plot, the axis "Data Values". This parameter indicates how the data values are distributed along the line profile. For a rule of thumb, if data values drop far below numbers of 100, then the statistical analysis becomes strongly dependent on the peaks (trajectories with very high kinetic energies and jumping heights). Deriving for example the Q95-value out of such strongly asymmetrical distribution might result in an overrated, non-representative Q95 value. In the following Figure 5-13, the line profile plot along a 87m long section is shown. The peak regions with jumping heights of ~3m coincide to very low data values of 10 and less (right red circles). In contrast, where data values exceed 200 or more (left red circles), the jumping heights are lower and are more representative for this scenario.

Barrier plots are only possible for *Jump Height*, *Velocity*, *Kin. Energy* and *Rot. Velocity* results.

Barrier Plot from new Line Profile

Draw a line profile by clicking (e.g. a dam or places that you are specifically interested in e.g. a place where several trajectories pass through). RAMMS opens both a *Line Profile Plot* and the *Barrier Plot* for the line:

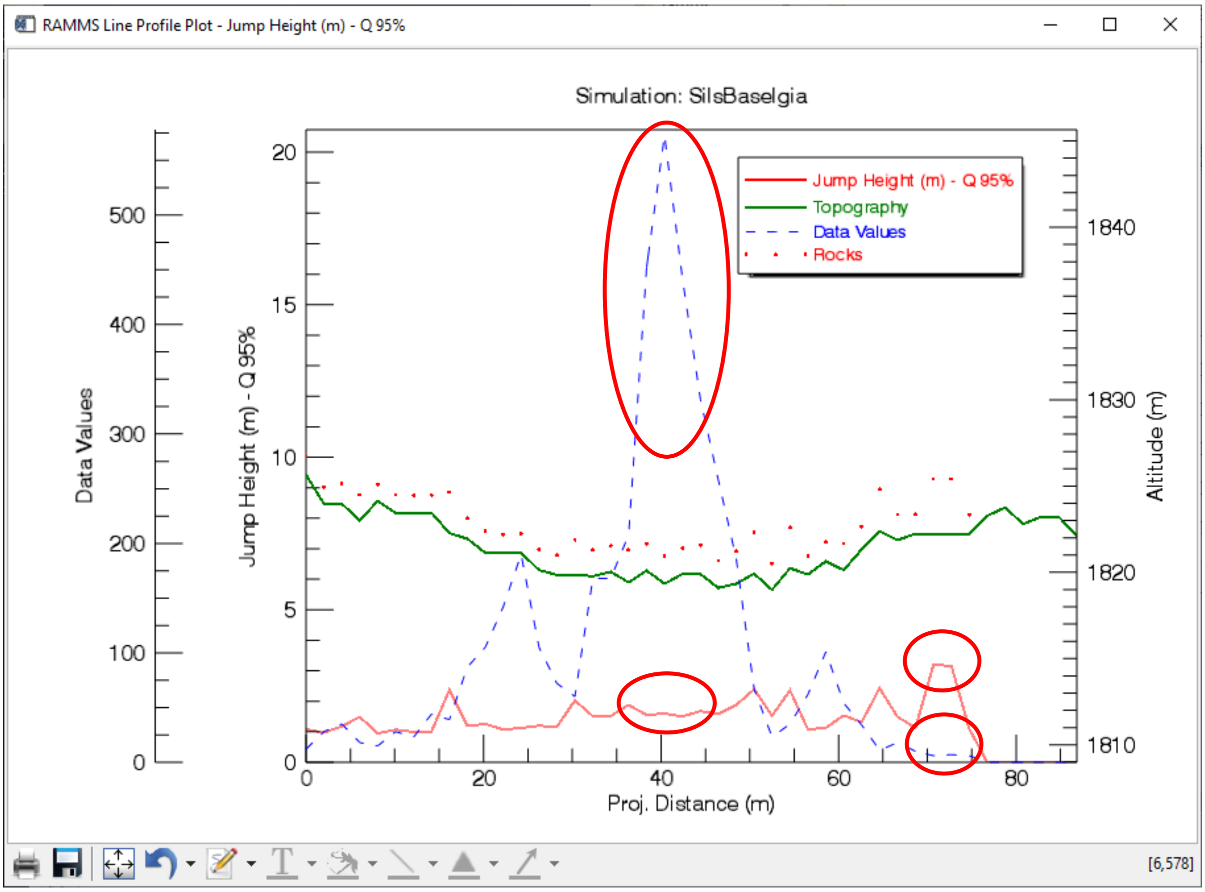


Figure 5-13: Line Profile Plot depicting the ***Topography*** (***green*** line, right y-axis), the jump height (rock position) on top of the topography (***red*** dots, ***Rocks***), the ***Data Values*** distribution (***blue*** dashed line, left outer y-axis) and the ***Jump Height*** values (***red*** line, left inner y-axis).

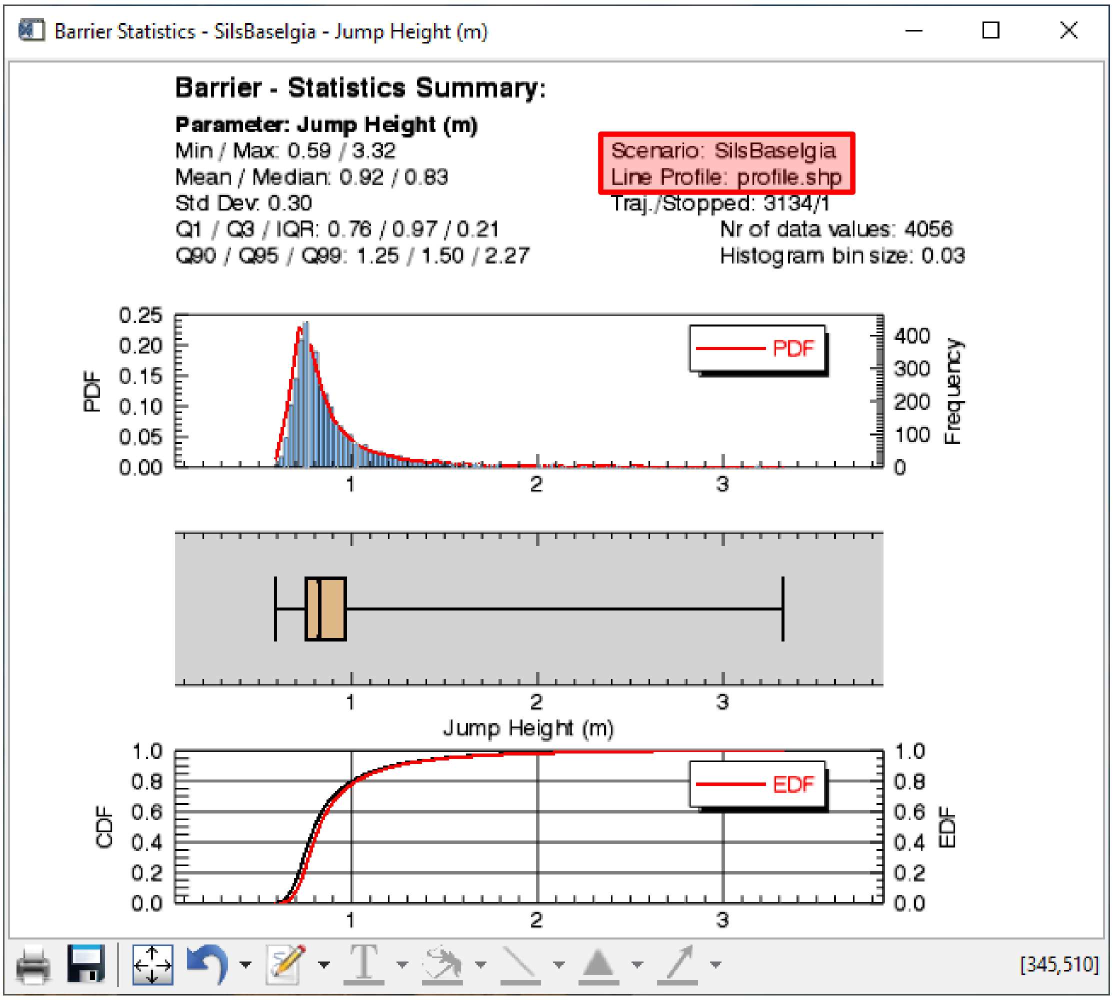


Figure 5-14: *Barrier Plot* of a line profile. Scenario and line profile name are marked in the upper right corner (red box). An empirical distribution plot (EDF, red line) is added to the CDF plot for smaller datasets.

Barrier Plot from file 

Use ***Statistics* → *Barrier Plot*** or the horizontal toolbar button  to select a polyline or polygon shapefile you wish to create a *Barrier Plot* for.

A window opens, displaying the *Statistics Barrier Plot* (see figure above). In the *Data information* part of the *Barrier Plot* you find the information about the selected scenario and the name of either the polyline or the polygon shapefile. Additionally, you will find a statistical summary with the most important statistic values, as well as information about the total number of trajectories passing the region (3134) and stopping in the region (1), see Figure below (Traj./Stopped: 3134/1).

Barrier - Statistics Summary:	
Parameter: Jump Height (m)	
Min / Max: 0.59 / 3.32	Scenario: SilsBaselgia
Mean / Median: 0.92 / 0.83	Line Profile: profile.shp
Std Dev: 0.30	Traj./Stopped: 3134/1
Q1 / Q3 / IQR: 0.76 / 0.97 / 0.21	Nr of data values: 4056
Q90 / Q95 / Q99: 1.25 / 1.50 / 2.27	Histogram bin size: 0.03

Figure 5-15: Data information part of *Barrier Plot*

5.1.6 Number of Rocks

Number of rocks that passed through a given cell.

