



# **Protective Structures in RAMMS::ROCKFALL**

*Modeling, Simulation and Performance Evaluation of  
Rockfall Protection Systems*

**Marc Christen and Perry Bartelt**  
**RAMMS AG, Davos Wiesen, Switzerland**

# Types of Protective Structures



Flexible barriers (Geobrugg)

Protective structures are engineering measures designed to **intercept, deflect, or withstand falling rocks** before they reach infrastructure or exposed areas.

## Typical objectives:

- Stop or capture falling blocks
- Reduce kinetic energy
- Protect roads, railways and settlements

RAMMS allows protective structures to be considered in simulations.



Rockfall sheds / RhB Aulta GR



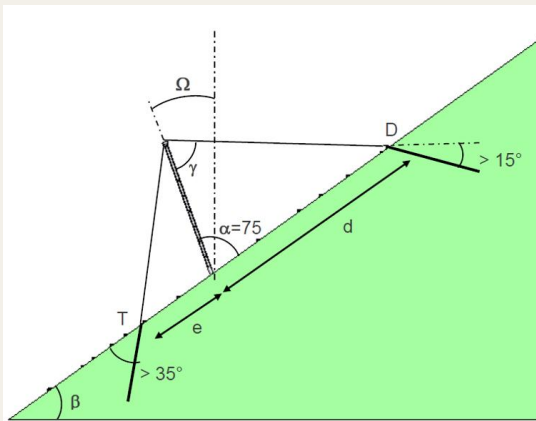
Rockfall dam / Klosters GR

# Representation of Barriers in RAMMS



In RAMMS, each **barrier segment** is represented as an **individual object** that interacts with rock trajectories during the simulation:

- Nets are modeled as **thin-wall obstacles**
- Each **net field** (post to post) is modeled separately
- Geometry represented as **convex hull point clouds**
- Nets can be **created interactively** in RAMMS (by drawing lines) or created from existing polyline shapefiles.



Important geometric parameters:

- **Barrier height (m)**
- **Post angle relative to terrain**
- **Support post spacing**

Default value: **Post angle relative to terrain  $\alpha = 75^\circ$**



# Barrier Energy Absorption Capacity



Flexible barriers are designed to **absorb the kinetic energy of impacting rocks**. The kinetic energy of a falling rock is

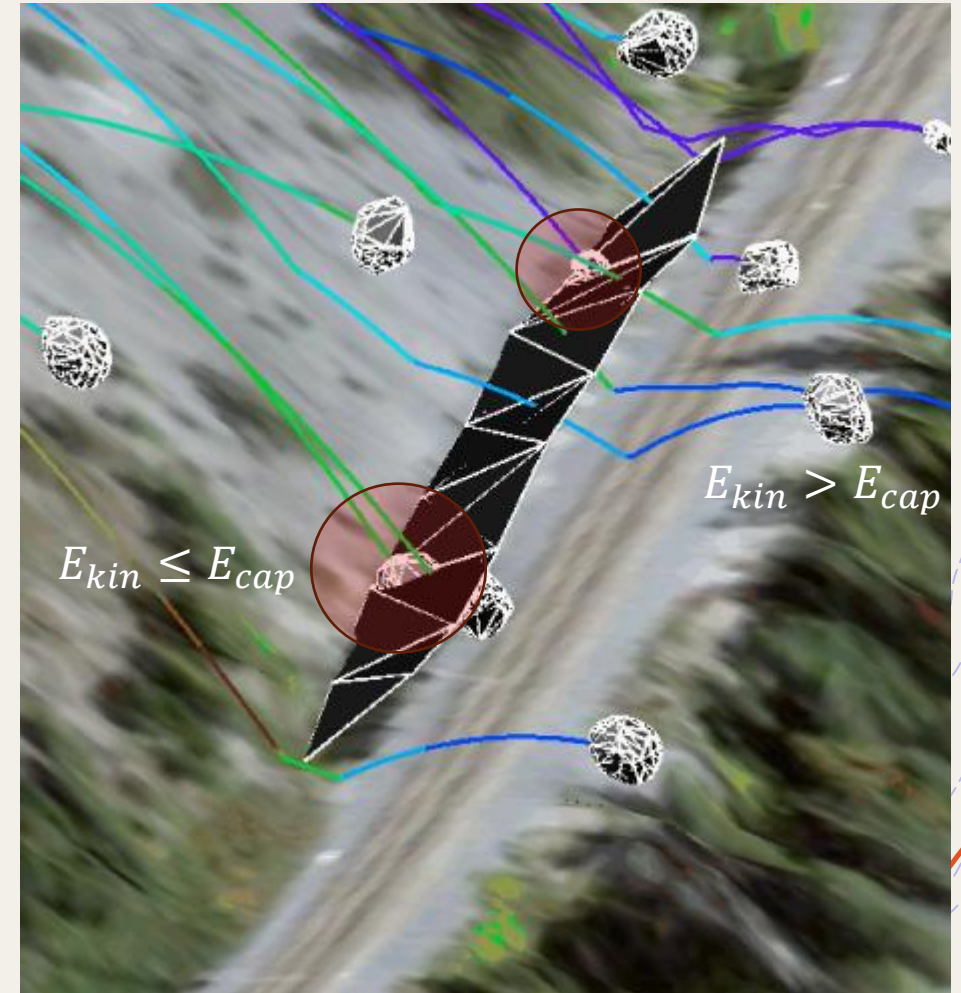
$$E_{kin} = \frac{1}{2}mv^2 \quad \text{where}$$

- $m$  = rock mass (kg)
- $v$  = rock velocity at impact (m/s)

Barrier performance follows a simple **energy criterion**:

$$E_{kin} \leq E_{cap} \Rightarrow \text{rock is stopped}$$
$$E_{kin} > E_{cap} \Rightarrow \text{rock passes through the barrier}$$

Each barrier is characterized by a **maximum energy absorption capacity**  $E_{cap}$



