Theory of RAMMS::Rockfall: Rigid-Body Dynamics and Ground Interaction

From Restitution Models to Deterministic Contact Mechanics

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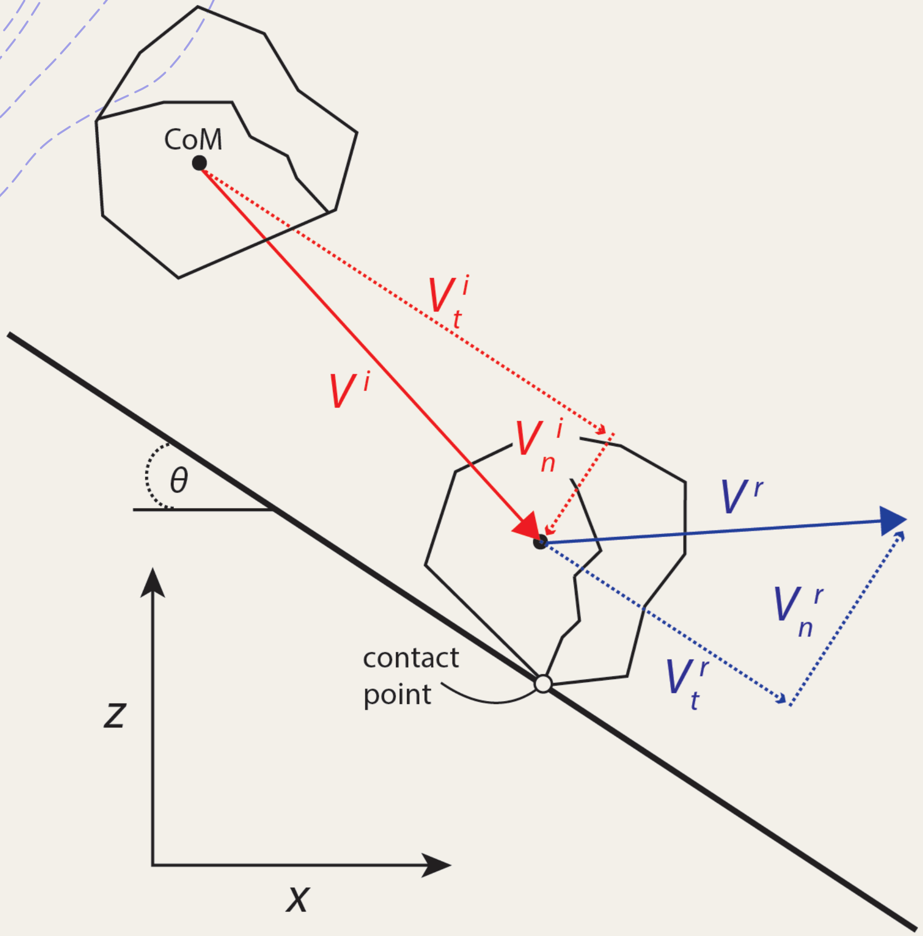
Fundamental Problem in Rockfall Modelling

The central challenge in rockfall science is determining the relationship between the **incoming and rebound velocity vectors after impact.**



Traditional rockfall models describe this relationship using **restitution coefficients**:

$$R_t = \frac{V_t^r}{V_t^i} \qquad R_n = \frac{V_n^r}{V_n^i}$$

However, restitution-based approaches cannot fully represent the physics of rock impacts because they neglect:

- **Complex rock geometries and orientations** at impact
- **Rigid-body dynamics**, particularly rotational motion
- **Deformable ground materials and soil compaction**

As a result, rebound behavior is often treated using **empirical or stochastic assumptions**.

Experimental Evidence for Energy Dissipation in Rockfall Mechanics

Parameters of rockfall impact

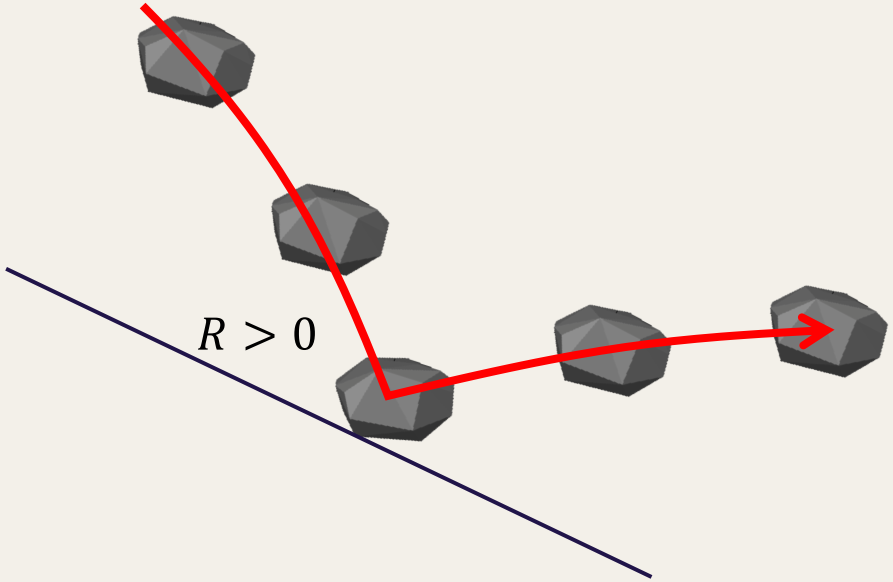
Rebound behavior cannot be described by a single restitution coefficient.

Contact parameters

- Material properties of rock and terrain
    - Friction, restitution, deformation

Impact configuration

- Roughness of terrain
    - Macro-scale terrain (slope convexity, gullies, cliffs)
    - Meso-scale roughness (trees, boulders)
    - Micro-scale roughness (surface, cracks and fissures)
- Translational velocity at impact
- Rotational velocity at impact
- Rock geometry
- Rock orientation at impact



Rockfall impact

Ground Properties	Impact Configuration
Terrain	**Velocity**
Soil	**Shape**

Rockfall vs Blockfall: Two Important Regimes

Rockfall

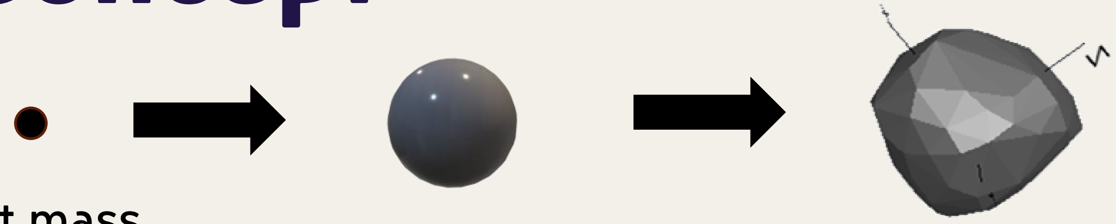
- Rocks **≤ ~1 m³**
- Energy dissipation dominated by **surface roughness**
- **High bounce heights**
- Strong influence of **vegetation drag**
- Mitigation: **flexible barriers / nets**

Blockfall

- Large boulders **≫ ~ 1 m³**
- Energy dissipation via **plastic deformation of soil**
- Motion dominated by **rolling and sliding**
- Vegetation influence **small**
- Mitigation: **dams / galleries**

Small rocks interact strongly with terrain roughness.