5.1.7 Number of Deposited Rocks

Number of rocks that stopped in a given cell.

5.1.8 Reach probability

Source:

The probability that a rock arrives in a given cell. The release cells (source) feeding a given cell are taken into account when calculating the ***Source*** *reach probability*.

Menu *Statistics* → *Reach Probability (Source*)

Total:

Same as above, but release cells are *not* considered; *Total reach probability* is calculated from total released rocks.

Menu *Statistics* → *Reach Probability (Total*)

Reach Probability from Shapefile:

Normal reach probabilities (Total and Source Reach Probability) are calculated on a grid cell basis. This can lead to lower values than expected. With this feature it is possible to calculate a “Source Reach Probability” for a polygon region.

Menu *Statistics* → *Reach Probability from Shapefile*

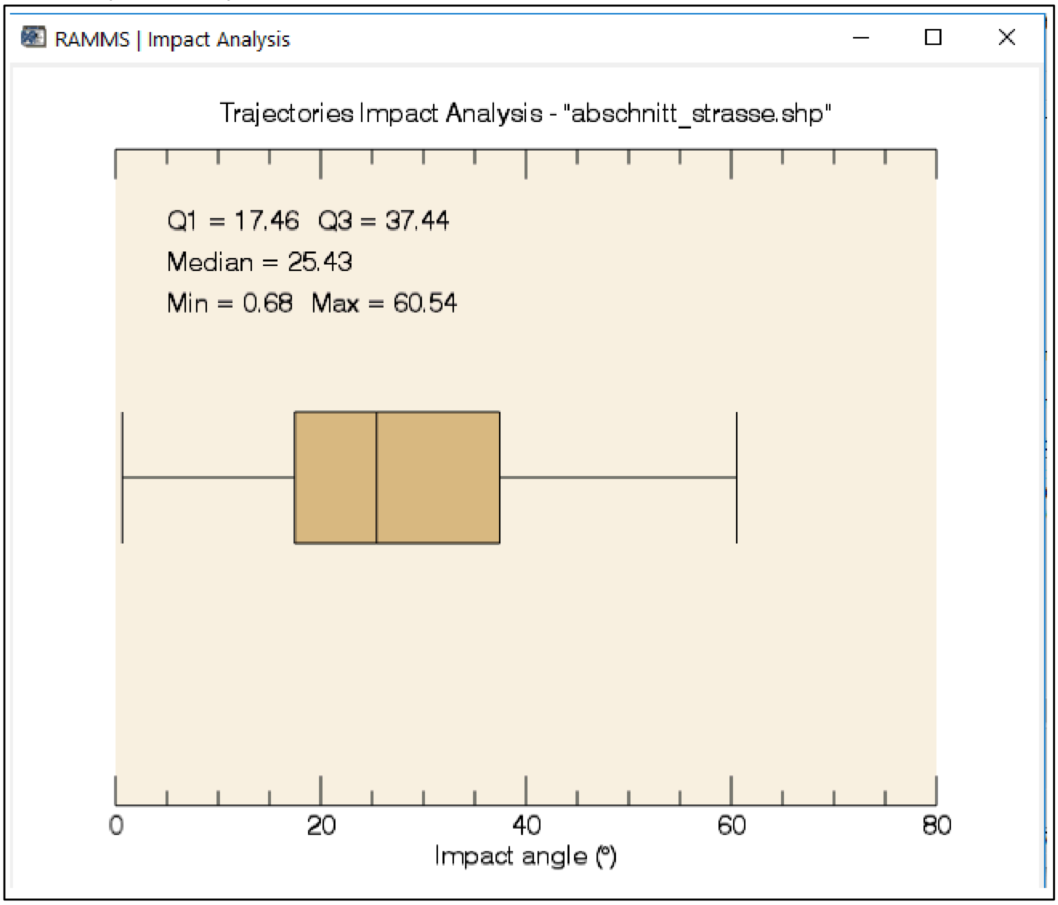
5.1.9 Trajectory Impact-Analysis from Shapefile

This feature can be used to analyze rock impacts on polygon areas, e.g. galleries, roads, dams, etc.

- Open a scenario in Statistics-Mode
- draw a polygon shapefile where you want to analyze trajectory impacts
- Choose "*Extras → Trajectory Impact-Analysis from Shapefile*" and select above shapefile

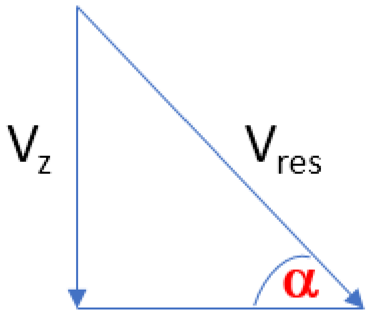
The following plot will then show impact angles in degrees:

Figure 5-16: Impact-Analysis



Impact angles (alpha α) are calculated according to the following sketch:

Figure 5-17: Impact angles



Additionally, two txt-files are saved in your scenario-directory:

- *impact_data.txt* and
- *impact_trajectories.txt*

impact_data.txt:
This file contains details of every trajectory impact (impact time and location, kin. Energy, velocities and impact angle). The first entry "i" is the index-value into "impact_trajectories.txt".

Figure 5-18: *impact_data.txt* file containing impact-analysis data

```
i, t (s), X (m), Y (m), Z (m), Ekin (kJ), Vx (m/s), Vy (m/s), Vz (m/s), Vres (m/s), Angle (°)

 0, 35.300, 778061.97, 145328.14, 1798.17, 21.02, 5.19, -9.15, -2.64, 10.85, 14.08
 1, 49.961, 778083.54, 145348.46, 1798.19, 3.72, 3.33, -2.33, -2.51, 4.77, 31.75
 2, 33.881, 778078.86, 145340.24, 1798.41, 83.93, 5.29, -14.35, -18.00, 23.62, 49.65
 3, 35.763, 778065.73, 145333.59, 1798.26, 35.12, 4.58, -13.05, -5.15, 14.76, 20.43
 4, 61.304, 778076.88, 145350.41, 1799.02, 10.40, 4.00, -5.87, -4.72, 8.52, 33.60
 5, 61.501, 778078.55, 145346.55, 1798.44, 29.92, 7.26, -8.94, -8.12, 14.09, 35.20
 6, 32.102, 778069.55, 145322.85, 1797.22, 117.79, 3.89, -19.19, -18.07, 26.64, 42.70
 7, 34.042, 778086.22, 145351.55, 1798.21, 2.68, 2.34, -2.99, -0.83, 3.89, 12.32
 8, 31.401, 778071.65, 145343.48, 1798.50, 24.82, 6.91, -9.00, -6.33, 12.99, 29.15
 9, 56.742, 778043.99, 145320.58, 1798.30, 0.96, 1.17, -1.70, -1.06, 2.32, 27.30
10, 50.922, 778076.89, 145346.46, 1798.51, 67.99, 8.39, -14.20, -15.41, 22.57, 43.06
12, 50.822, 778037.37, 145315.76, 1798.23, 1.49, 1.58, -1.82, -1.85, 3.03, 37.45
14, 44.642, 778027.15, 145294.12, 1798.18, 15.58, 0.82, -8.93, -3.44, 9.61, 20.99
```

impact_trajectories.txt:
This file shows all trajectories passing your shapefile, even if they do not impact.

5.1.10 Open Trajectories from Shapefile

Use *Extras* → *Open Trajectories from Shapefile* to select a shapefile (polygon or polyline), and open all the trajectories passing or stopping in the specified shapefile.

5.1.11 Analyse Gallery Impacts

This analysis is based on the following Swiss-guidelines "Effects of rockfall on protective galleries" (ASTRA-Richtlinie 12006: Einwirkungen infolge Steinschlags auf Schutzgalerien). According to the guidelines we can calculate the force at the point of impact F_k *(kN)* as well as the penetration depth *t (m)* according to these equations:

$$F_k = 2{,}8 \cdot e^{-0{,}5} \cdot r^{0{,}7} \cdot M_{E,k}^{\;0{,}4} \cdot \tan \varphi_k \cdot \left(\frac{m_k \cdot v_k^{\;2}}{2} \right)^{0{,}6}$$

$$t = \left(\frac{m_k \cdot v_k^{\;2}}{F_k} \right)$$

Figure 5-19: Equations to calculate force F_k and penetration depth *t*.

Using the following parameters:

- Rock mass m_k *(t)* (from simulation)
- Radius of the rock's surrounding sphere *r (m)* (from simulation)
- Impact velocity v_k *(m/s)* (from simulation)
- Layer thickness of covering *e [m]* (manual input)
- Static compression modulus of material $M_{e,k}$ *(kN/m²)* (manual input)
- Friction angle of covering material φ_k *(°)* (manual input)
- Density of rock ρ *(kg/m³)* (manual input)

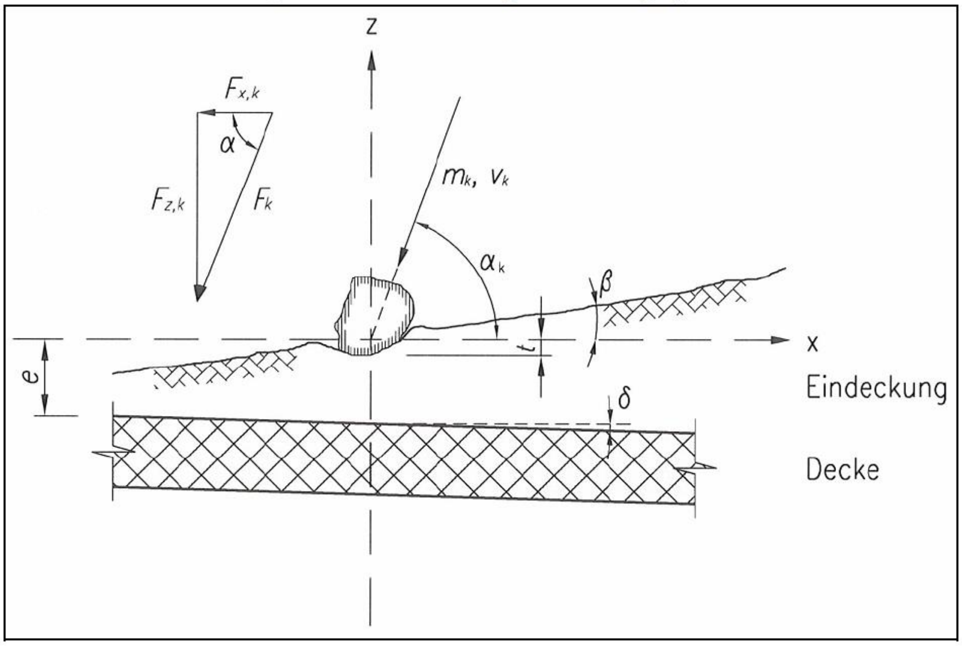


Figure 5-20: Oblique impact of rock on gallery

Use “*Extras →Analyse Gallery Impacts*” to start the gallery-analysis.