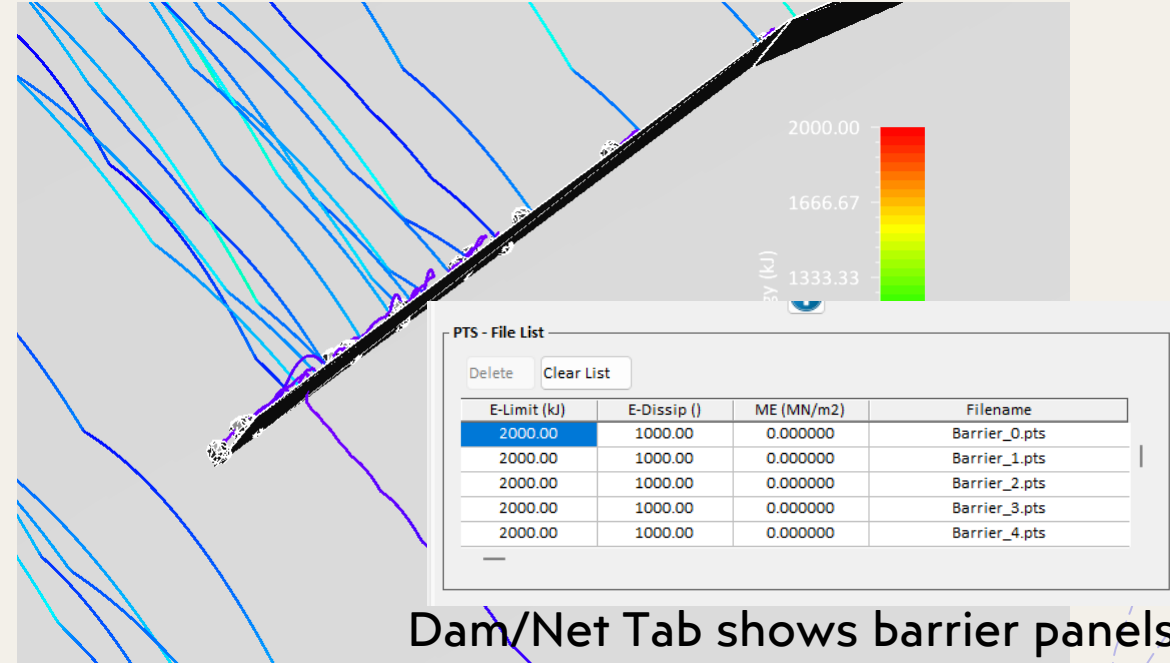
# Creating Barriers in RAMMS



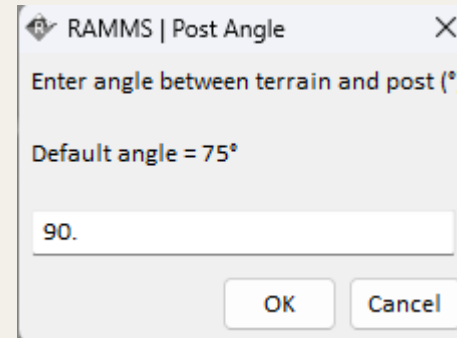
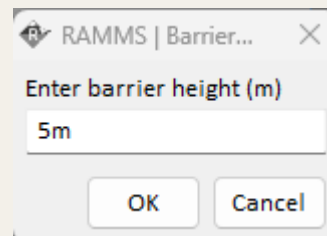
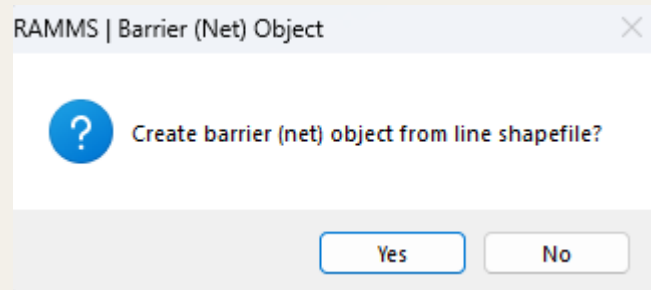
Two possible workflows:

## Option 1 – Draw barriers in RAMMS

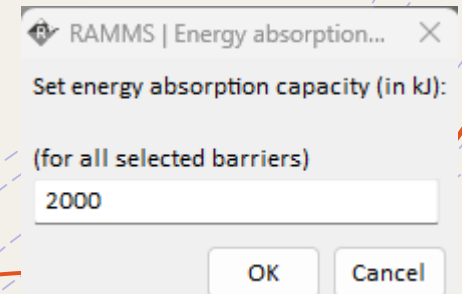
- Draw line shapefile
- Define post spacing (each point along the line defines a post)
- RAMMS generates barrier objects



Dam/Net Tab shows barrier panels



Energy absorption capacity for every single net



Enter barrier (net) height in (m).

Enter angle between terrain and posts.

# Creating Barriers in RAMMS



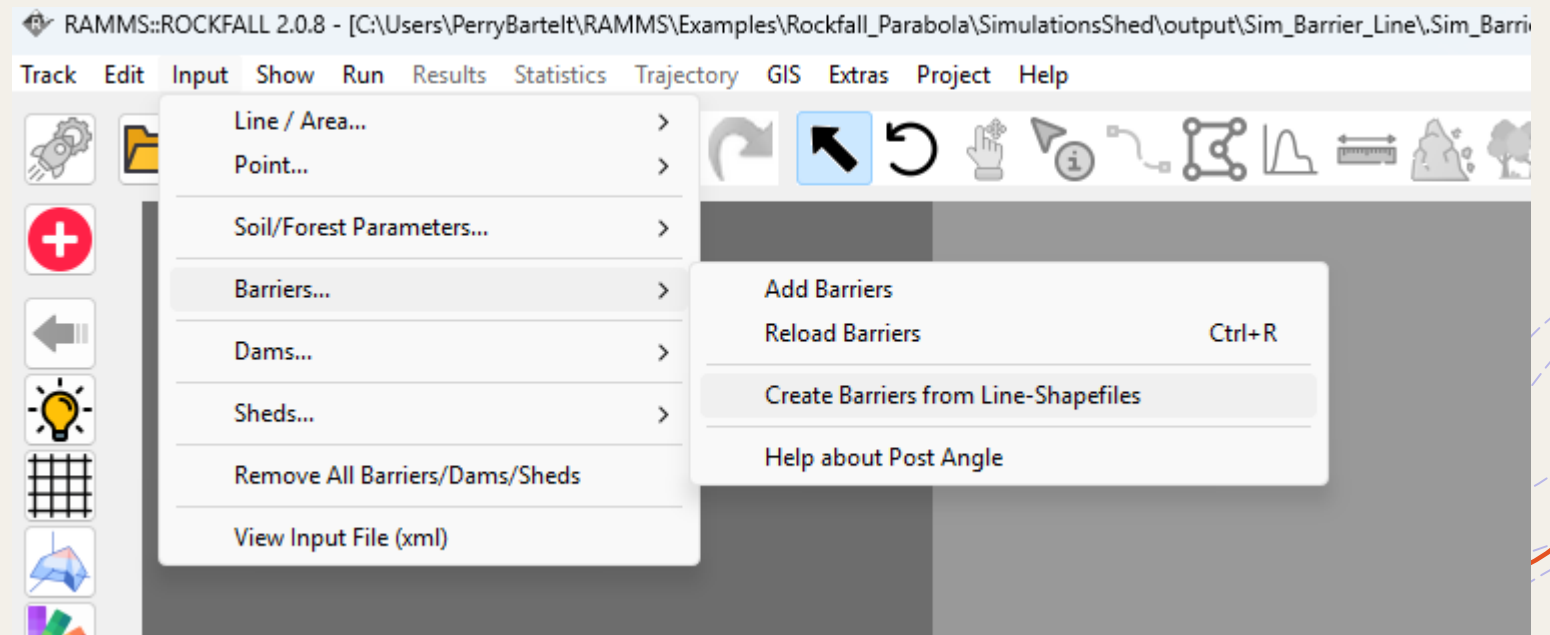
Two possible workflows:

## Option 2 – Import existing shapefiles

- Use *Input* → *Barriers* → *Create Barriers from Line-Shapefiles*
- Used to keep barrier geometry, but change input parameters

Input parameters:

- Height
- Post angle
- Energy absorption capacity



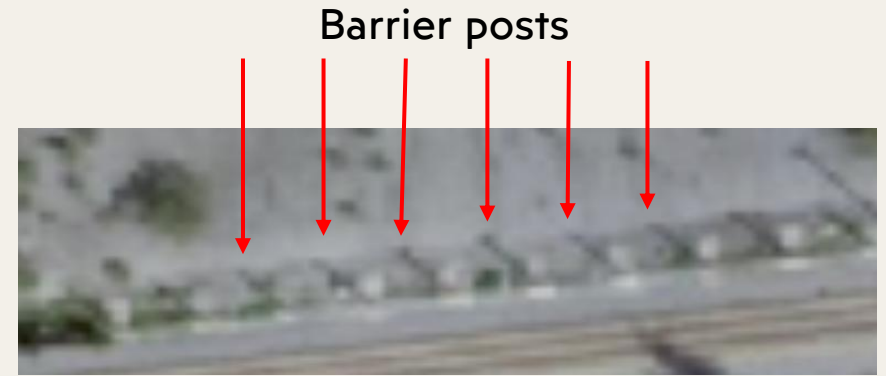
# Some Helpful Barrier Tools



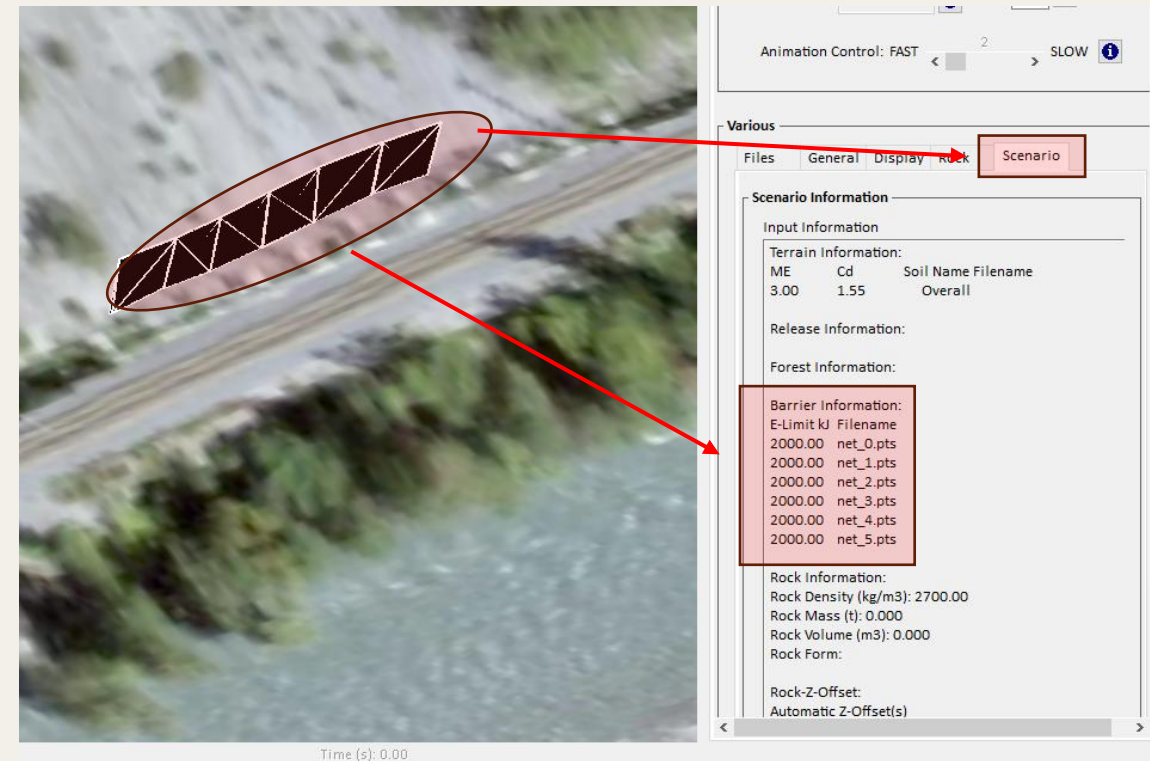
- While drawing the line shapefile, RAMMS indicates the distance from the mouse pointer to the last click.



- Remove all barrier objects with *Input* → *Remove Barriers/Dams*



Net objects can be visualized in RAMMS.



# Jump Height vs. Kinetic Energy at Target Line

Used to visualize the **impact energy and jump height** of rock trajectories along a line shapefile.

## Purpose

- Visualize rock trajectory behavior at a target line.
- Each point represents one rock crossing the line shapefile.

## Axes

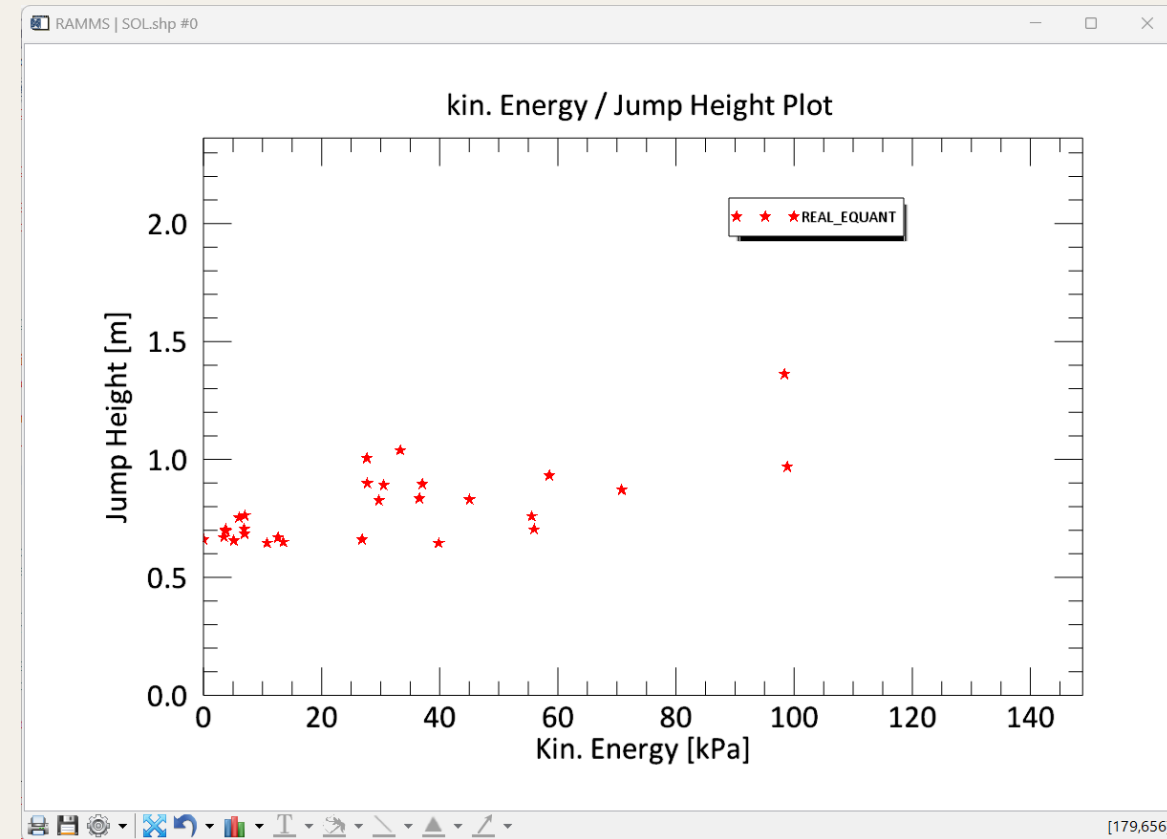
- Y-axis: Jump Height (m) – rock jump when crossing the line.
- X-axis: Kinetic Energy (kPa) – impact energy at that point.

## Interpretation

- Lower-left: low energy & low jump height → lower risk.
- Upper-right: high energy & large jumps → potentially critical impacts.

## Output

- Color-coded rock types for comparison.
- CSV export of jump height, kinetic energy, and trajectory file.



Statistics → JumpH vs KinEnergy Plot for Target Line

# Probability of Reaching Target Line (SOL)



## Purpose

- Quantifies how many simulated rockfall trajectories reach and cross user-defined SOL lines.
- Used to evaluate exposure of infrastructure such as roads, railways, or protective lines.

## Key Outputs

- Reach probability (pEr) for each rock type and SOL segment.
- Probability of occurrence (prA) for trajectories reaching the SOL.

## Applications

- Verify placement of protective measures (roads, fences, barriers).
- Provide crossing probabilities for quantitative risk analyses.