The RAMMS Rockfall Concept



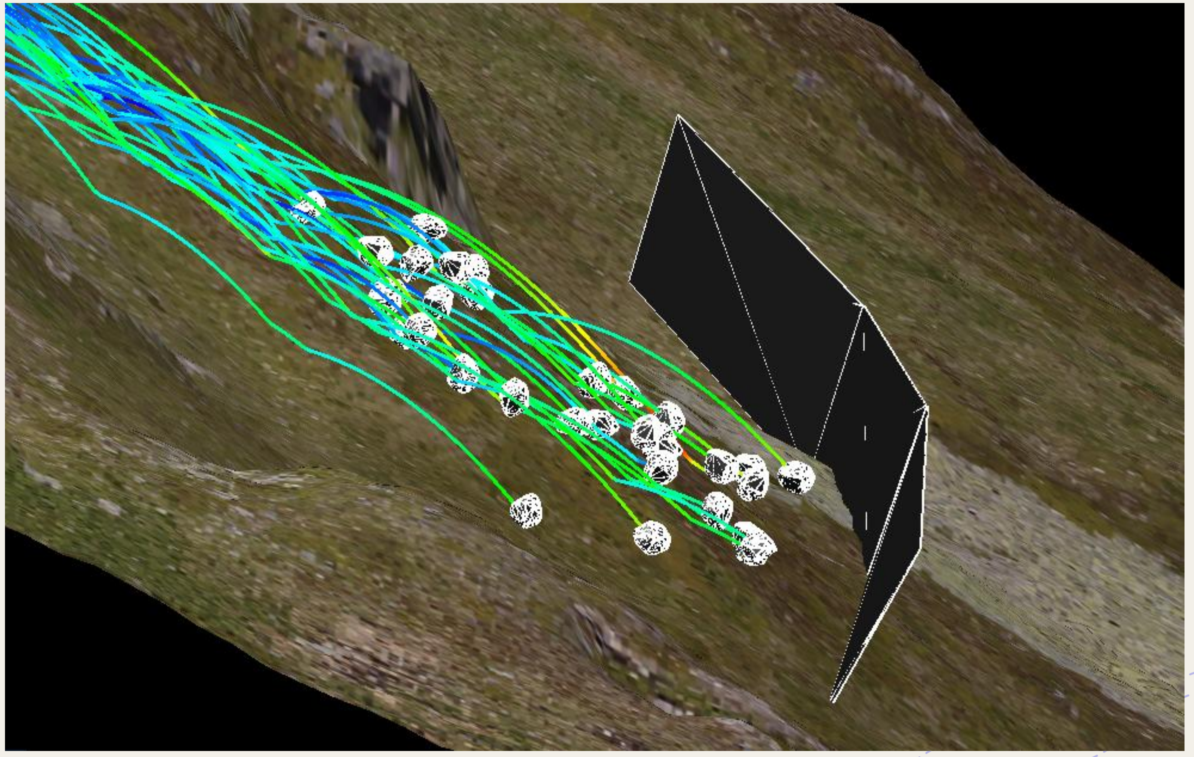
RAMMS introduces:

- **rigid-body mechanics**
- **hard-contact dynamics**
- **real rock shapes**
- **deterministic terrain parameters**
- **interaction with barriers**
- **interaction with forests**
- **three-dimensional**
- **graphical visualization**

No stochastic restitution.

Trajectory variation comes from:

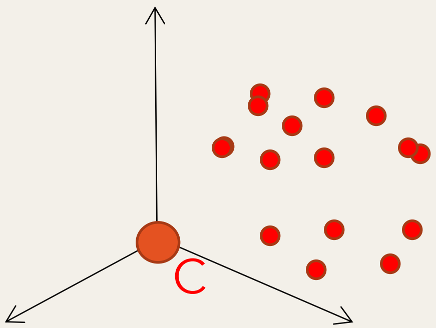
- initial conditions
- rock orientation.



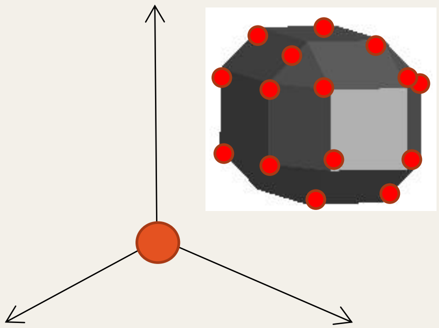
Leine, R. I., Schweizer, A., Christen, M., Glover, J., & Bartelt, P. (2013).
The physics of rockfall: motion of a rigid body on a rough surface with contact and friction.
Multibody System Dynamics, **32**, 1–27.
https://doi.org/10.1007/s11044-013-9394-y

Rock Representation in RAMMS

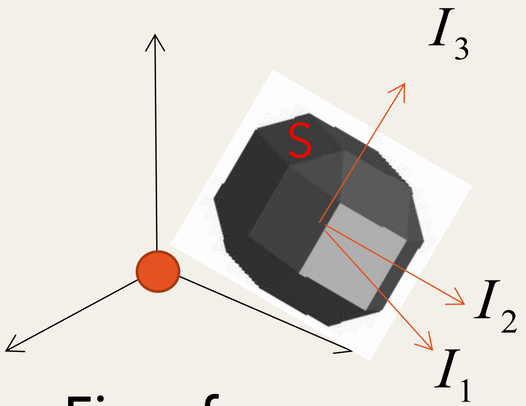
Rocks in RAMMS are represented as **rigid polyhedral bodies**.



Point Cloud

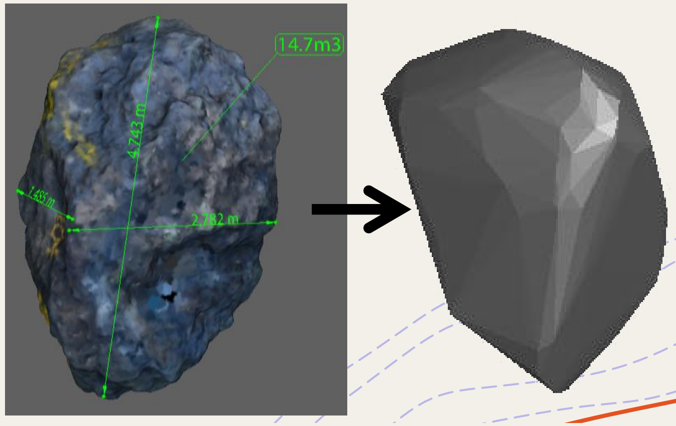


Convex Hull



Eigenframe
(Center of mass, Moments of inertia)

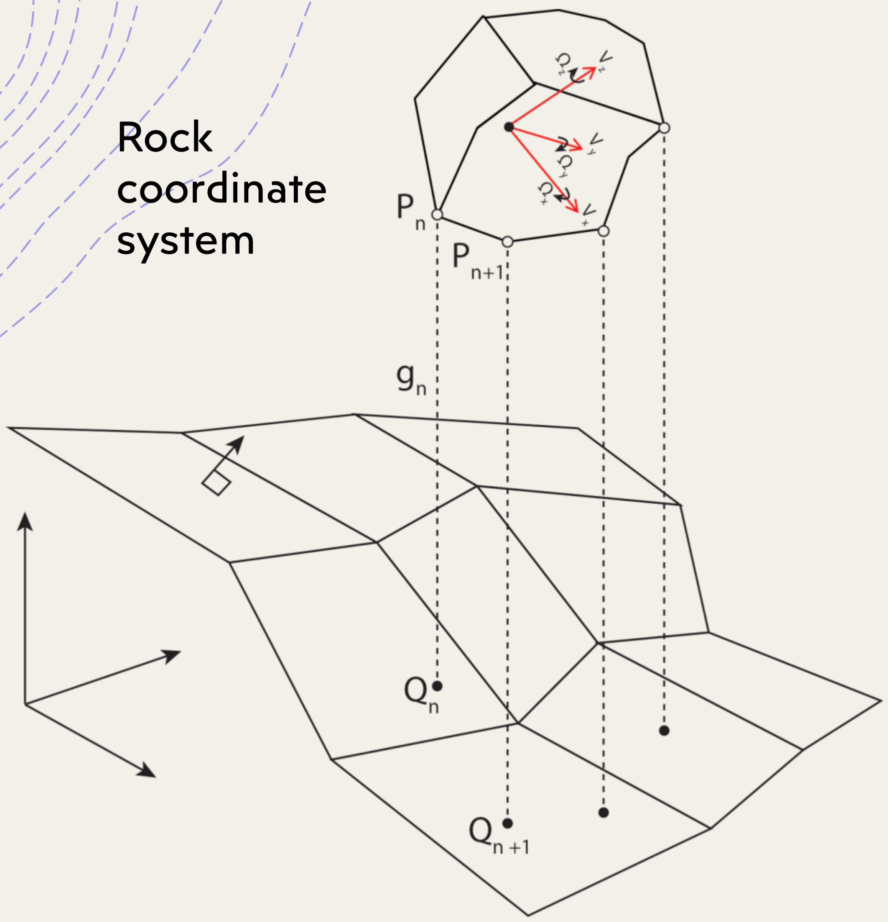
- Geometry defined by a **point cloud (.pts)**
- Large number of points require more computational time.
- Convex hull constructed automatically
- Mass properties computed
    - center of mass
    - inertia tensor
    - principal axes