RAMMS::ROCKFALL will then show the following window, where the “manual input” parameters from above must be specified (or the default values can be adopted).

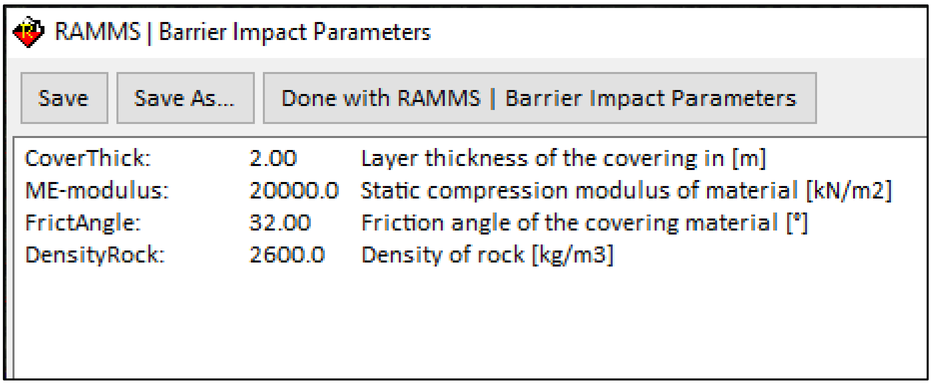
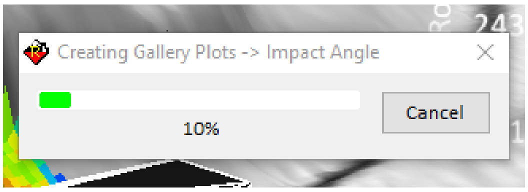


Figure 5-21: Input window for gallery-analysis parameters.



Remarks:

- Only the **FIRST** impact of each rock trajectory on the gallery is used for the analysis (assumption: subsequent impacts are less severe).
- RAMMS creates a point-shapefile containing all impact-points with key attributes (impact force, angle, speed, etc.).

FID	Shape	Id	t (s)	Angle (°)	Vres pre (	Ekin pre (	F_R (kN)	Pen_R (m)
0	Point	0	12.433	57.075	31.634	2976.6	6325.5	0.855
1	Point	1	12.489	58.927	28.429	2458.6	5564.6	0.785
2	Point	2	13.501	61.955	23.004	1602	4316	0.6627
3	Point	3	13.977	64.94	25.653	1950.5	4919	0.7231
4	Point	4	12.567	31.467	19.748	1498.3	3593.7	0.5865
5	Point	5	13.191	60.229	29.69	2630	5861.9	0.8127
6	Point	6	13.447	59.857	25.546	1986.7	4894.3	0.7206
7	Point	7	12.087	51.942	29.848	2715.3	5899.4	0.8162
8	Point	8	13.649	52.357	26.963	2291.8	5221.9	0.7524
9	Point	9	11.497	52.067	29.999	2774.5	5935.4	0.8195
10	Point	10	17.581	52.846	13.746	582	2325.4	0.4389
11	Point	11	13.217	27.506	19.217	1254.7	3476.2	0.5738
12	Point	12	12.675	54.626	31.686	2980.3	6334.7	0.8561
13	Point	13	13.189	51.073	27.671	2287.5	5384.2	0.7681
14	Point	14	13.227	54.642	27.447	2179.8	5332.1	0.7632
15	Point	15	14.725	59.233	23.525	1555.6	4431.4	0.6746
16	Point	16	13.437	60.269	27.938	2291.7	5446.7	0.7741
17	Point	17	14.117	55.401	29.369	2534.6	5783.2	0.8056
18	Point	18	14.193	56.917	25.728	1894.7	4933.7	0.7247
19	Point	19	18.893	25.382	15.885	769.4	2766.1	0.4927
20	Point	20	11.835	56.344	29.58	2618.3	5835.9	0.8103
21	Point	21	12.781	55.906	26.022	2036.9	5004	0.7314
22	Point	22	11.049	32.828	22.17	1718.8	4128.9	0.6434
23	Point	23	13.387	56.268	27.912	2515.8	5443.4	0.7736
24	Point	24	13.057	56.956	27.197	2221.2	5276.5	0.7577
25	Point	25	12.669	22.757	14.64	769.02	2509.4	0.4616
26	Point	26	11.615	57.744	26.785	2217.9	5180.6	0.7485
27	Point	27	12.305	62.17	30.303	2631.1	6007.6	0.8261
28	Point	28	11.705	55.392	29.982	2704.9	5931.2	0.8191
29	Point	29	14.711	62.707	26.636	2025.9	5143.6	0.7451
30	Point	30	14.017	26.048	15.191	743.7	2621.9	0.4754
31	Point	31	11.971	56.328	29.622	2667.8	5842.9	0.8112
32	Point	32	11.383	60.678	28.705	2545.9	5626.7	0.791
33	Point	33	14.865	61.196	23.525	1574.2	4431.4	0.6746
34	Point	34	17.669	39.397	12.502	514.7	2075.3	0.4068
35	Point	35	14.315	42.145	11.106	364.88	1800.3	0.37

Figure 5-22: Point-shapefile with impact points on gallery.

- Additionally, RAMMS creates two raster files (GeoTIFF, linear interpolation):
    - Distribution of Impact-Force F_k (by Richtlinie) over gallery-area
    - Distribution of pentration-depth (by Richtlinie) over gallery-area

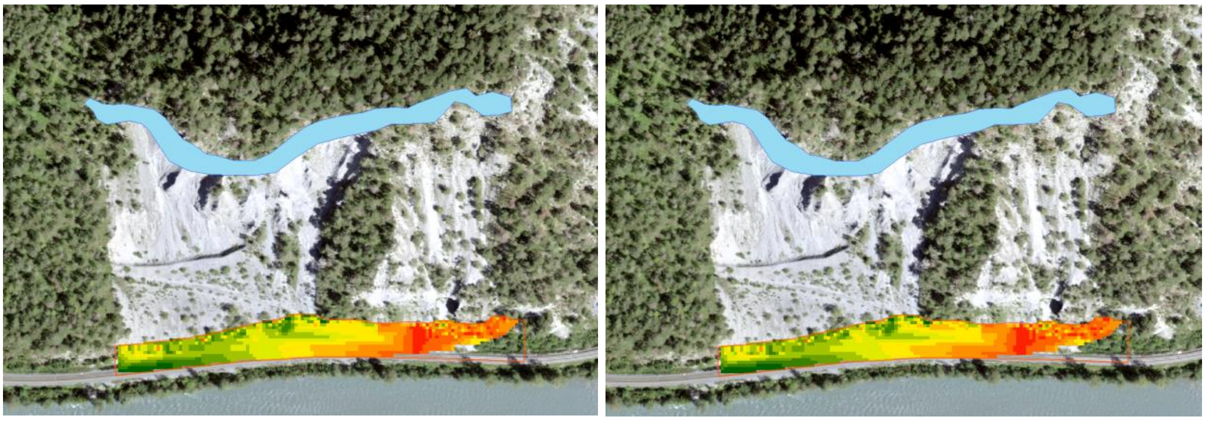


Figure 5-23: Raster results of impact force F_k (left) and penetration depth t (right).

5.2 Trajectory Mode

To analyze simulation results in more detail, the rocks can be opened in *Trajectory Mode*. This mode enables a detailed analysis of single trajectories of specific rocks. No statistic is available in *Trajectory Mode*.