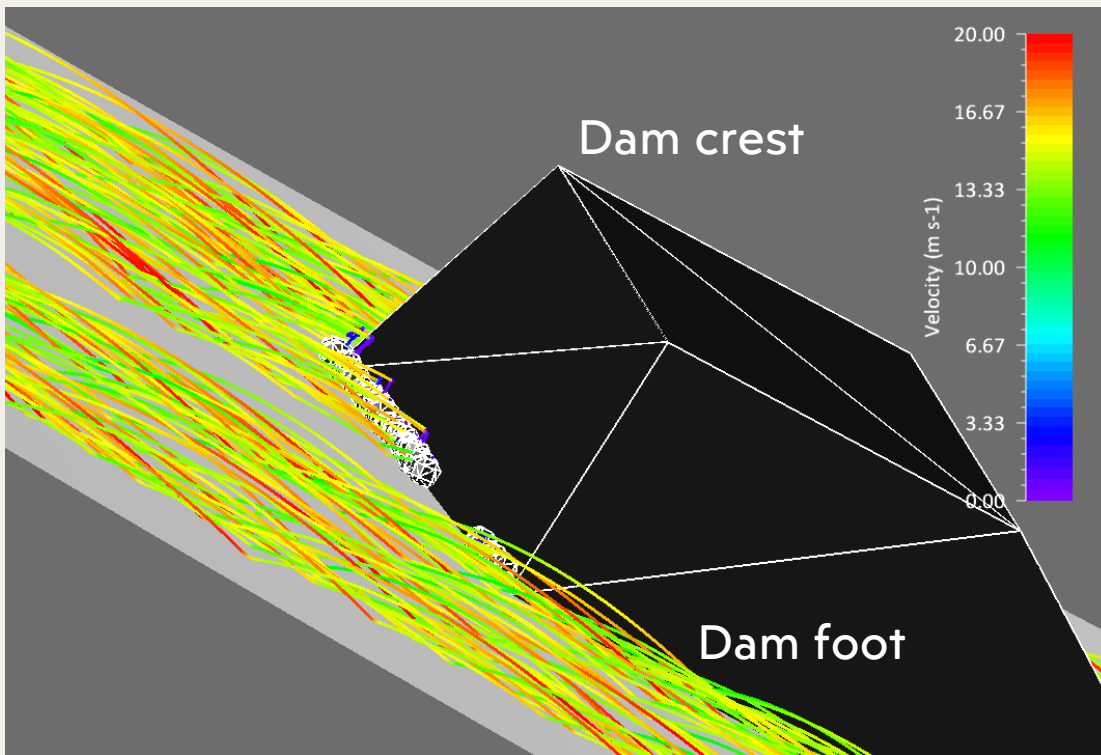
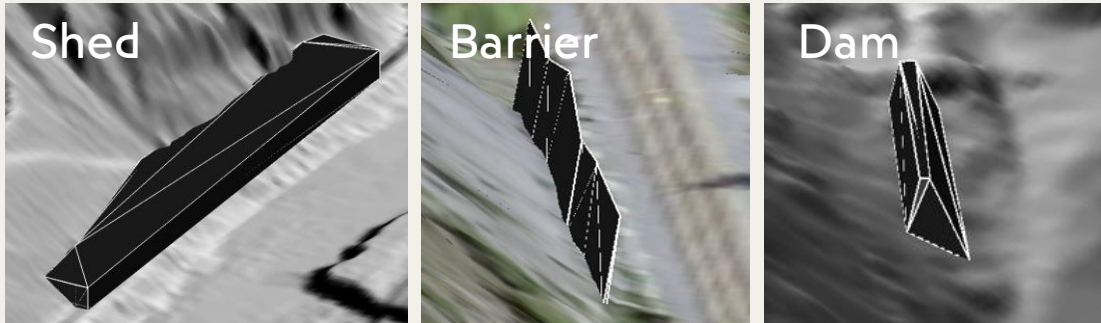
## Additional Feature

- Identified trajectories can be opened directly in Trajectory Mode for detailed inspection

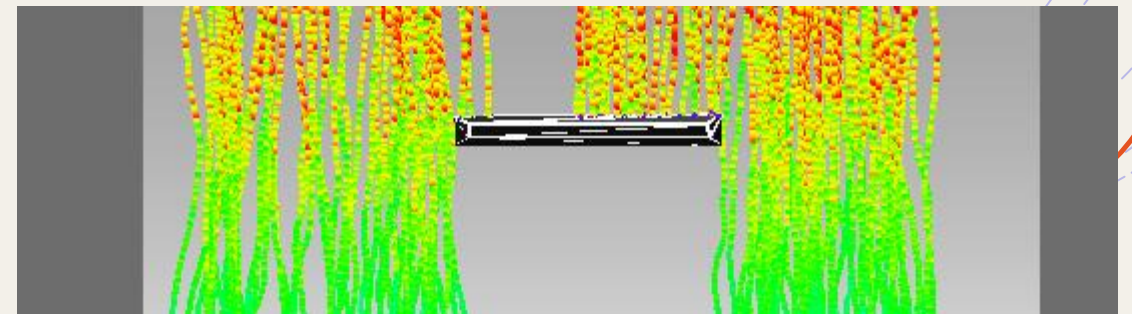
## Statistics → Probability of reaching Target Line (SOL)

```
RAMMS | SOL Report
Save Save As... Done with RAMMS | SOL Report
--- RAMMS::Rockfall 2.0.4 DEV ---
--- SOL / prA Report ---
Generated:      Sat Nov 22 21:05:04 2025
Project:        ██████████
Scenario:       Test_RTS_Files_Normal
SOL-file:      SOL.shp
SOL segments:  1
Rock types:    1 ( REAL_EQUANT.PTS )
Total simulations: 1000
--- SOL-Segment 1 Analysis ---
Length [m]: 56.33 (2793246.68/1180089.38 <-> 2793298.52/1180067.32)
Total prA (sum over types): 1.55686E-002
Per rock type:
- nSim=1000 nEr= 28 pEr=2.80 % prA=1.55686E-002 vol=1.40 m3 type=REAL EQUANT.PTS
Explanations:
SOL: Schadenobjektline (Damage object line)
nSim: Simulated/kept trajectories per rock type, after envelope
nEr: How many trajectories per rock type reached the SOL segment
pEr: Probability of reaching the SOL segment per rock type
prA: Probability of occurrence for SOL segment
vol: Volume of rock type (in m3)
Calculations according to "Leitfaden Sturzprozesse", BAFU and SBB, 2021, Switzerland
```

# Rockfall Dams as 3D Protective Structures



- **Rockfall dams** are rigid three-dimensional obstacles embedded in the terrain.
- RAMMS has **special routines to generate dams**.
- Used to **intercept, deflect, or stop** falling rocks.
- Interaction with rocks depends on:
  - **geometry**
  - **impact energy**
  - **structural resistance** parameters
- RAMMS records **impact number, energy, and impact angle**.



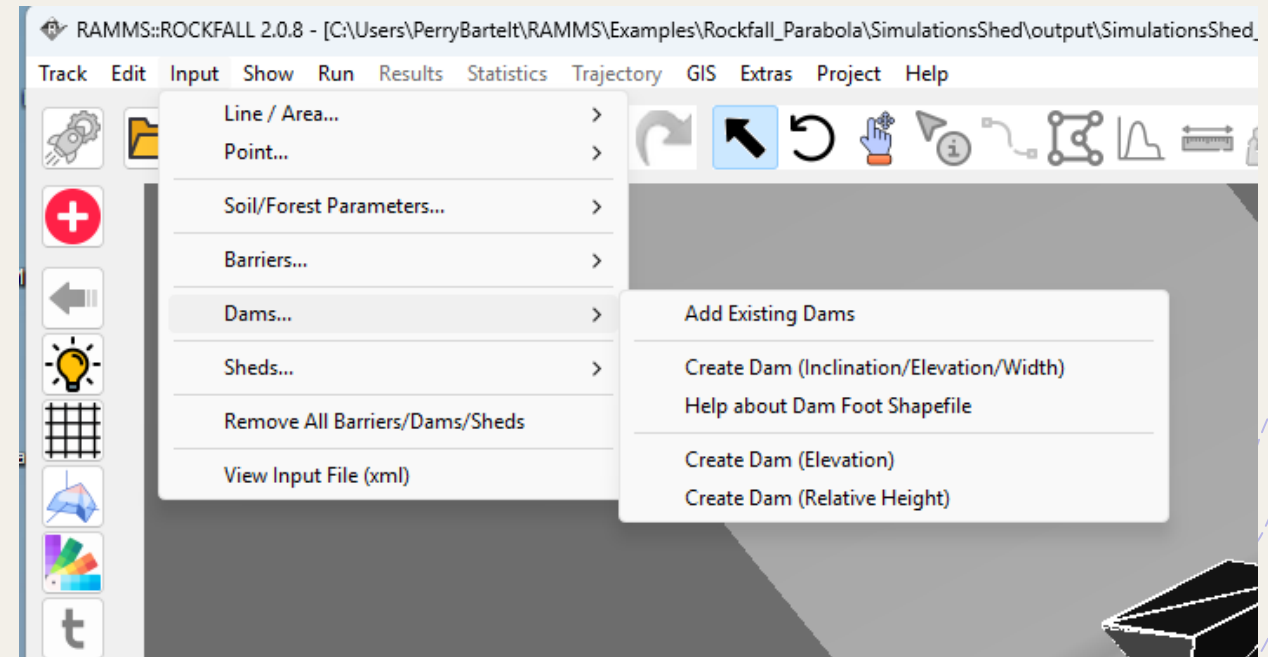
# Methods of Defining Dam Geometry



RAMMS provides **four methods** to define dam geometry:

- **Import point cloud (.pts)**
  - full 3D geometry defined externally.
- **Create dam (inclination / elevation / width)**
  - defined from dam footprint.
- **Create dam from shapefiles (Elevation)**
  - crest elevation specified.
- **Create dam from shapefiles (Relative Height)**
  - crest height relative to footprint