Laser scanned rockfall deposits

Hard Contact Approach

RAMMS models impacts using **non-smooth rigid-body contact mechanics**. **Impact forces generate torques that naturally produce rolling, sliding, and jumping.**



Terrain coordinate system

- Three-dimensional terrain defined by **digital terrain models** – as is usual with all RAMMS modules.
- Orientation mapping during flight in three-dimensional terrain requires **three-separate coordinate systems**.
- Calculate gap length g_n: vertical distance between rock corner point **P** and vertical projection point **Q**

$$g_n > 0 = \text{non-contact}$$
$$g_n < 0 = \text{contact}$$

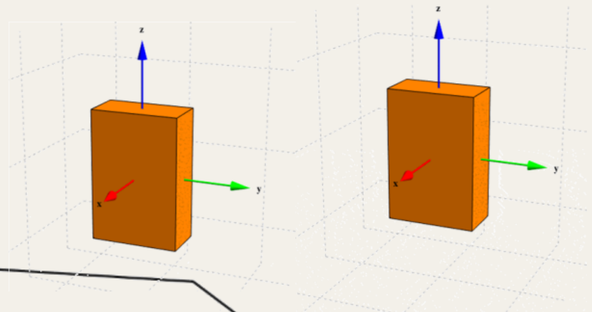
- Contact forces are applied directly at **rock vertices and edges**. Components of the contact force:

$$\lambda = (\lambda_N, \lambda_T)$$

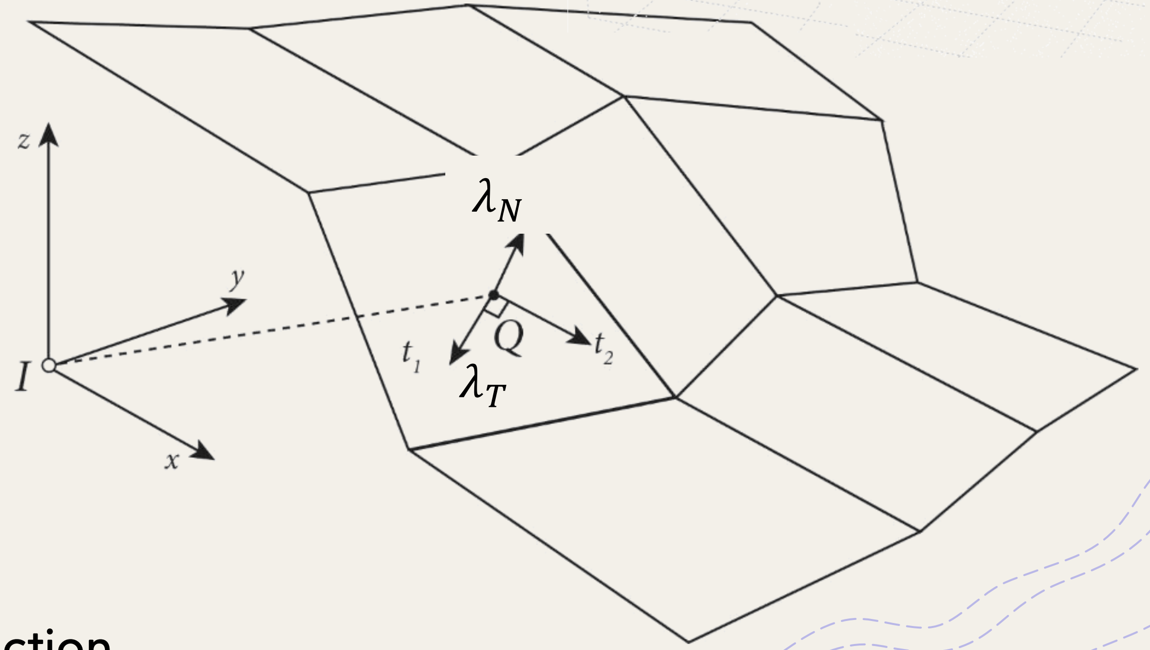
- **Normal force** enforces non-penetration
- **Tangential forces** represent Coulomb friction

Rigid-Body Equations of Motion

Rigid body motion $$\mathbf{M}\dot{u} - \mathbf{h}(q,u) = W(q)\lambda$$

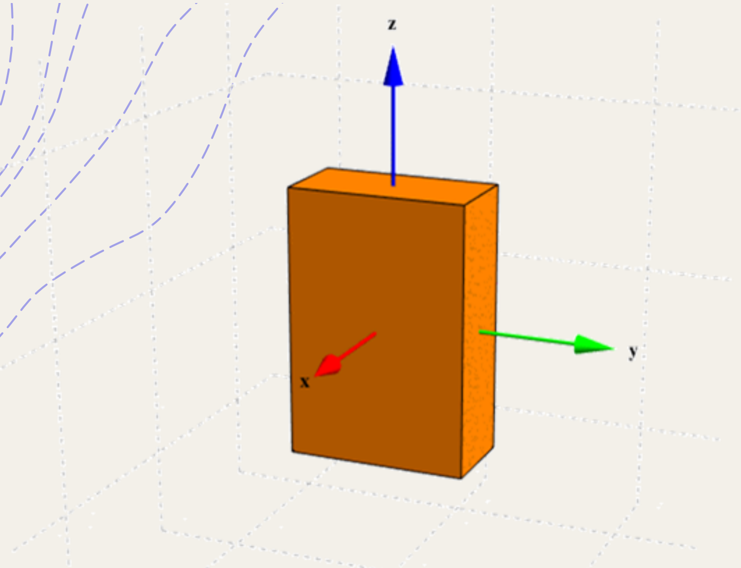


- **Rock** represented as a rigid body with **six degrees of freedom**
  - three translational
  - three rotational
- State variables: **position** q, **velocity** u
- **External forces** $h(q,u)$
  - gravity
  - gyroscopic forces
  - drag forces during scarring)
- **Contact forces** $W(q)\lambda$
  - Forces applied at rock vertices and edges
  - Normal component enforces non-penetration
  - Tangential component represents Coulomb friction
- **Contact forces** generate torques that produce **rolling**, **sliding** and **jumping**.