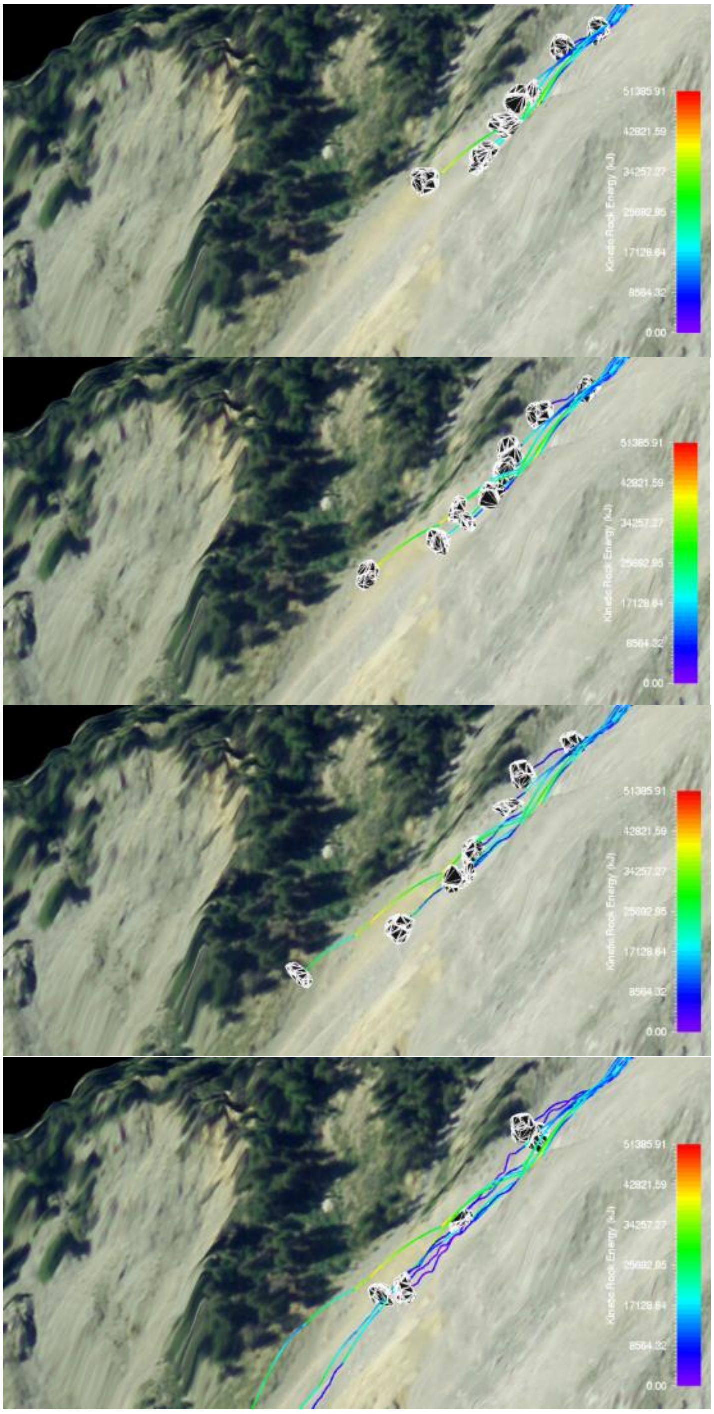


Figure 5-24: Rockfall trajectories; different colors depict different kinetic rock energies (KJ).

5.2.1 Open results in Trajectory Mode

Open trajectories with the button , the keyboard combination ***Ctrl+T*** or go to ***Track*** → ***Open*** → ***Rockfall Trajectories***. Choose the trajectories that you are interested in from the *traj_files* folder in the *output* scenario folder and click *Open*.

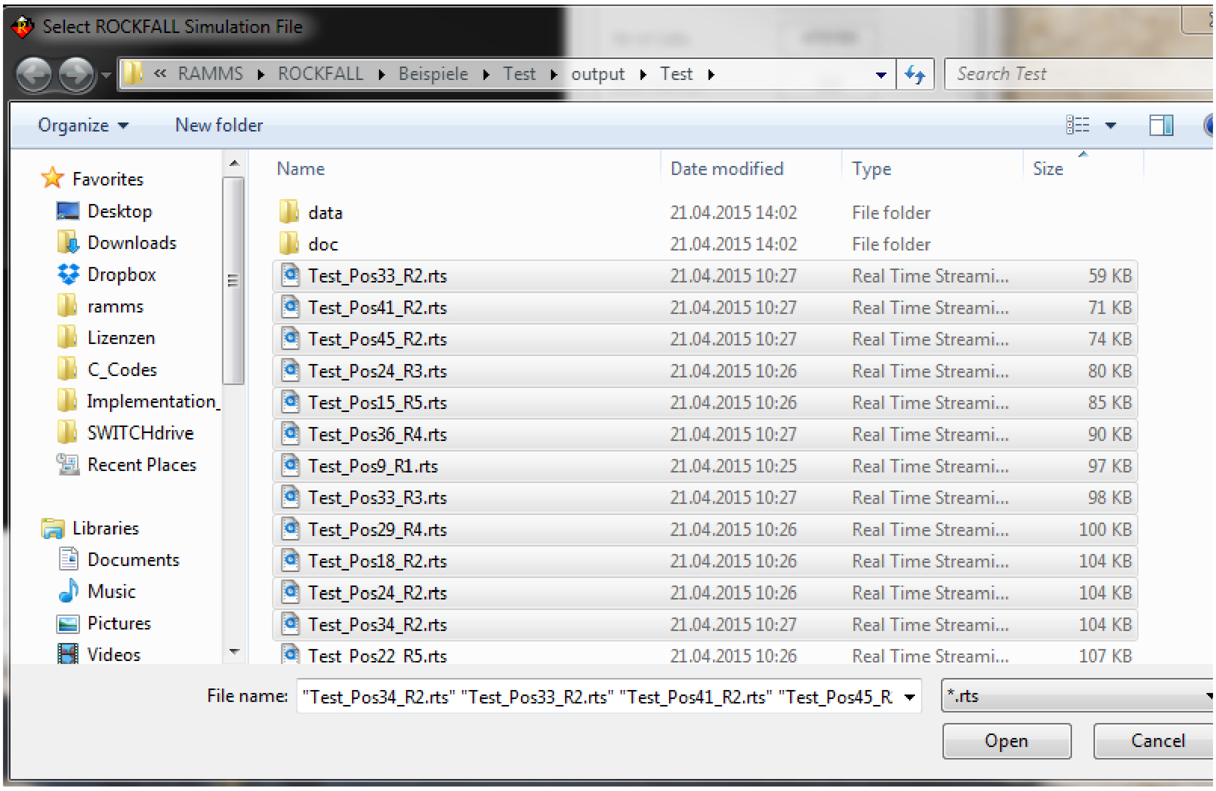


Figure 5-25: Open trajectories dialog window

RAMMS will then open all the selected trajectories. If you want to add trajectories from another scenario, or filter your output files, then use ***Track*** → ***Open*** → ***Rockfall Trajectories (Filter/Multi).*** In Figure 5-26 you could filter your selected trajectories (use a colon to use multiple filter strings). Otherwise click ***OK***.

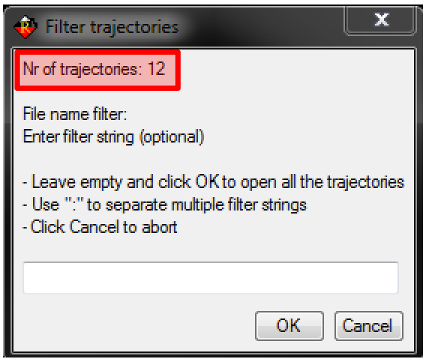


Figure 5-26 Filter options for selected trajectories

Add trajectories from other scenarios (but within the same project). Click ***Yes*** in Figure 5-27 to select more trajectories, click ***No*** otherwise.

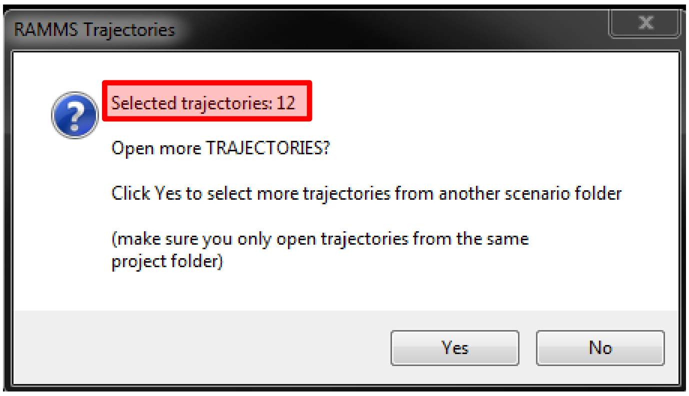


Figure 5-27 Possibility to add trajectories from another scenarios.

It is suggested to open only up to 100 single trajectories at one time (e.g. from a specific scenario). Although it is possible to open more trajectories, it is not recommended, because the memory usage will increase strongly, and the handling of your visualization will get very slow. Control if the trajectory mode is ON (in the general tab of the right field) and the toolbar shows the number of trajectories.

The buttons  provide quick access to Jump Height, Velocity and Kinetic Rock Energy of the simulation.

5.2.2 Visualize different parameters

The drop-down menu ***Results*** offers the following functions in the trajectory mode:

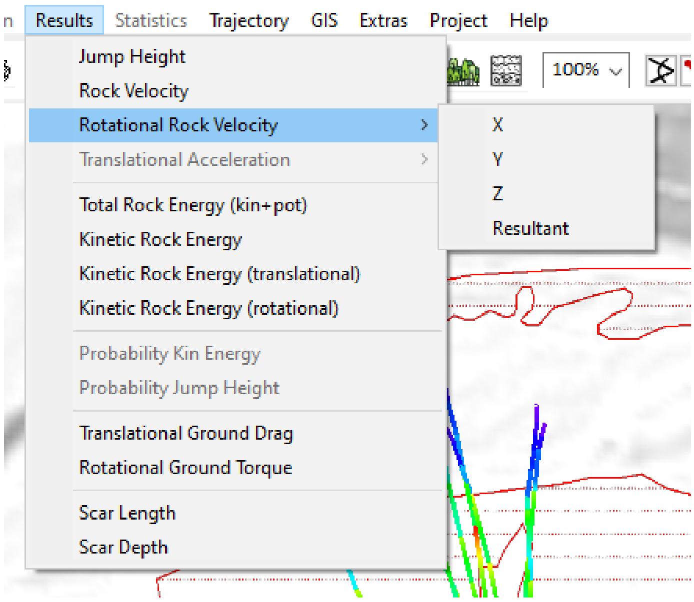


Figure 5-28: Trajectory Mode: Dropdown menu Results

- Jump Height (m)
- Rock Velocity (m/s)
- Rotational Rock Velocity → X, Y, Z, Resultant (rad/s, deg/s or rot/s)

(the unit of rotation can be adjusted in *Additional Preferences*, ROT_UNIT, default rotation unit is rot/s)

- Total Rock Energy (kin + pot) (kJ)
- Kinetic Rock Energy (kJ)
- Kinetic Rock Energy (translational) (kJ)
- Kinetic Rock Energy (rotational) (kJ)

- Translational Ground Drag (kN)
- Rotational Ground Torque (kNm)

- Scar Slippage (m)
- Scar Depth (m)

Exercise 5.2a: Displaying calculation values.