*Input → Dams → ....*

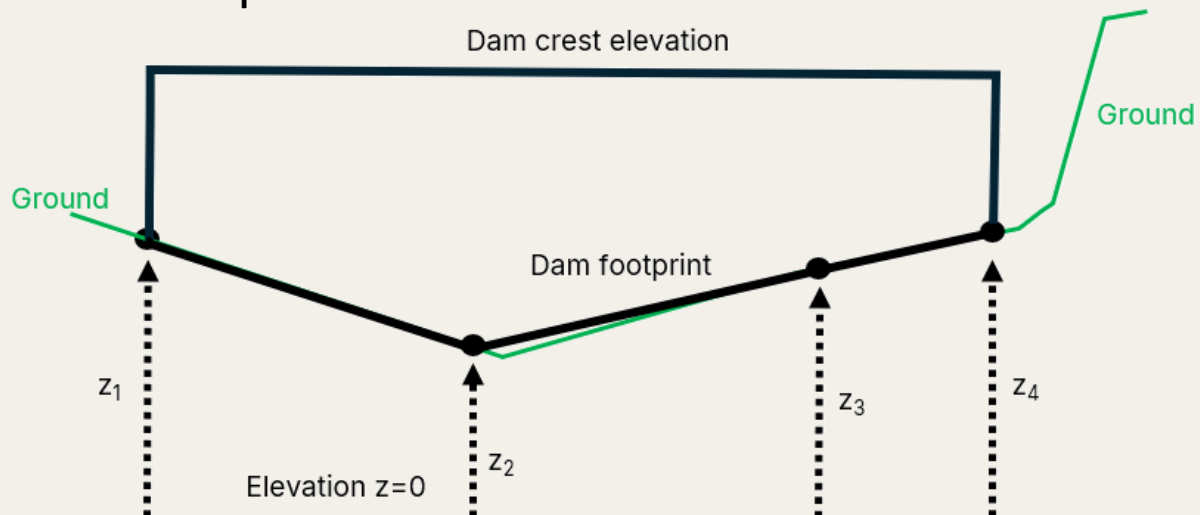


# Dam Footprint Geometry



Definition of dam geometry begins with **dam footprint**

- **Dam footprint** defined using polygon shapefile.
- **Vertex order must be clockwise!**
- **Face orientation determined from the last footprint edge.**
- Elevation between footprint points is linearly interpolated.



**Important modelling rule:** Too few footprint points can create **artificial holes beneath the dam**, allowing rocks to pass through!

# Rock-Dam Impact Model



## Failure condition:

Structure fails if:

$$E_{impact} > E_{abs} = \text{energy absorption capacity (kJ)}$$

If failure occurs → dam **no longer affects rock trajectory**.

## If structure survives impact:

Energy dissipation controlled by **compression modulus**  $M_E$

$$f = 80 e^{-4 \times 10^5 M_E}$$

## Resistance force:

$$F_{res} = C_d v^2$$

with

$$C_d = \frac{fM}{dA\rho}$$

## Input masks for structural parameters

RAMMS | Dam Energy Threshold

RAMMS | Dam Energy Absorption Capacity

Set energy absorption capacity (in kJ):  
(for all selected dams)

OK Cancel

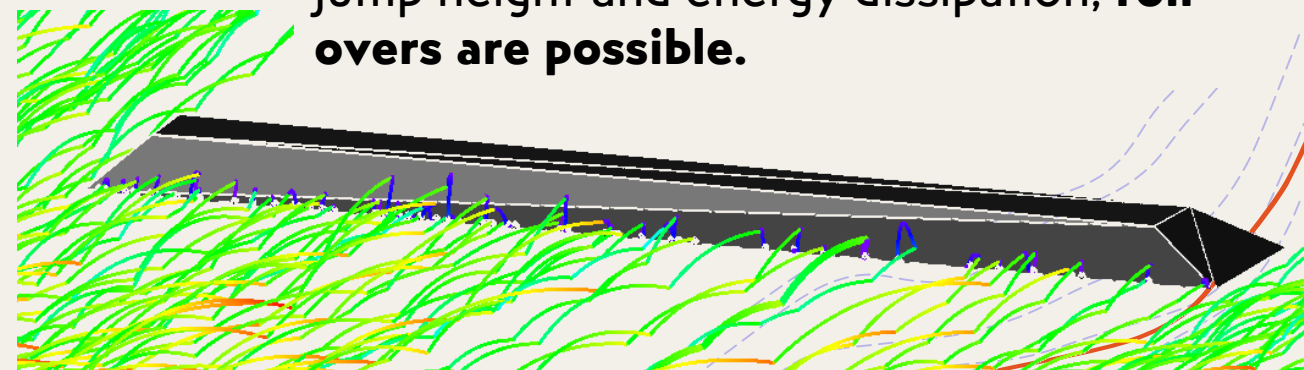
RAMMS | Dam ME Value

RAMMS | Dam ME compression modulus

Set ME (MN/m2) value:  
(for all selected dams)

OK Cancel

Depending on dam inclination, rock speed, jump height and energy dissipation, **roll-overs are possible**.



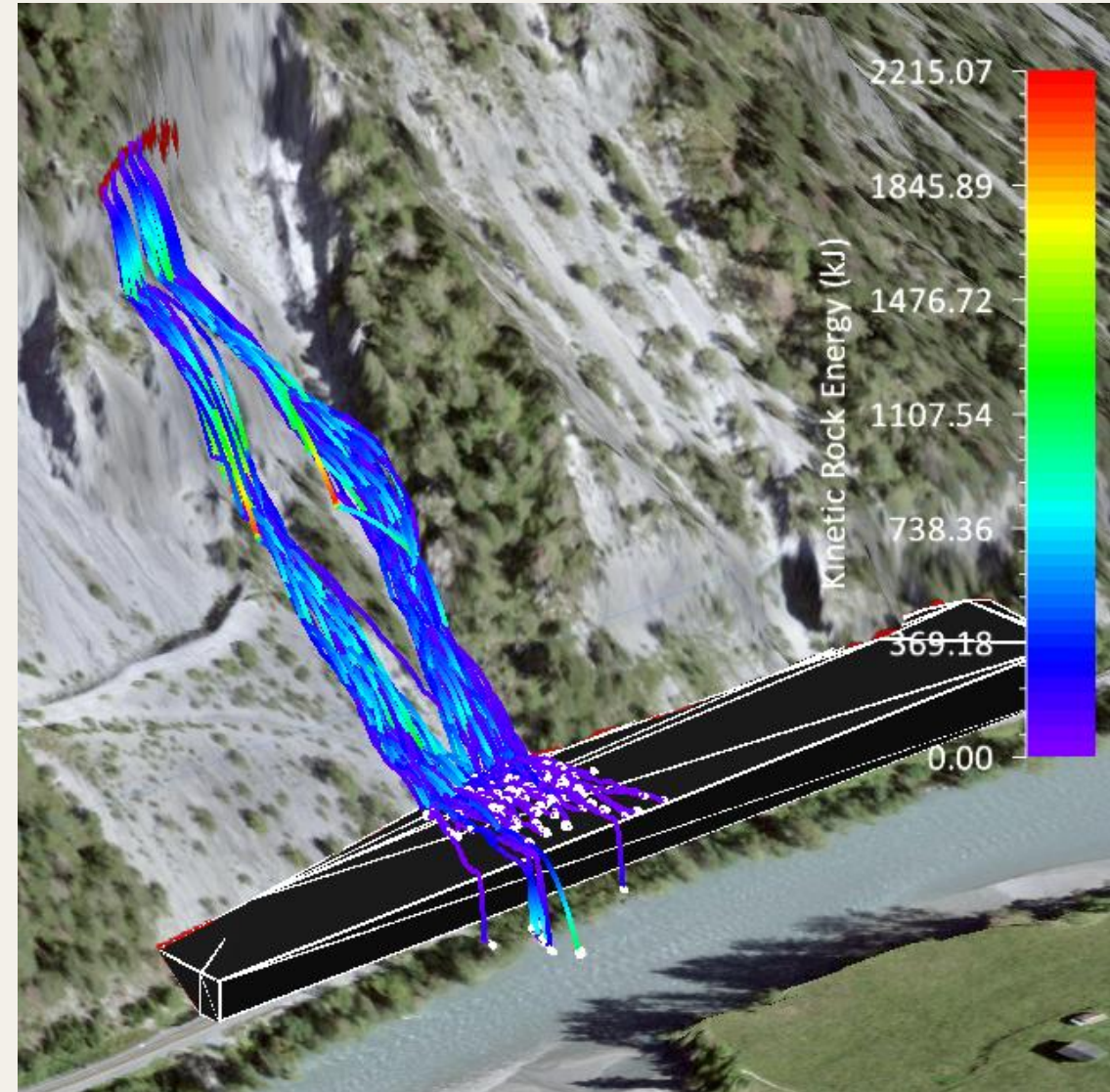
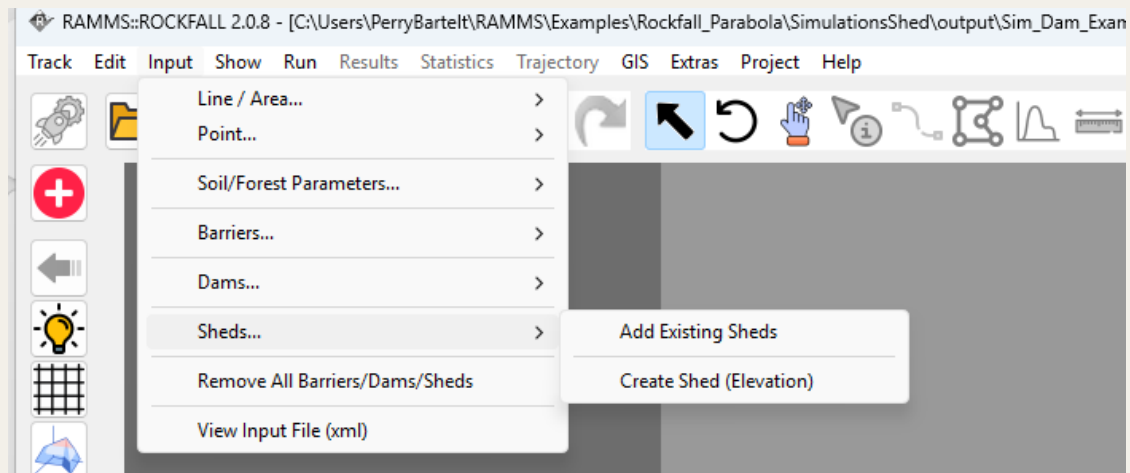
Determines impact behavior at dam face