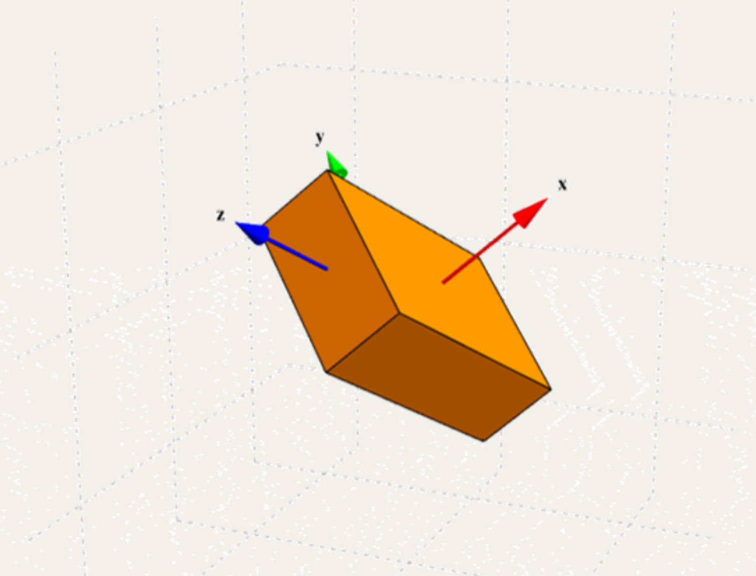


Axial Stability of Rotating Rocks

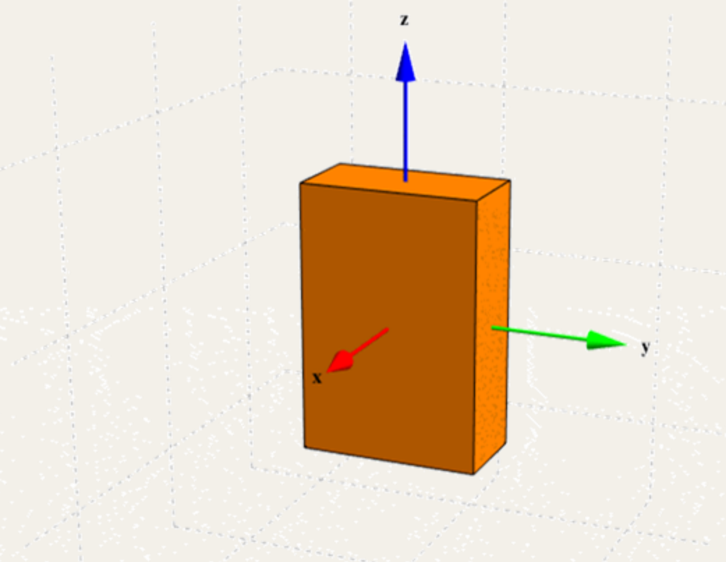
Axis with smallest moment of inertia I_1



Axis with medium moment of inertia I_2



Axis with largest moment of inertiaI_3



Rigid bodies rotating freely tend toward the **minimum energy configuration**. In the case of slab-shaped stones $I_1 \approx I_2 < I_3$ => Only one stable axis of rotation is possible!

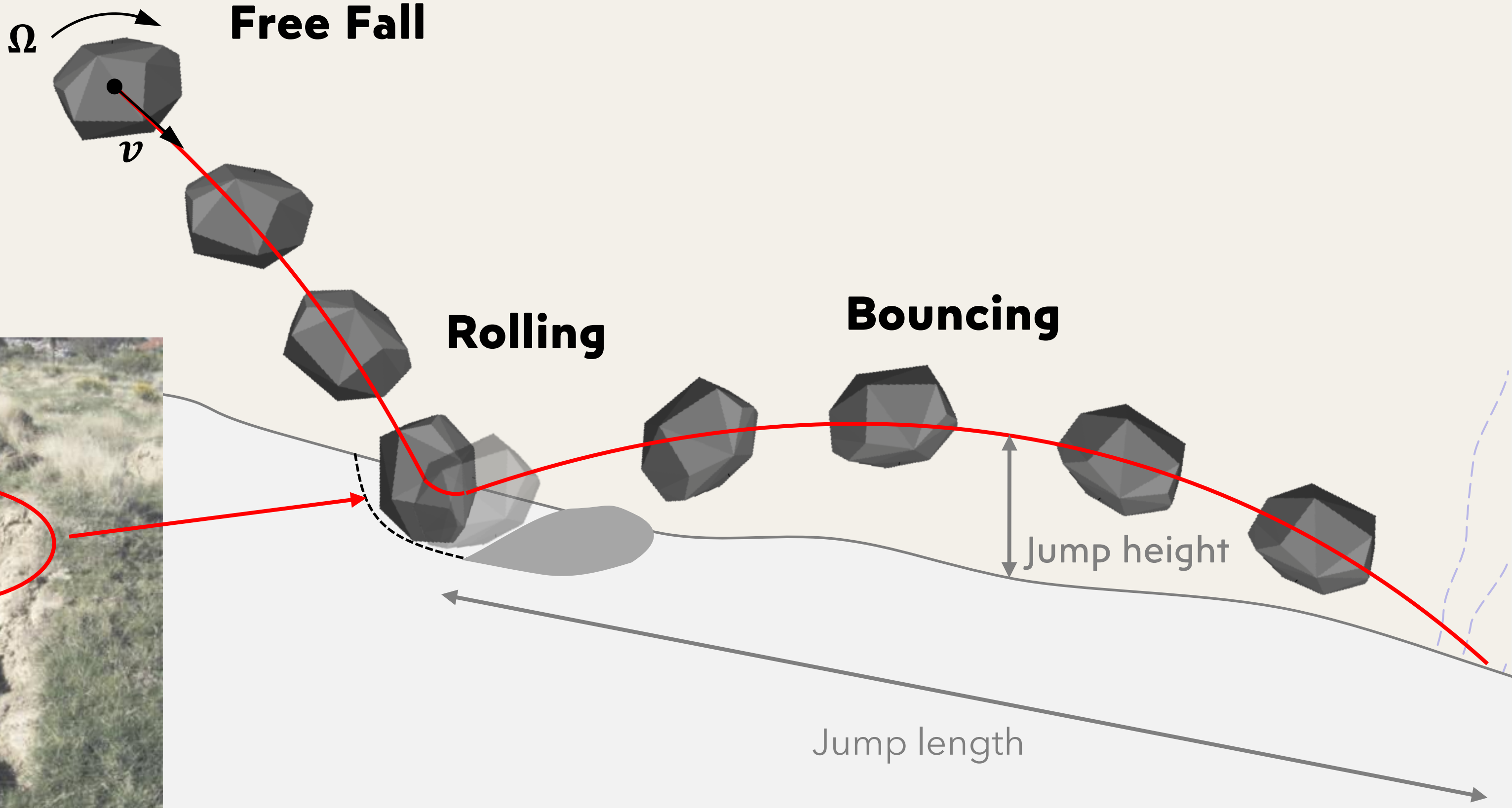
A rotating rock tends to align with the axis of largest moment of inertia.

Flat rocks with sufficient rotational speed will naturally **stabilize around this axis**, producing **wheel-like rolling and skipping motion** that can significantly increase runout distances.

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. https://doi.org/10.1007/s11044-021-09792-y