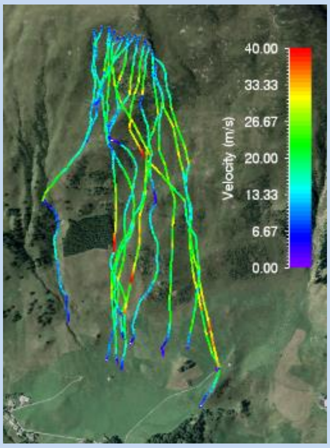


Figure 5-29: Results Velocity

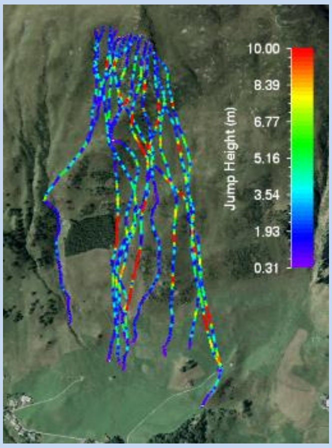


Figure 5-30: Results Jump Height

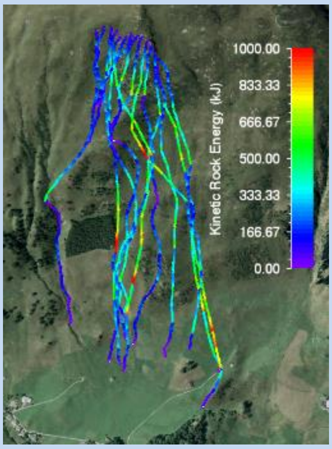


Figure 5-31: Results Kinetic Rock Energy

The values of **Jump Height**, **Rock Velocity** and **Kinetic Rock Energy** give a good overview of the dimension of the rockfall event in the trajectory mode. You can choose the parameters in the horizontal toolbar under ***Results***.

5.2.3 Working with trajectories

Select a trajectory with the mouse:

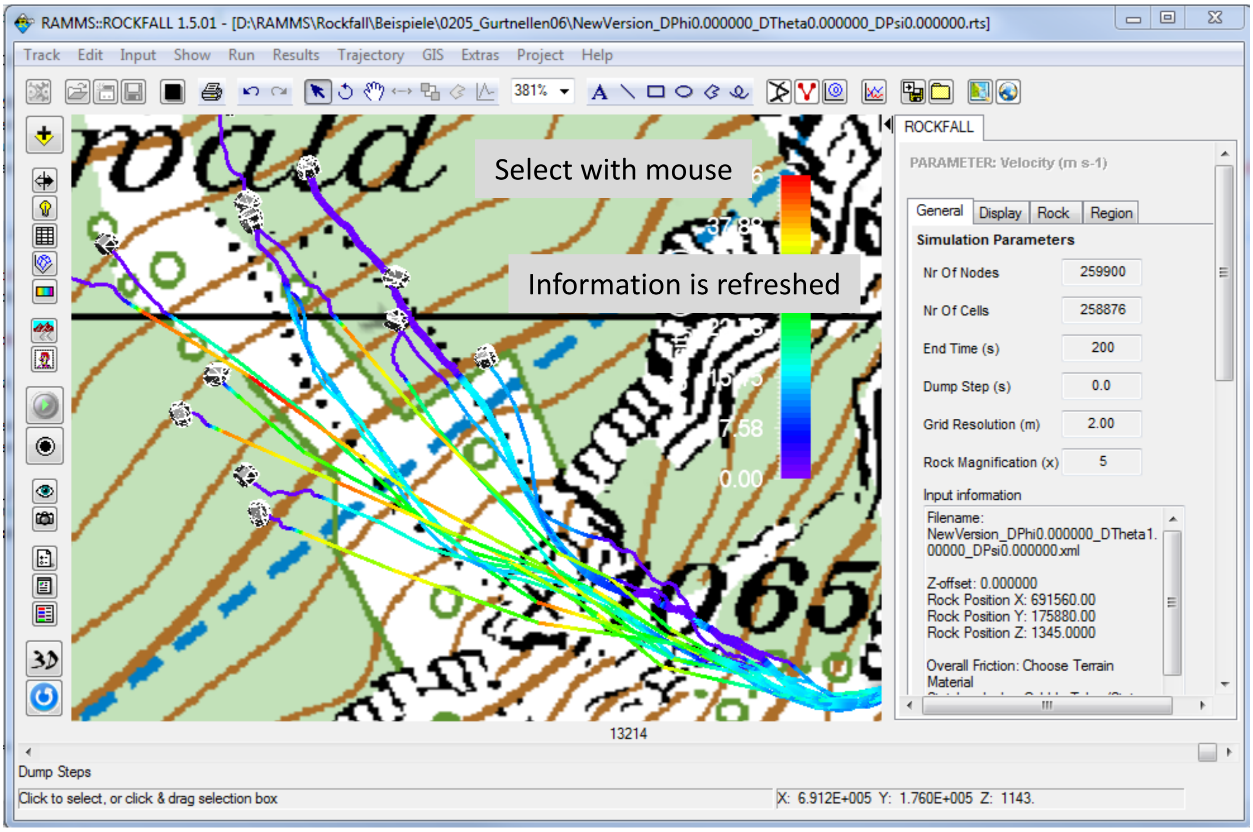


Figure 5-32: Trajectory information – *General* tab. The information (filename, start position of trajectory, etc.) is refreshed in the *General* tab on the right side. Additionally, the *Rock* tab indicates the rock used for the selected trajectory (see next figure).

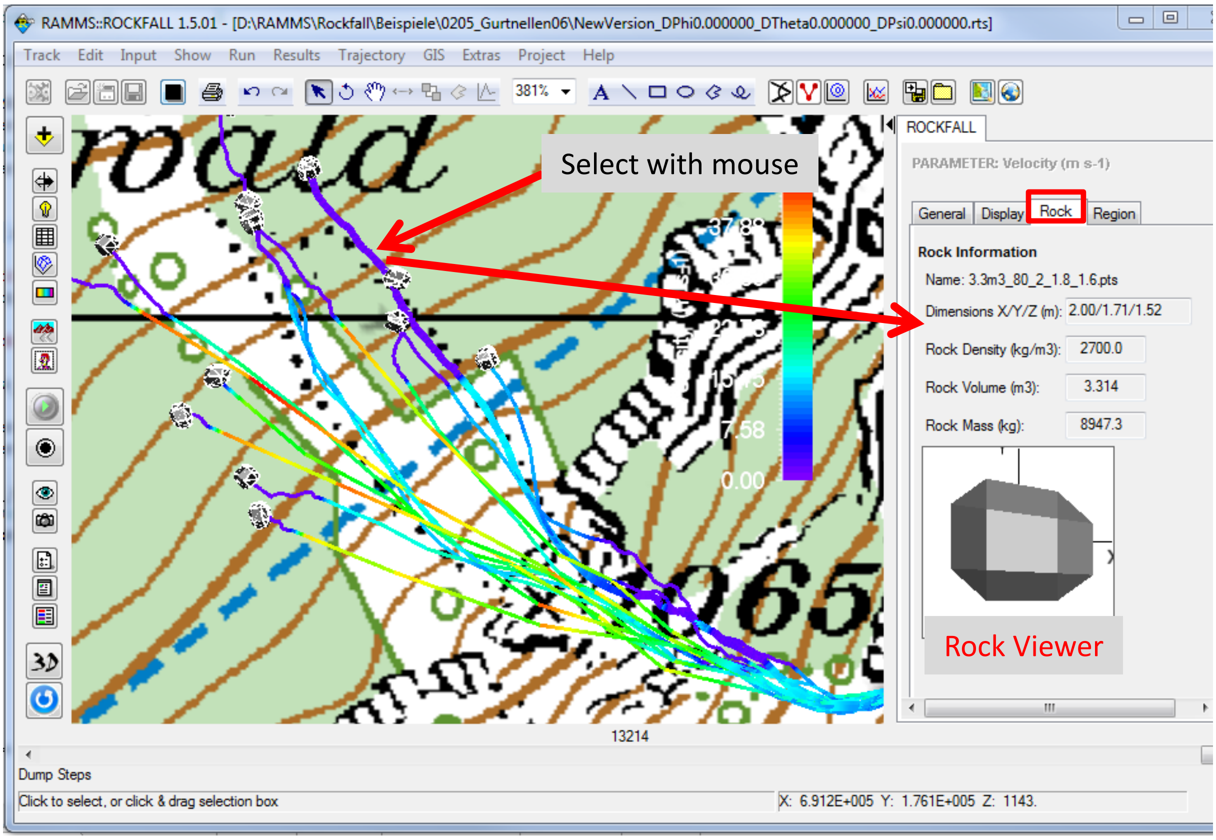


Figure 5-33: Trajectory information – *Rock* tab.