# Rockfall Sheds (Galleries)



Rockfall sheds protect infrastructure by **allowing rocks to pass over the structure.**

- **Modeled as rigid convex-hull obstacles.**
- **Defined similarly to rockfall dams.**
- **Designed to:**
  - intercept impacts
  - dissipate energy
  - redirect rocks over the structure.
- **Use:** *Input* → *Sheds* → *Create Shed (Elevation)*



# Practical Modeling Considerations for Sheds



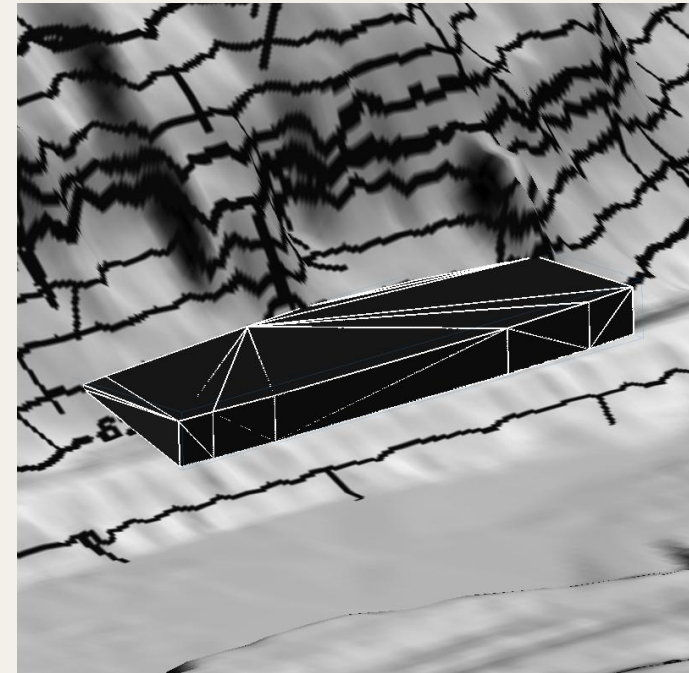
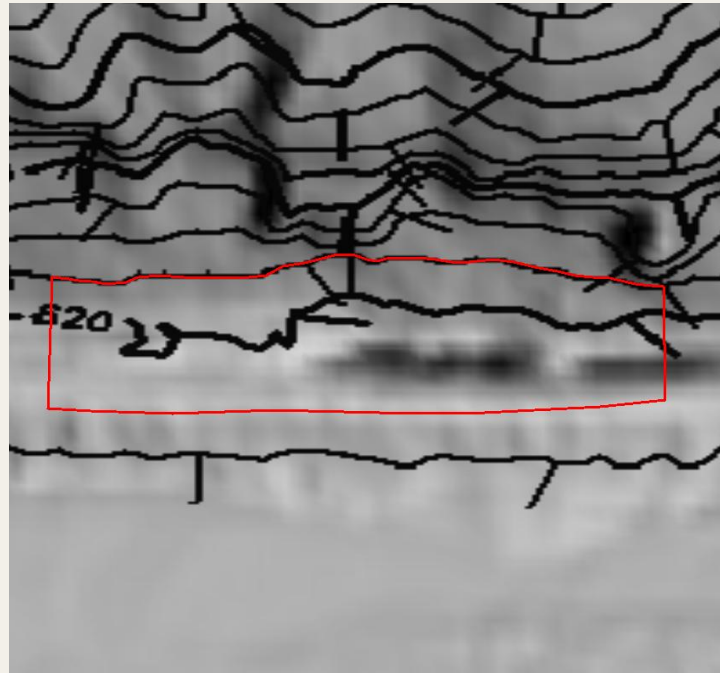
Rockfall sheds can be represented efficiently in RAMMS, but **careful geometric definition is important when working in complex terrain.**

## Terrain and Geometry

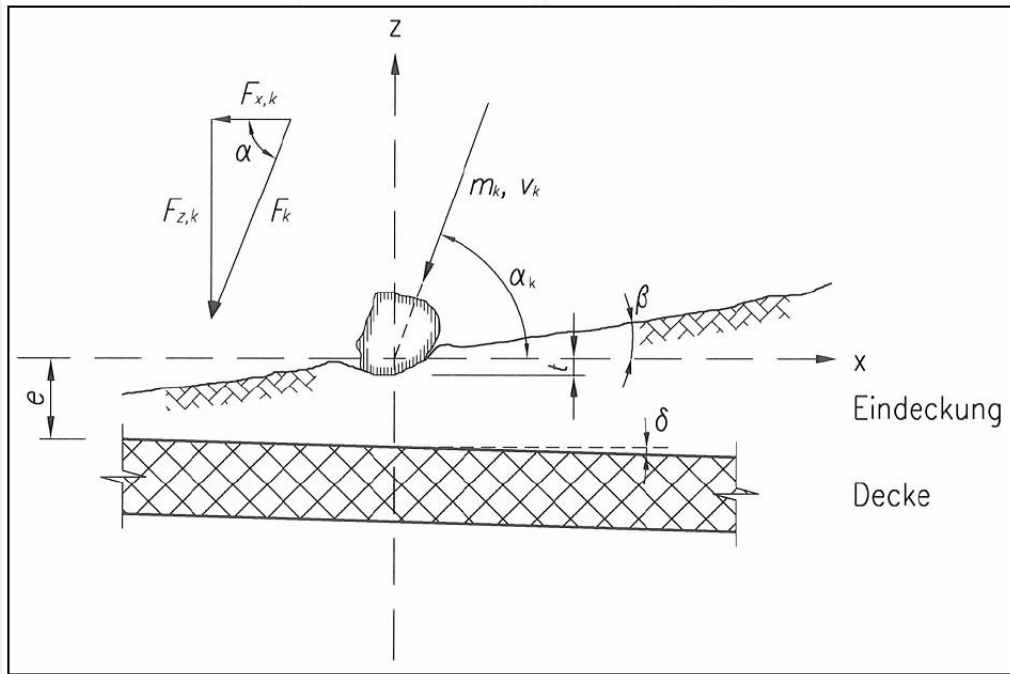
- The standard shed workflow assumes a horizontal roof surface.
- In steep or irregular terrain, contour lines are useful guides when defining the shed footprint.
- The mountain-side boundary of the shed should generally follow a terrain contour.