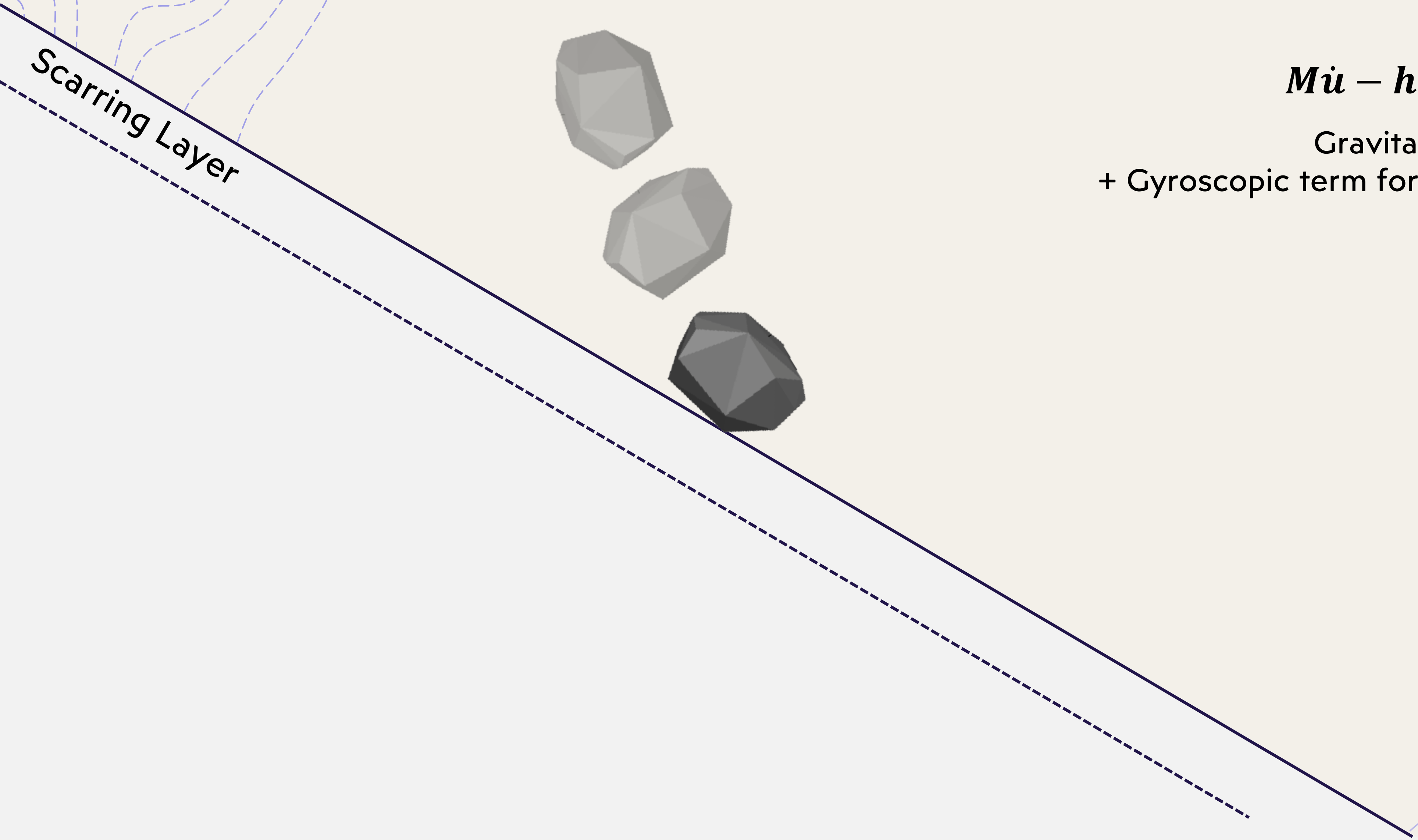
Ground Interaction Model with Scarring

Ground Scarring: Soil deformation beneath the rock produces a scar and generates additional drag forces.



Lu, G., Caviezel, A., Christen, M., Demmel, S. E., Ringenbach, A., Bühler, Y., ... Bartelt, P. (2019). Modelling rockfall impact with scarring in compactable soils. *Landslides, 16*, 2353-2367. https://doi.org/10.1007/s10346-019-01238-z