The menu ***Trajectory*** offers the following functions:

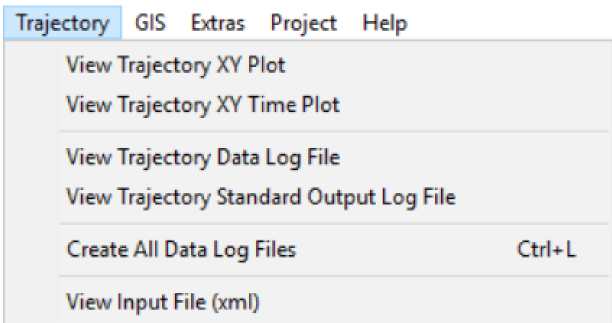
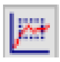


Figure 5-34: Trajectory Mode: Menu *Trajectory*.

- View Trajectory XY Plot
- View Trajectory XY Time Plot
- View Trajectory Data Log File
- View Trajectory Standard Output Log File
- Create All Data Log Files
- View Input File (xml)

In the horizontal toolbar you can find the following functions:

- Rock Trajectory XY Plot 
- Rock Trajectory XY Time Plot 
- Line Profile 

5.2.4 Rock Trajectory XY Plot

Click on a rock trajectory. You can find the function *View Trajectory XY Plot* in the horizontal toolbar (button ) or in the menu ***Trajectory*** → ***View Trajectory XY Plot***. If you want to analyze a trajectory in detail, the XY plot of a trajectory is the way to go. The graph shows the currently active parameter (you can change it by clicking one of the buttons in the upper horizontal toolbar  or by selecting another result parameter via the ***Results*** menu). You can keep the *Trajectory XY Plot* by saving it, see Exercise 5.2b below *"How to create a Trajectory XY Plot"*.

Exercise 5.2b : How to create a Trajectory XY Plot

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once. Then click on the specific rock trajectory you want to plot.
- Go to ***Trajectory*** → ***View Trajectory XY Plot*** or click .

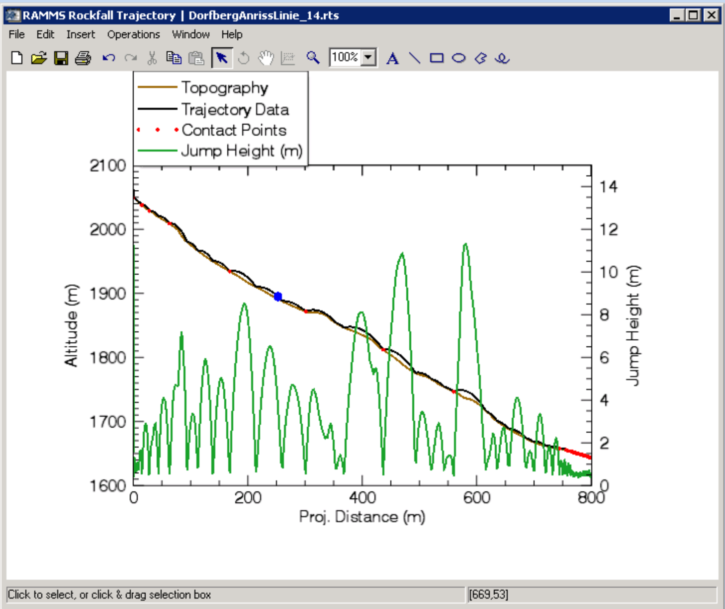


Figure 5-35: Trajectory XY Plot.

- A window opens, displaying the **Trajectory XY Plot**.
- You can save, print and modify the plot with the tools in the upper toolbar or open another plot.

Plot explanations:

- Brown line: terrain surface (scale on the left side).
- Black line: rock trajectory added to the terrain surface (altitude in m a.s.l., scale on the left side).
- Green line: active parameter (scale on the right side).
- Blue dot: current rock position (according to the dump step shown in your simulation).
- Red dots: points of contact/scarring (consider the time step of your simulation – missing contact points are possible if time steps are too large).
- Bottom scale: projected profile distance (m).

5.2.5 Line profile

Go to ***Extras*** → ***Profile...*** → ***Draw Line Profile*** or click  to draw a line profile. The line profile function provides a graph of the currently active parameter along a specific line through the rockfall area. This is helpful when it is of interest to know the values and maximum values at these places (e.g. close to a road or dam). Line profiles are saved in the file *profile.txt* in the project directory. If you want to keep a line profile, you have to save it, see Exercise 5.2c *"How to draw a line profile"*.

Exercise 5.2c : How to draw a line profile

(1) Draw a new line profile:

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once, then click  or choose ***Extras*** → ***Profile...*** → ***Draw New Line Profile***.
- Define the line profile in the same way you specify a new release line (see Exercise 4.4b *"How to create a new release line"*). Finish the line profile with a right-click on the mouse button.

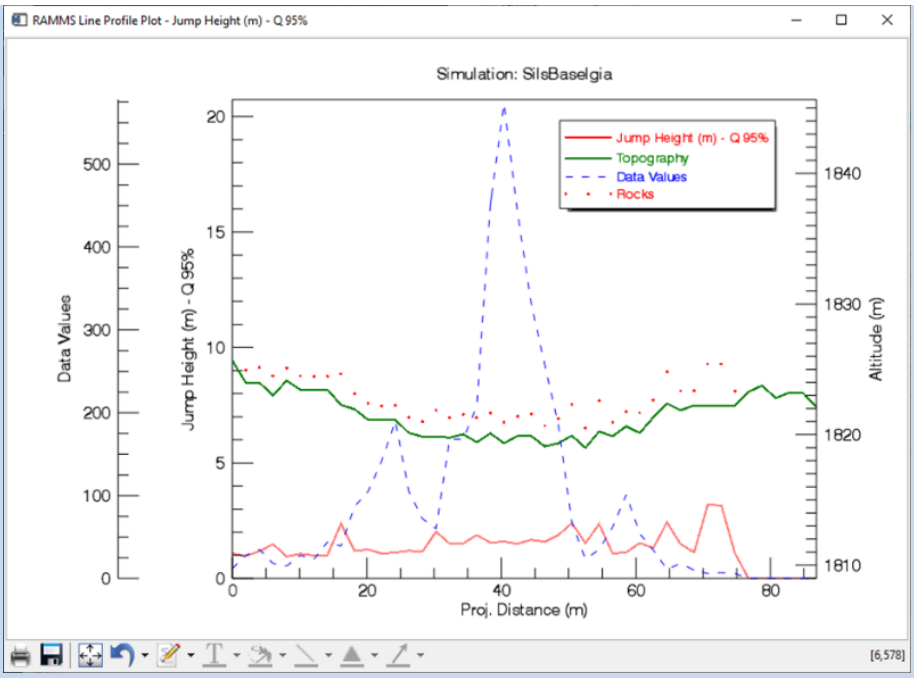


Figure 5-36: Line Profile Plot

- A window opens, displaying the **Line Profile**.

  Plot explanations:
  - **Green line**: track profile (altitude, y-axis on the right side).
  - **Red dots**: active parameter (rock position) on top of the topography (altitude, y-axis on the right side).
  - **Red line**: active parameter (inner y-axis on the left side).
  - **Blue dashed line**: the ***Data Values*** distribution.
  - Bottom x-axis: projected profile distance (m).

  If you change the active parameter or the *Min* and *Max* values in the *Display* tab in RAMMS, the plot will be directly updated.

- To save the coordinates of the points belonging to the line profile, select ***Extras*** → ***Profile…*** → ***Save Line Profile Points*** and enter a file name.
- To save the line profile parameter's data (distance (m) and the active parameter, e.g. the jump height (m)) at the current dump step, select ***Extras*** → ***Profile…*** → ***Export Line Profile Plot Data*** and enter a file name.

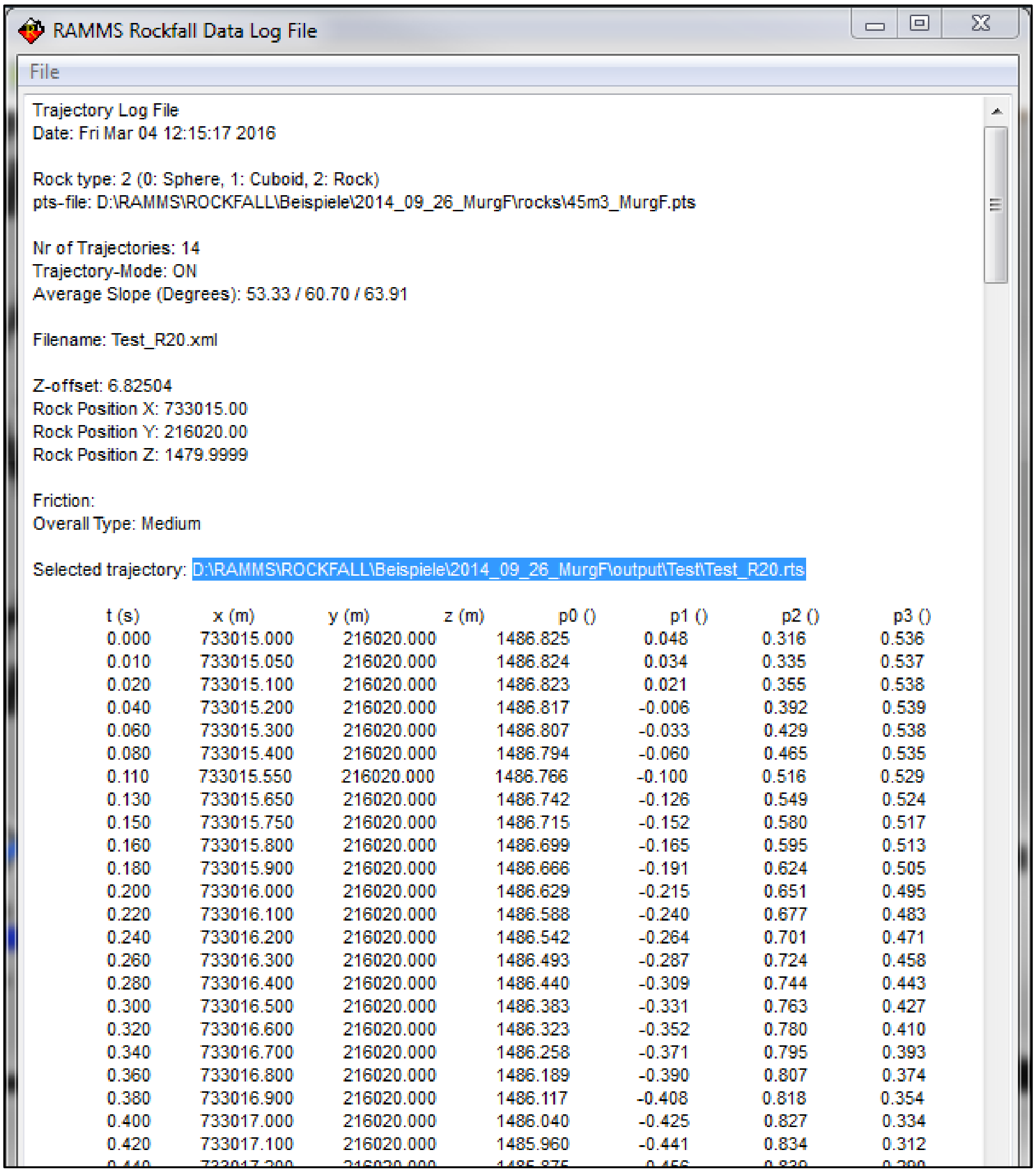
(2) Load an existing line profile:

- Switch to 2D mode by clicking .
- Activate the project by clicking on it once, then click or choose ***Extras*** → ***Profile…*** → ***Draw New Line Profile***.

- Click the *middle mouse button* once.
- A window pops up and you can browse for the line profile you wish to open.

5.2.6 Trajectory Data Log File

To see the exact values of the simulation results, check the *Trajectory Data Log File* which shows the results for every dump step of a single trajectory. After running a simulation click on a rock trajectory in the trajectory mode and go to ***Trajectory → View Trajectory Data Log File*** to open it.



RAMMS Rockfall Data Log File

File

Trajectory Log File
Date: Fri Mar 04 12:15:17 2016

Rock type: 2 (0: Sphere, 1: Cuboid, 2: Rock)
pts-file: D:\RAMMS\ROCKFALL\Beispiele\2014_09_26_MurgF\rocks\45m3_MurgF.pts

Nr of Trajectories: 14
Trajectory-Mode: ON
Average Slope (Degrees): 53.33 / 60.70 / 63.91

Filename: Test_R20.xml

Z-offset: 6.82504
Rock Position X: 733015.00
Rock Position Y: 216020.00
Rock Position Z: 1479.9999

Friction:
Overall Type: Medium

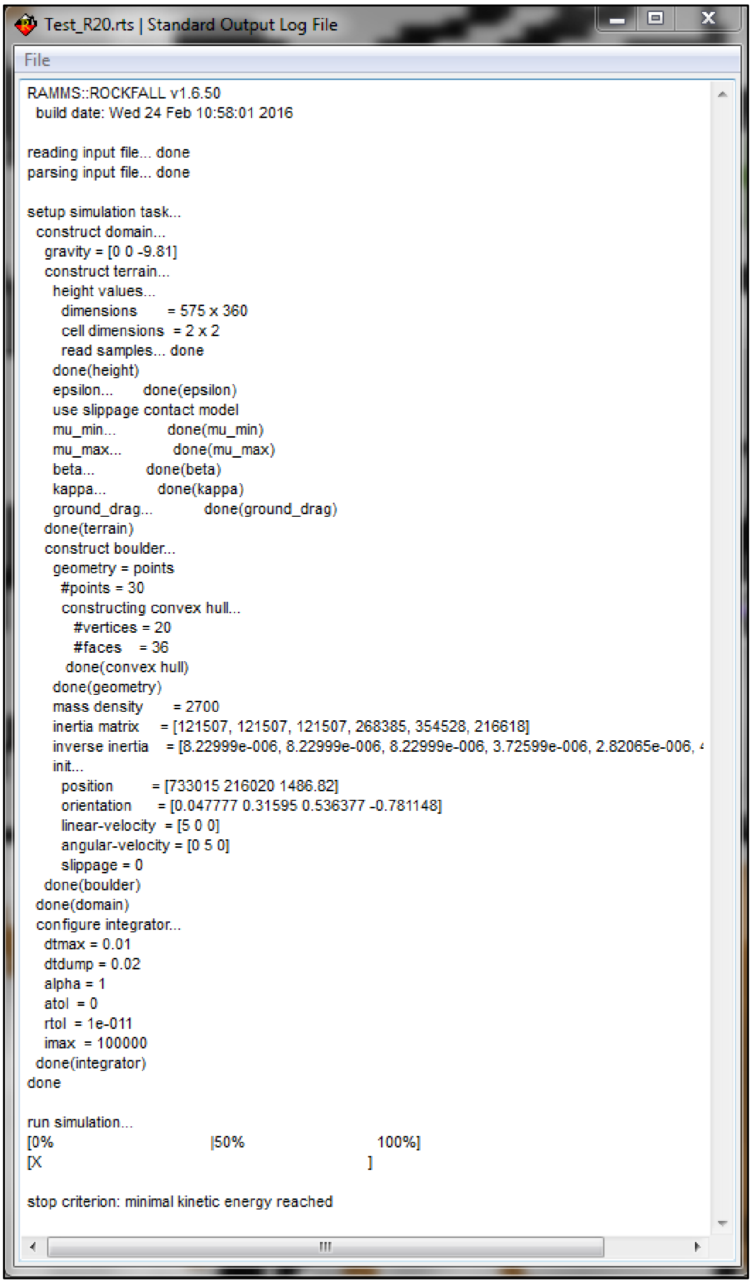
Selected trajectory: D:\RAMMS\ROCKFALL\Beispiele\2014_09_26_MurgF\output\Test\Test_R20.rts

t (s)	x (m)	y (m)	z (m)	p0 ()	p1 ()	p2 ()	p3 ()
0.000	733015.000	216020.000	1486.825	0.048	0.316	0.536	
0.010	733015.050	216020.000	1486.824	0.034	0.335	0.537	
0.020	733015.100	216020.000	1486.823	0.021	0.355	0.538	
0.040	733015.200	216020.000	1486.817	-0.006	0.392	0.539	
0.060	733015.300	216020.000	1486.807	-0.033	0.429	0.538	
0.080	733015.400	216020.000	1486.794	-0.060	0.465	0.535	
0.110	733015.550	216020.000	1486.766	-0.100	0.516	0.529	
0.130	733015.650	216020.000	1486.742	-0.126	0.549	0.524	
0.150	733015.750	216020.000	1486.715	-0.152	0.580	0.517	
0.160	733015.800	216020.000	1486.699	-0.165	0.595	0.513	
0.180	733015.900	216020.000	1486.666	-0.191	0.624	0.505	
0.200	733016.000	216020.000	1486.629	-0.215	0.651	0.495	
0.220	733016.100	216020.000	1486.588	-0.240	0.677	0.483	
0.240	733016.200	216020.000	1486.542	-0.264	0.701	0.471	
0.260	733016.300	216020.000	1486.493	-0.287	0.724	0.458	
0.280	733016.400	216020.000	1486.440	-0.309	0.744	0.443	
0.300	733016.500	216020.000	1486.383	-0.331	0.763	0.427	
0.320	733016.600	216020.000	1486.323	-0.352	0.780	0.410	
0.340	733016.700	216020.000	1486.258	-0.371	0.795	0.393	
0.360	733016.800	216020.000	1486.189	-0.390	0.807	0.374	
0.380	733016.900	216020.000	1486.117	-0.408	0.818	0.354	
0.400	733017.000	216020.000	1486.040	-0.425	0.827	0.334	
0.420	733017.100	216020.000	1485.960	-0.441	0.834	0.312	

Figure 5-37: Trajectory Data Log File.

5.2.7 Trajectory Standard Output Log File

Further information of a simulation run is available under ***Trajectory*** → ***Standard Output Log File*** and




```
RAMMS::ROCKFALL v1.6.50
 build date: Wed 24 Feb 10:58:01 2016

reading input file... done
parsing input file... done

setup simulation task...
 construct domain...
  gravity = [0 0 -9.81]
  construct terrain...
   height values...
    dimensions      = 575 x 360
    cell dimensions  = 2 x 2
    read samples... done
   done(height)
   epsilon...      done(epsilon)
   use slippage contact model
   mu_min...          done(mu_min)
   mu_max...          done(mu_max)
   beta...         done(beta)
   kappa...          done(kappa)
   ground_drag...          done(ground_drag)
  done(terrain)
  construct boulder...
   geometry = points
    #points = 30
    constructing convex hull...
     #vertices = 20
     #faces    = 36
    done(convex hull)
   done(geometry)
   mass density      = 2700
   inertia matrix    = [121507, 121507, 121507, 268385, 354528, 216618]
   inverse inertia   = [8.22999e-006, 8.22999e-006, 8.22999e-006, 3.72599e-006, 2.82065e-006,
   init...
    position       = [733015 216020 1486.82]
    orientation     = [0.047777 0.31595 0.536377 -0.781148]
    linear-velocity  = [5 0 0]
    angular-velocity = [0 5 0]
    slippage = 0
  done(boulder)
 done(domain)
 configure integrator...
  dtmax = 0.01
  dtdump = 0.02
  alpha = 1
  atol  = 0
  rtol  = 1e-011
  imax  = 100000
 done(integrator)
done

run simulation...
[0%                      |50%                    100%]
[X                                             ]

stop criterion: minimal kinetic energy reached
```