## Complex Geometries

- For complex structures or existing galleries, sheds can be imported as point-cloud objects (\*.pts).
- This allows full 3-D geometry to be defined externally (e.g., CAD or GIS).



# Impact Analysis of Rockfall Sheds (ASTRA)



RAMMS evaluates rockfall gallery performance using the **Swiss ASTRA guideline** “Effects of rockfall on protective galleries”.

The method computes:

- **Impact force on the roof  $F_k$**
- **Penetration depth of the rock  $t$**

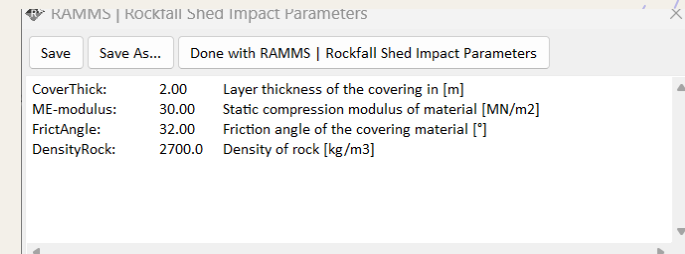
These quantities are calculated from **rock properties** and **impact kinematics** obtained during the simulation.

**Key Inputs from simulation:**

- rock mass  $m_k$
- impact velocity  $v_k$
- rock radius

**Additional input parameters:**

- covering thickness  $e$
- friction angle of covering material  $\varphi_k$
- compression modulus  $M_{e,k}$



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

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

# Outputs of the ASTRA Shed Analysis

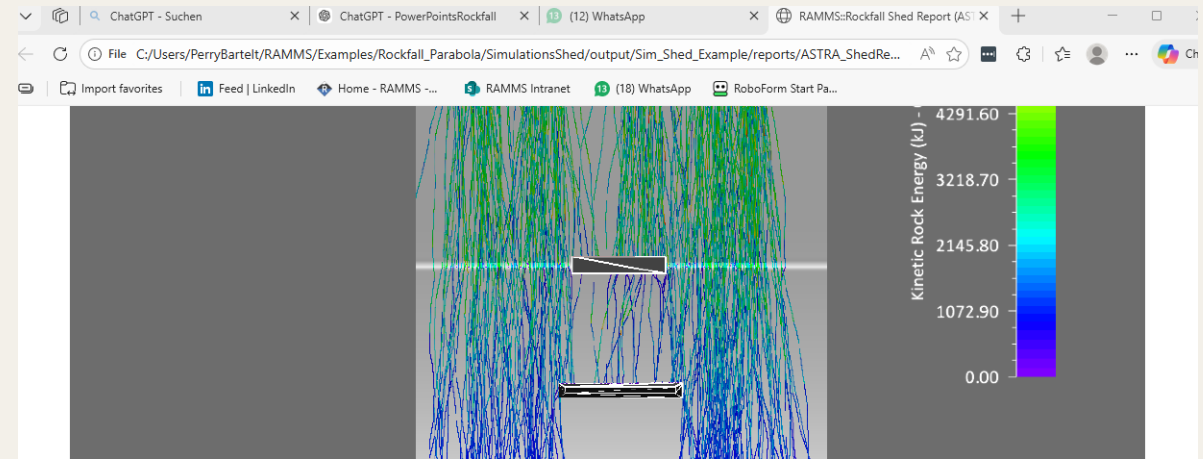


## Engineering report

After running the analysis, RAMMS produces a **complete engineering report**.

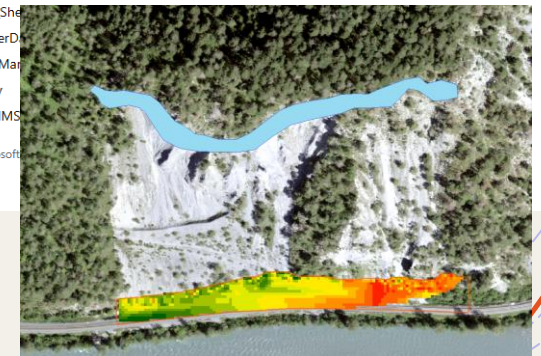
- **HTML Report.** Contains statistical plots of:
  - impact force  $F_k$
  - penetration depth  $t$
  - spatial distribution of impacts
  - Pre- and post velocity/energy
- **Impact point shapefile**
  - Contains location of every rock impact.
  - impact force
  - impact velocity
  - impact angle
- **Raster maps:**
  - Impact force  $F_k$
  - Penetration depth  $t$

Only the first impact of each trajectory is used (subsequent impacts are assumed less severe).

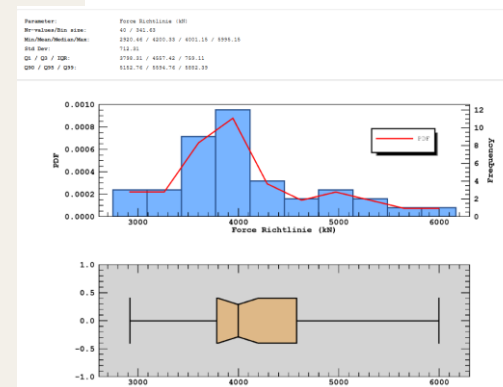


## RAMMS::Rockfall Shed Report (ASTRA)

RAMMS version 2.0.8  
Project SimulationsShed  
Scenario Sim\_Shed  
Shed Object UpperD  
Created Tue Mar  
User Perry  
Company RAMMS