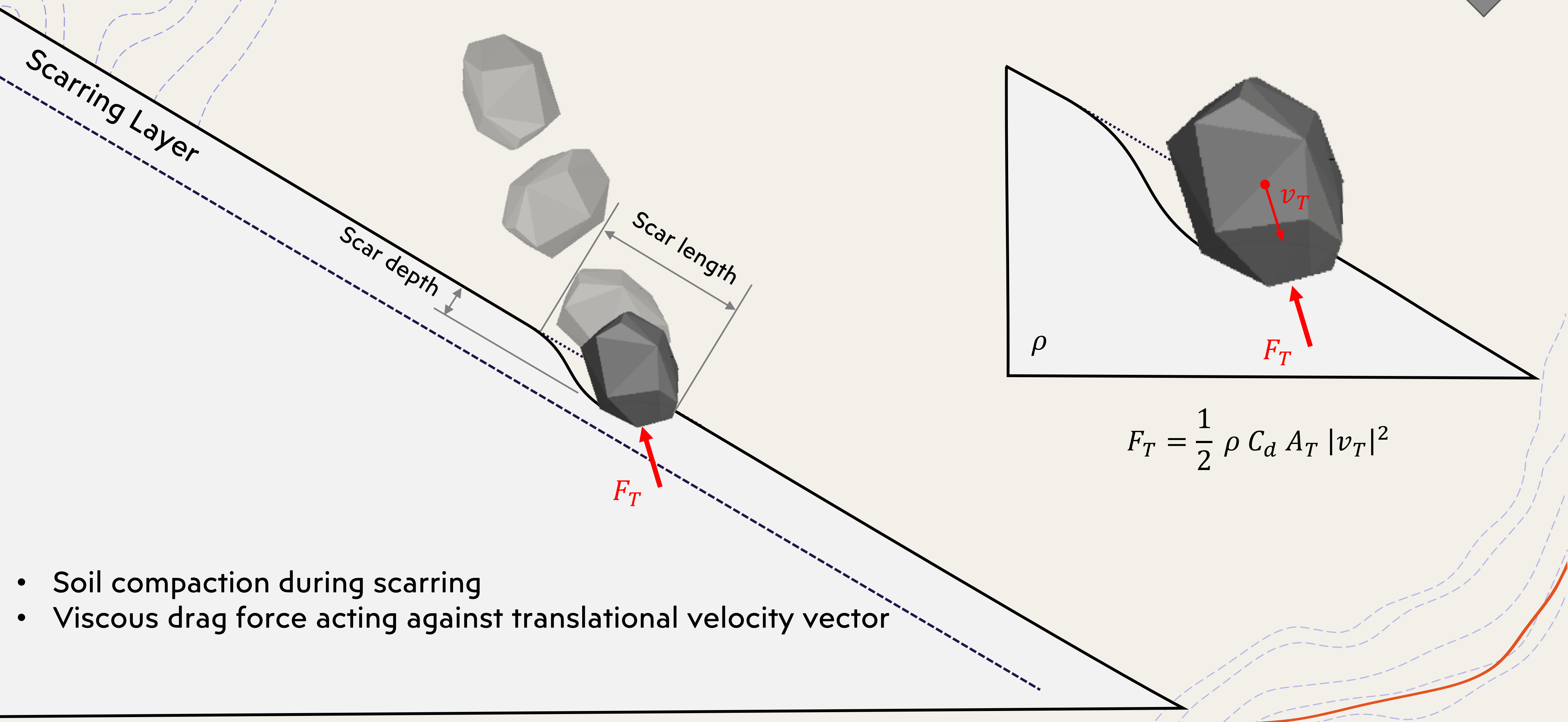
Ground Interaction Model with Scarring



$$M\dot{u} - h(q, u, t) = 0$$

Gravitational term
+ Gyroscopic term for non-spherical rock shape

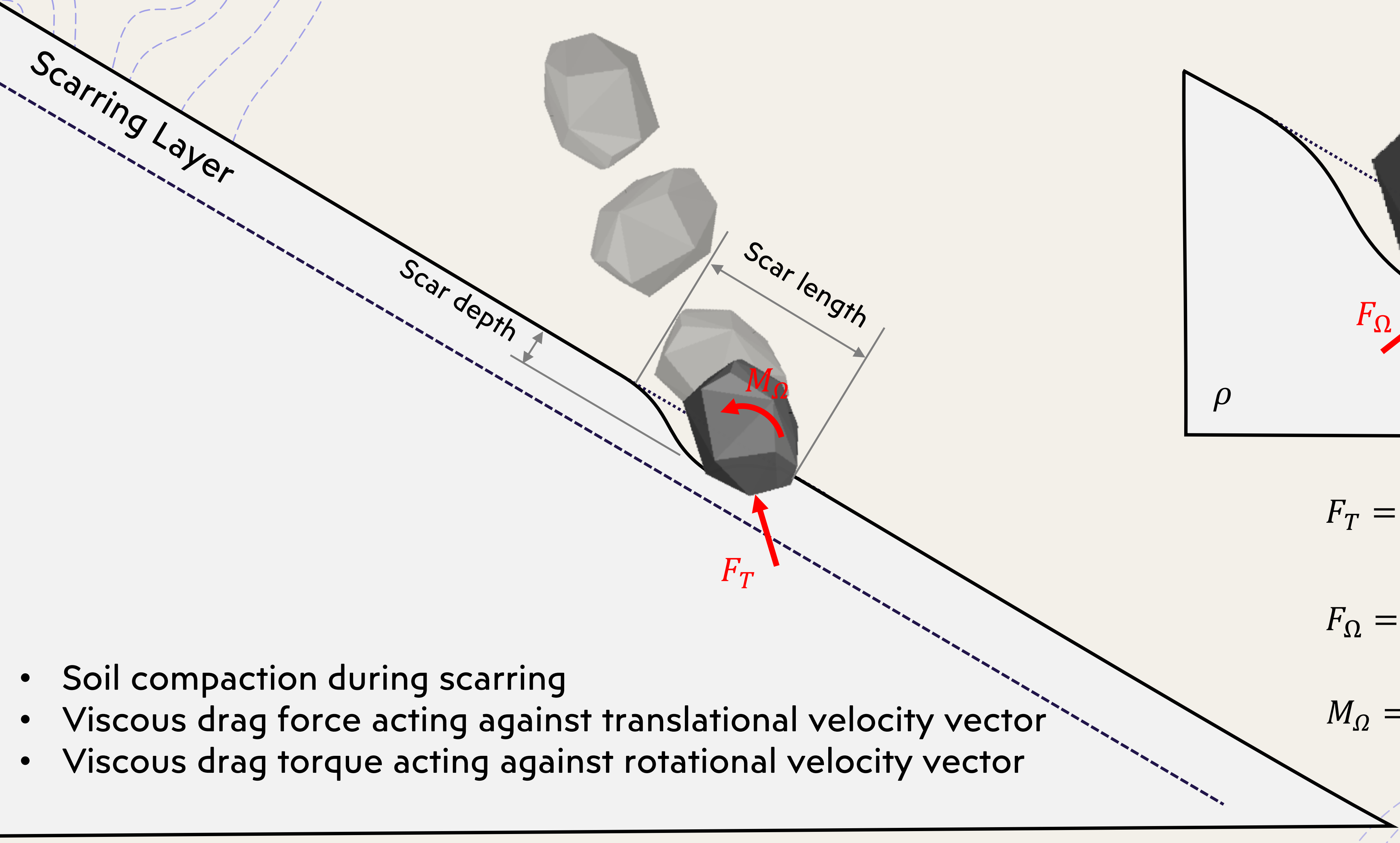
Ground Interaction Model with Scarring

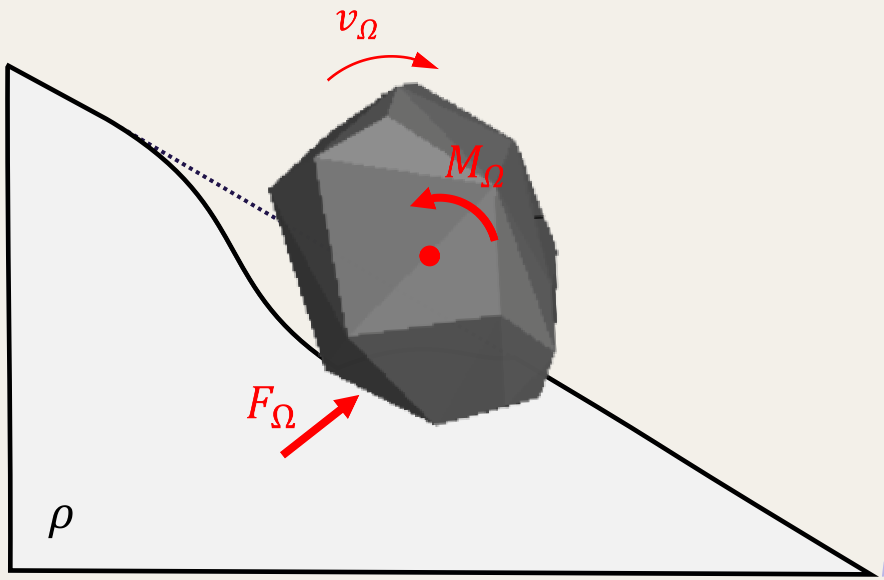


$$F_T = \frac{1}{2}\,\rho\, C_d\, A_T\, |v_T|^2$$

- Soil compaction during scarring
- Viscous drag force acting against translational velocity vector

Ground Interaction Model with Scarring





$$F_T = \frac{1}{2}\,\rho\,C_d\,A_T\,|v_T|^2$$

$$F_\Omega = \frac{1}{2}\,\rho\,C_d\,A_\Omega\,|v_\Omega|^2$$

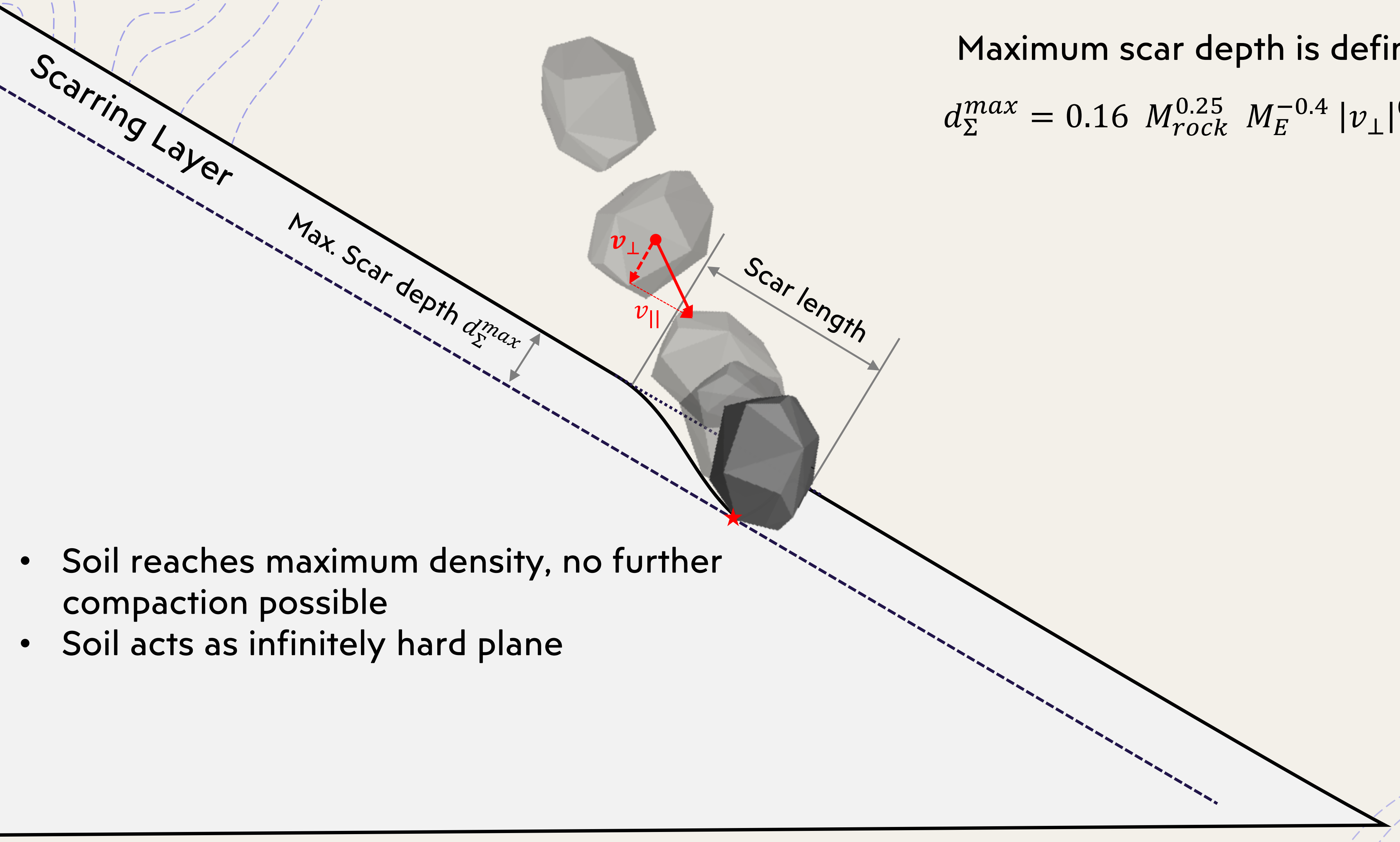
$$M_\Omega = F_\Omega\,d$$

- Soil compaction during scarring
- Viscous drag force acting against translational velocity vector
- Viscous drag torque acting against rotational velocity vector