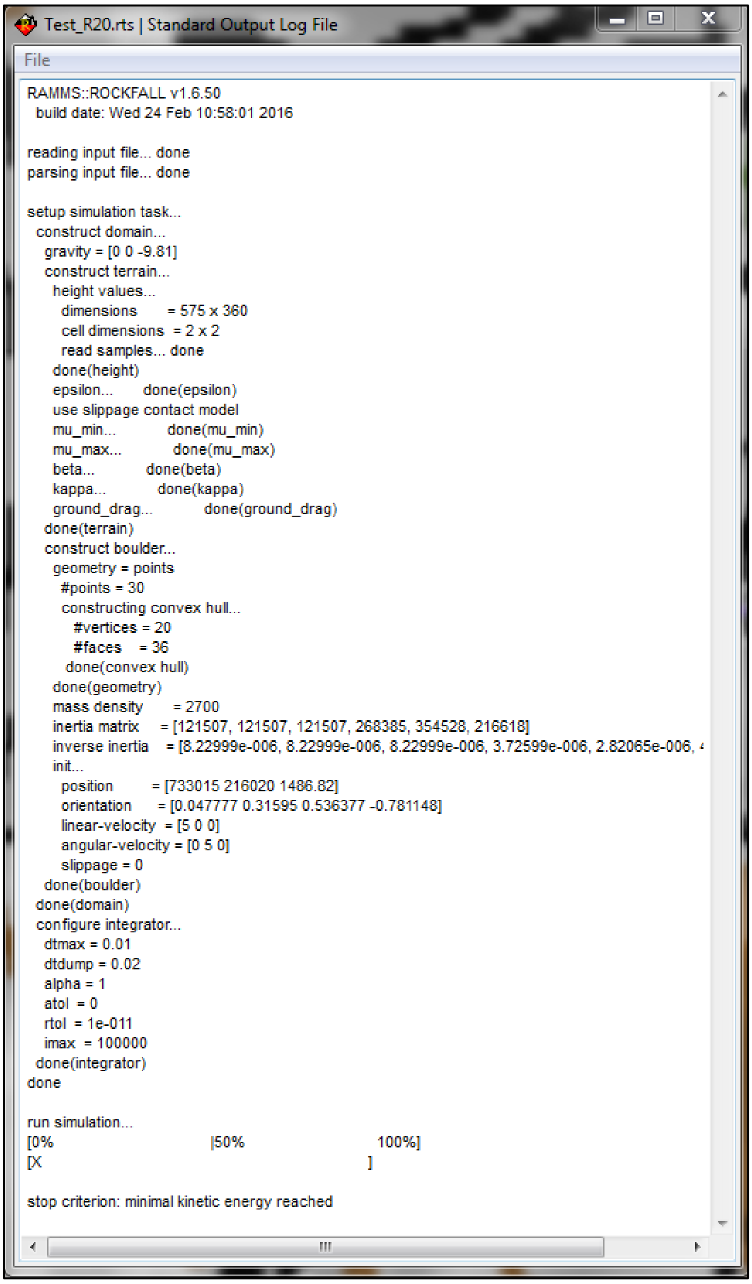
Figure 5-38: Trajectory Standard Output Log File.

5.2.8 Create All Data Log Files

Select **Trajectory -> Create All Data Log Files** or hit the combination **Ctrl+L** to create data log files for all currently opened trajectories. These data log files are the same as described in Figure 5-37 and will be saved in **../ProjectDirectory/output/ScenarioDirectory/data.** Note that depending on the amount of opened trajectories, generating all log files could take a long time and use a lot of disk space.

5.2.9 Trajectory Input File

The input file is a simple xml file and can be viewed from within RAMMS. Use ***Trajectory* → *View Input File (xml)*** to open a selected trajectory's input file.



Test_R20.rts | Standard Output Log File

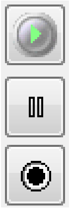
File

```
RAMMS::ROCKFALL v1.6.50
 build date: Wed 24 Feb 10:58:01 2016

reading input file... done
parsing input file... done

setup simulation task...
 construct domain...
  gravity = [0 0 -9.81]
  construct terrain...
   height values...
    dimensions     = 575 x 360
    cell dimensions  = 2 x 2
    read samples... done
   done(height)
   epsilon...     done(epsilon)
   use slippage contact model
   mu_min...        done(mu_min)
   mu_max...        done(mu_max)
   beta...        done(beta)
   kappa...        done(kappa)
   ground_drag...        done(ground_drag)
  done(terrain)
  construct boulder...
   geometry = points
    #points = 30
    constructing convex hull...
     #vertices = 20
     #faces    = 36
    done(convex hull)
   done(geometry)
   mass density     = 2700
   inertia matrix   = [121507, 121507, 121507, 268385, 354528, 216618]
   inverse inertia   = [8.22999e-006, 8.22999e-006, 8.22999e-006, 3.72599e-006, 2.82065e-006,
   init...
    position       = [733015 216020 1486.82]
    orientation     = [0.047777 0.31595 0.536377 -0.781148]
    linear-velocity  = [5 0 0]
    angular-velocity = [0 5 0]
    slippage = 0
  done(boulder)
 done(domain)
 configure integrator...
  dtmax = 0.01
  dtdump = 0.02
  alpha = 1
  atol  = 0
  rtol  = 1e-011
  imax  = 100000
 done(integrator)
done

run simulation...
[0%                    |50%                    100%]
[X                                             ]

stop criterion: minimal kinetic energy reached
```

Figure 5-39: Trajectory Input File.

5.2.10 Rock trajectory animation

It is possible to start an animation of all trajectories. Switch to 3D mode by clicking (2D mode is working as well).



Start the animation (Alternative: *F8*)

Pause the animation (Alternative: *F8*)

Stop/Restart the animation (Alternative: *F9*)

Change the speed of the animation in the *Display* tab on the right side (speed slider from fast to slow).

Figure 5-40: Animation speed control slider.

5.3 Exporting image or GIF animation

Image

It is possible to export your results as an image in different formats (e.g. .png, .jpg, .gif, .tif etc.). Click or choose ***Track → Export... → Image File*** and define a file name with the corresponding extension. An image of the visible part in the viewer will then be exported.

GIF animation

Creating a GIF animation is only possible in output mode. Click or choose ***Track → Export... → GIF Animation***. Enter a file name and location and wait until the simulation stopped. As soon as the simulation finished, the GIF animation file is saved. In the *Preferences* you can define the interval for the GIF animation (GIF animation interval (s)) in the *Rockfall* tab.

6 References and further reading

6.1 References

Maps and aerial images

➔ All topographic base maps and aerial images from Source: Swiss Federal Office of Topography

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6.2 Publications

The development of RAMMS::ROCKFALL is based on scientific findings published in international scientific journals. A list of the most important scientific publications about RAMMS::ROCKFALL and its applications is given below (chronological order). This publication-list is also available on our webpage: https://www.ramms.ch/ramms-rockfall/

Key ROCKFALL Publications

Leine, R.I.; Capobianco, G.; Bartelt, P.; Christen, M.; Caviezel, A., 2021: Stability of rigid body motion through an extended intermediate axis theorem: application to rockfall simulation. Multibody System Dynamics, 52: 431-455. doi: 10.1007/s11044-021-09792-y

Caviezel, A.; Ringenbach, A.; Demmel, S.E.; Dinneen, C.E.; Krebs, N.; Bühler, Y.; Christen, M.; Meyrat, G.; Stoffel, A.; Hafner, E.; Eberhard, L.A.; Von Rickenbach, D.; Simmler, K.; Mayer, P.; Niklaus, P.S.; Birchler, T.; Aebi, T.; Cavigelli, L.; Schaffner, M.; ... Bartelt, P., 2021: The relevance of rock shape over mass - implications for rockfall hazard assessments. Nature Communications, 12: 5546 (9 pp.). doi: 10.1038/s41467-021-25794-y

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Lu, G.; Caviezel, A.; Christen, M.; Demmel, S.E.; Ringenbach, A.; Bühler, Y.; Dinneen, C.E.; Gerber, W.; Bartelt, P., 2019: Modelling rockfall impact with scarring in compactable soils. Landslides, 16: 2353-2367. doi: 10.1007/s10346-019-01238-z

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Third-Party Software

The following third-party software components are used in RAMMS::Rockfall:

7-zip:

- We sometimes use *7za.exe* to zip data.
- *7-zip* is licensed under GNU LGPL.
- The source code of *7-zip* is available at www.7-zip.org.

Mtee:

- *Mtee* is a Win32 console application that sends any data it receives to stdout and to any number of files.
- *Mtee* is released under MIT License https://ritchielawrence.github.io/mtee/.

Bullet v2.85

Bullet Continuous Collision Detection and Physics Library
http://bulletphysics.org

zlib-License (http://opensource.org/licenses/Zlib):

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and

The National Science and Technology Research Center for
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(The Geometry Center)
University of Minnesota

email: qhull@qhull.org

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VolInt

```
 /*******************************************************
*                                                       *
 *  volInt.c                                              *
 *                                                        *
 *  This code computes volume integrals needed for       *
 *  determining mass properties of polyhedral bodies.    *
 *                                                        *
 *  For more information, see the accompanying README    *
 *  file, and the paper                                   *
 *                                                        *
 *  Brian Mirtich, "Fast and Accurate Computation of     *
 *  Polyhedral Mass Properties," journal of graphics     *
 *  tools, volume 1, number 1, 1996.                      *
 *                                                        *
 *  This source code is public domain, and may be used   *
 *  in any way, shape or form, free of charge.            *
 *                                                        *
 *  Copyright 1995 by Brian Mirtich                       *
 *                                                        *
 *  mirtich@cs.berkeley.edu                               *
 *  http://www.cs.berkeley.edu/~mirtich                   *
*                                                       *
 *******************************************************/
```

/*

List of Figures

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