Raster plots

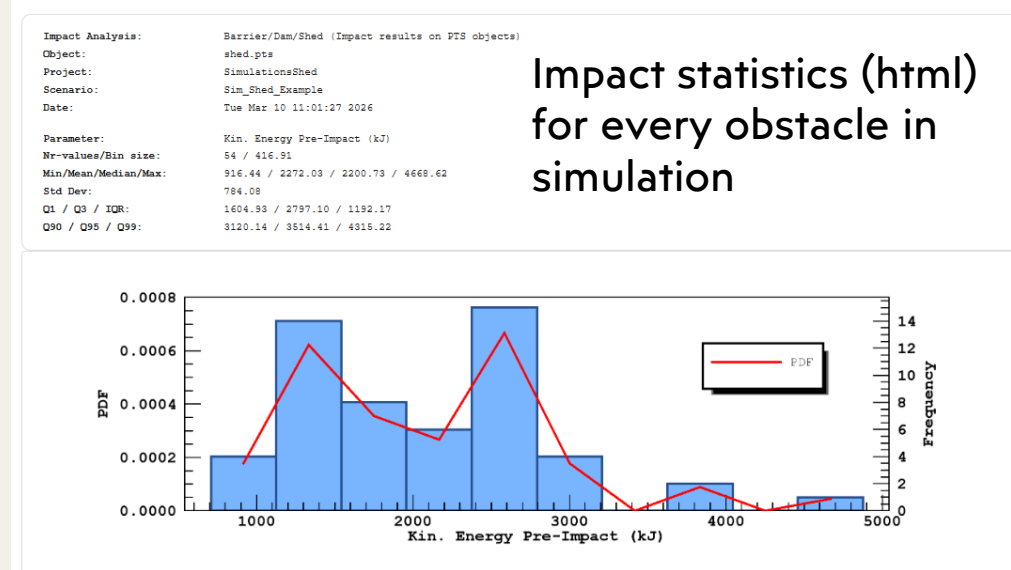
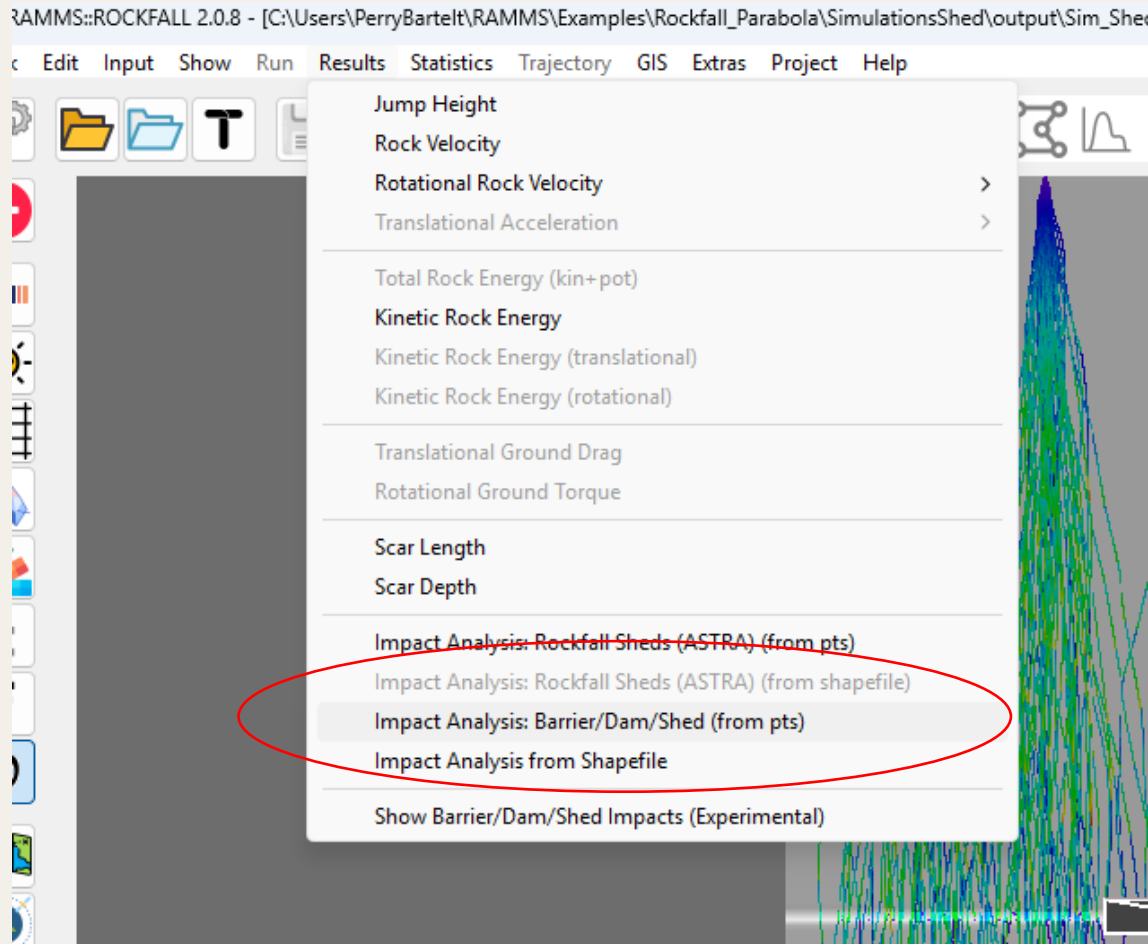


Impact statistics

# General Obstacle Impact Analysis



RAMMS also provides a **general obstacle impact analysis tool**.



RAMMS | Analyse Obstacle Impacts

Successfully analysed the following obstacles:

- UpperDam.pts
- shed.pts

Saved csv-files:

- ObstacleImpact\_UpperDam\_DATA.csv
- ObstacleImpact\_shed\_DATA.csv

at C:\U\ulat

\*.csv files for each obstacle

A1	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U
1	RAMMS	Obstacle Impact Data																			
2	Scenario:	Sim_Shed_Example																			
3	Obstacle-File:	C:\Users\PerryBartelt\RAMMS\Examples\Rockfall_Parabola\SimulationsShed\shed.pts																			
4	Date:	10/Mar/26																			
5	X-Coord (r	Y-Coord (r	Z-Coord (r	Impact An	Kin. Energ	Kin. Energy	Velocity_R	Velocity_X	Velocity_Y	Velocity_Z	Velocity_R	Velocity_X	Velocity_Y	Velocity_Z	Rock mas	Trajectory-Name					
6	2764116	1171436	411.94	54.7	2330.34	0	36.57	-1.09	-29.84	-21.11	0.02	0	0	-0.02	2701.34	Sim_Shed_Example_Pos2_PTSEOTA_111_1.0m3_O11.rts					
7	2764141	1171434	411.99	47.1	1446.98	1026.1	30.23	1.72	-20.51	-22.14	23.89	0.27	-23.37	-4.92	2701.34	Sim_Shed_Example_Pos2_PTSEOTA_111_1.0m3_O14.rts					
8	2764154	1171433	411.96	52.19	1771.56	42.09	33.97	1.69	-20.75	-26.84	0.57	0.12	-0.55	0.08	2701.34	Sim_Shed_Example_Pos2_PTSEOTA_111_1.0m3_O23.rts					
9	2764181	1171434	411.95	54.12	4001.83	118.12	51.66	4.99	-29.87	-41.86	1.32	0.48	-1.14	0.45	2701.34	Sim_Shed_Example_Pos2_PTSEOTA_111_1.0m3_O38.rts					
10	2764175	1171434	411.99	32.16	1606.22	1301.84	30.32	0.38	-25.67	-16.14	26.49	-2.82	-26.28	-1.78	2701.34	Sim_Shed_Example_Pos2_PTSEOTA_111_1.0m3_O51.rts					
11	2764117	1171436	411.98	41.4	1548.12	0	31.54	-2.21	-20.86	-23.55	0.02	0	0	-0.02	2701.34	Sim_Shed_Example_Pos2_PTSEOTA_111_1.0m3_O6.rts					
12	2764293	1171429	412	43.73	1783.95	1005.35	33.75	-0.47	-24.38	-23.33	23.27	-6.86	-22.23	-0.66	2701.34	Sim_Shed_Example_Pos3_PTSEOTA_111_1.0m3_O1.rts					
13	2764293	1171435	411.97	51.61	3968.32	1706.16	50.95	0.65	-31.64	-39.94	30.82	0.4	-30.81	0.77	2701.34	Sim_Shed_Example_Pos3_PTSEOTA_111_1.0m3_O10.rts					
14	2764298	1171436	411.98	47.24	1765.41	0	33.18	-5.68	-24.36	-21.8	0.02	0	0	-0.02	2701.34	Sim_Shed_Example_Pos3_PTSEOTA_111_1.0m3_O13.rts					
15	2764232	1171430	411.98	50.56	2714.54	122.06	41.93	-1.25	-26.6	-32.38	1.54	-0.09	-1.46	0.49	2701.34	Sim_Shed_Example_Pos3_PTSEOTA_111_1.0m3_O14.rts					

Results → Impact Analysis: Barrier / Dam / Shed (from pts)

# Summary



## 1. **Protective structures can be explicitly modeled in RAMMS:Rockfall.**

Flexible barriers, rockfall dams and rockfall sheds can be represented as objects interacting with simulated rock trajectories. These structures allow engineers to evaluate mitigation effectiveness before construction.

## 2. **Flexible barriers are modeled as energy-absorbing obstacles.**

Barrier performance is governed by the kinetic energy of impacting rocks

$$E_{kin} = \frac{1}{2}mv^2$$

If the rock energy exceeds the barrier capacity, the rock passes through; otherwise the rock is stopped.

## 3. **Trajectory statistics help identify critical impact conditions.** Tools such as **Jump Height vs. Kinetic Energy plots** and **SOL crossing probability** allow engineers to analyze trajectory behavior and quantify the probability that rocks reach infrastructure or protective lines.

Thank you for your attention!

# Summary



**4. Rockfall dams and sheds are represented as rigid 3-D obstacles.**

These structures interact with falling rocks through geometry, impact energy and structural resistance parameters, allowing simulation of interception, deflection or rollover of blocks.

**5. Structural impact behavior can be evaluated using engineering models.**

For example, the ASTRA gallery method computes **impact force**  $F_k$  and **penetration depth**  $t$  using rock mass, velocity and material properties derived from the simulation.

**6. RAMMS provides detailed outputs for engineering analysis.**

Impact analyses produce **HTML reports, GIS maps and CSV datasets** containing impact locations, energies, velocities and angles. These outputs enable post-processing in GIS or statistical tools and support design verification of protective structures.