Ground Interaction Model with Scarring

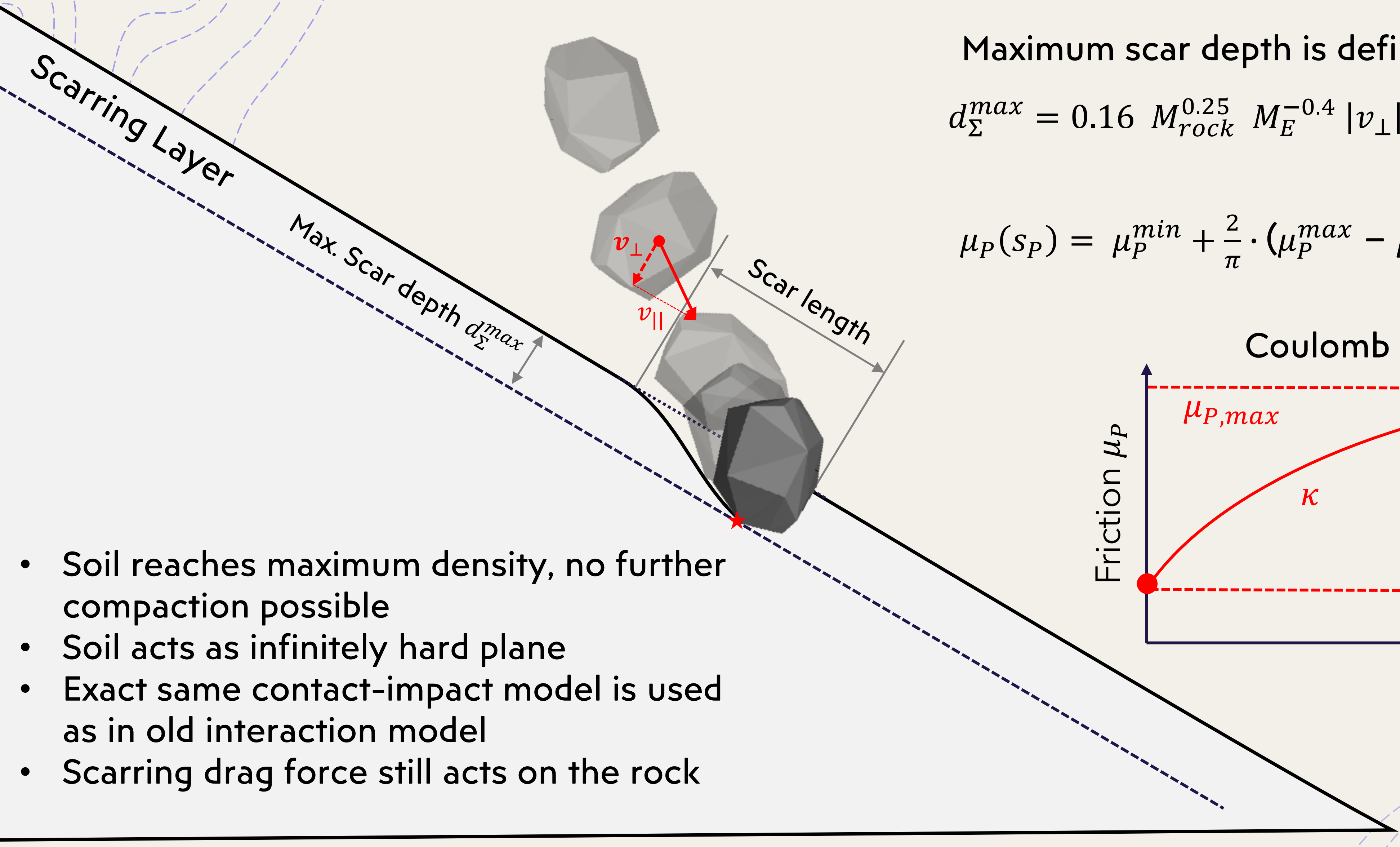
Maximum scar depth is defined **before** impact

$$d_{\Sigma}^{max} = 0.16\ M_{rock}^{0.25}\ M_{E}^{-0.4}\ |v_{\perp}|^{0.8}$$ [Gerber, 2019]



- Soil reaches maximum density, no further compaction possible
- Soil acts as infinitely hard plane

Ground Interaction Model with Scarring

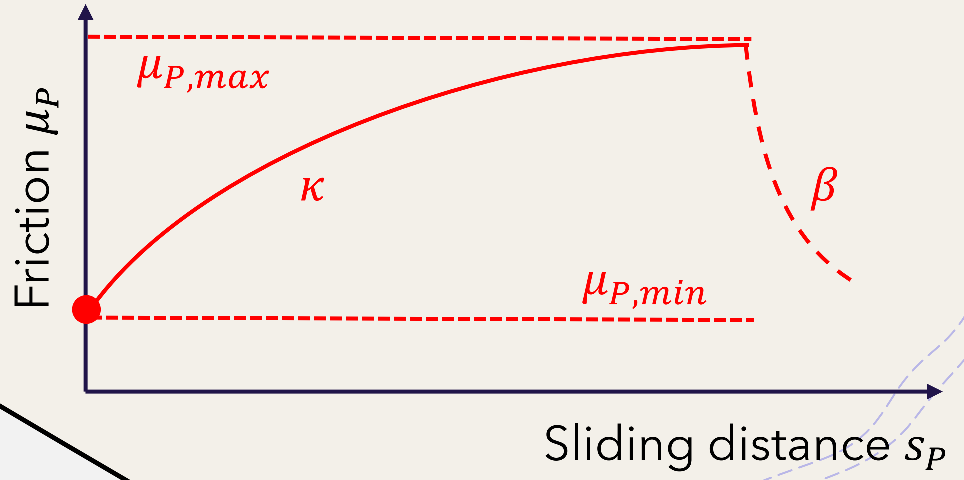


Maximum scar depth is defined **before** impact

$$d_\Sigma^{max} = 0.16\ M_{rock}^{0.25}\ M_E^{-0.4}\ |v_\perp|^{0.8} \qquad \text{[Gerber, 2019]}$$

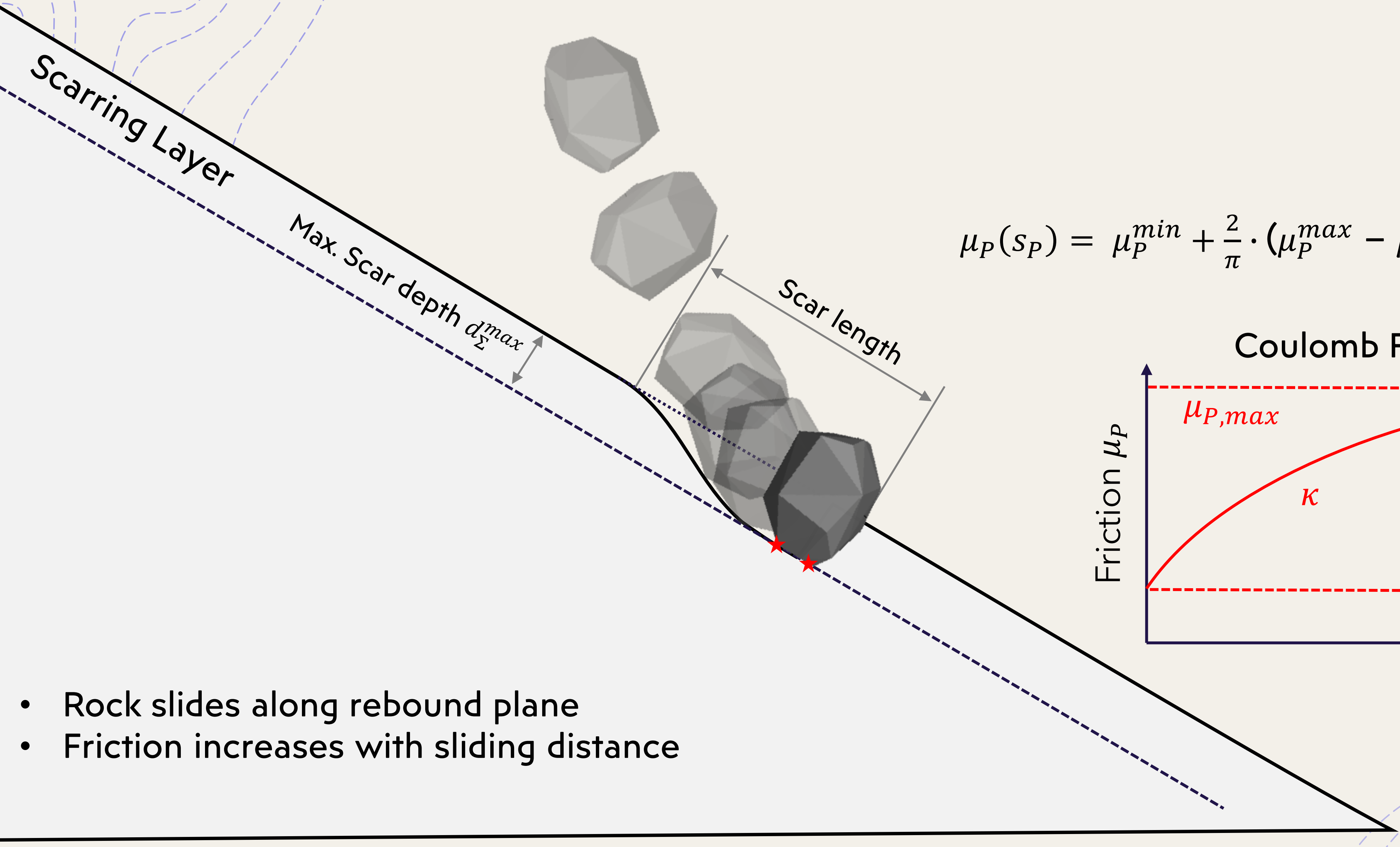
$$\mu_P(s_P) = \mu_P^{min} + \frac{2}{\pi} \cdot (\mu_P^{max} - \mu_P^{min}) \cdot \arctan(\kappa \cdot s_P)$$

Coulomb Friction Law



- Soil reaches maximum density, no further compaction possible
- Soil acts as infinitely hard plane
- Exact same contact-impact model is used as in old interaction model
- Scarring drag force still acts on the rock

Ground Interaction Model with Scarring



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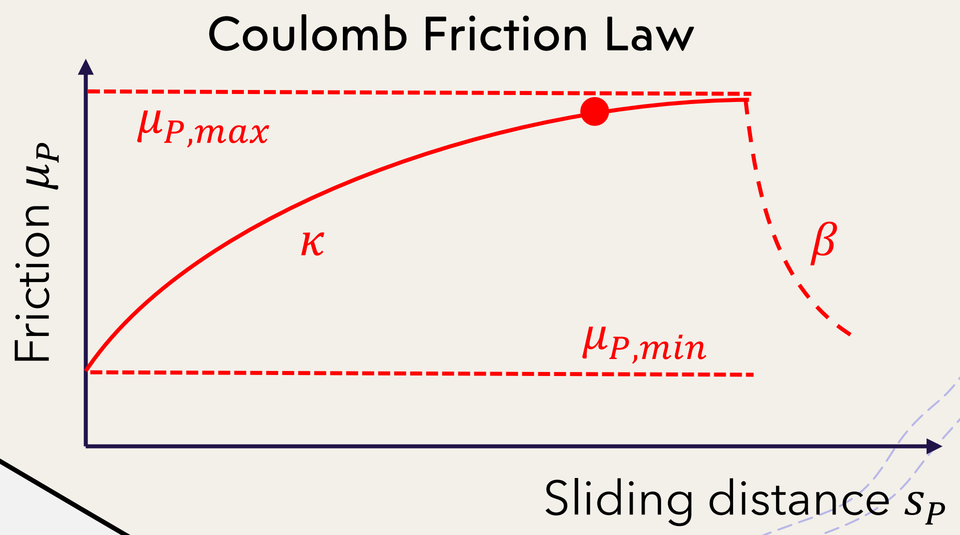
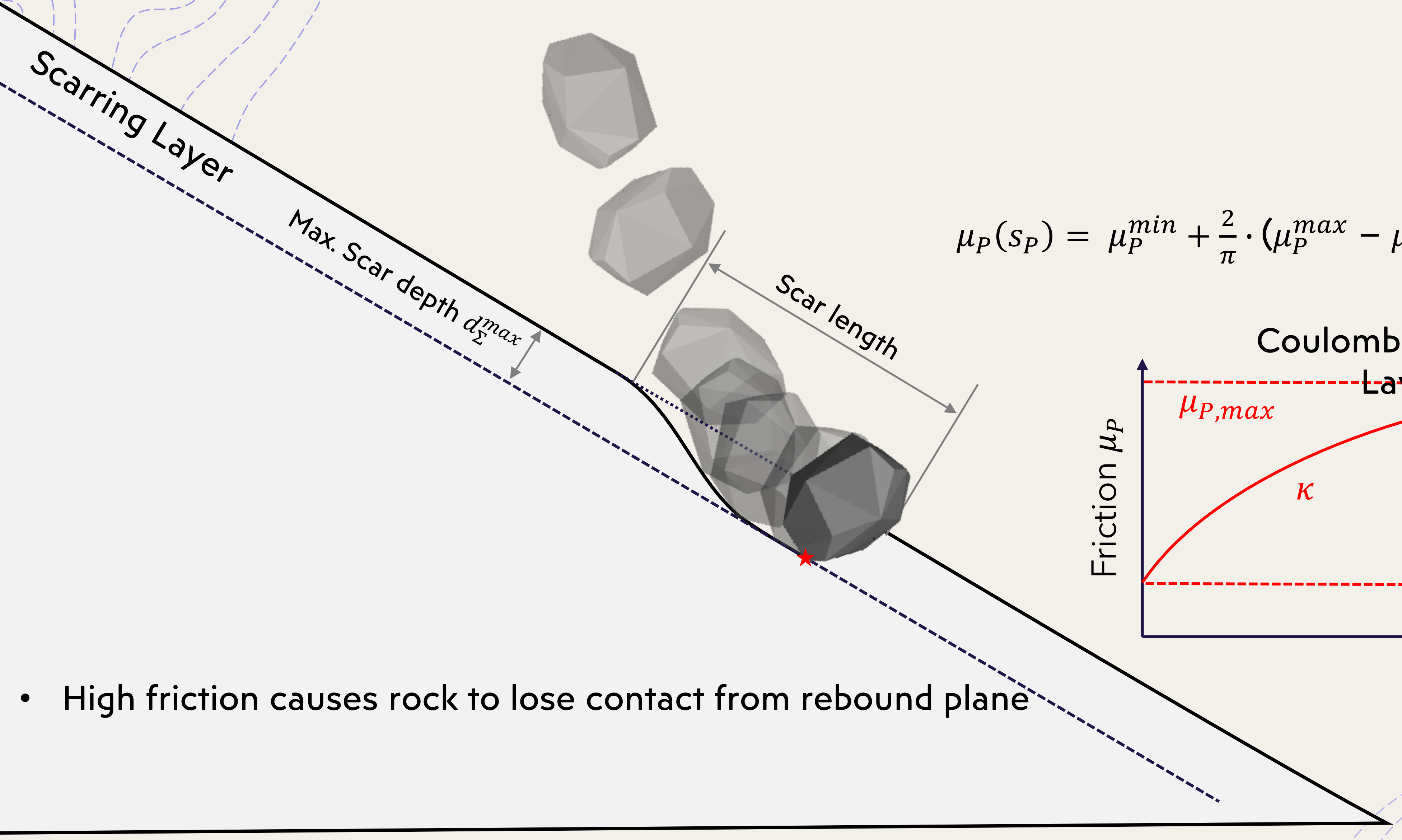


- Rock slides along rebound plane
- Friction increases with sliding distance

Ground Interaction Model with Scarring



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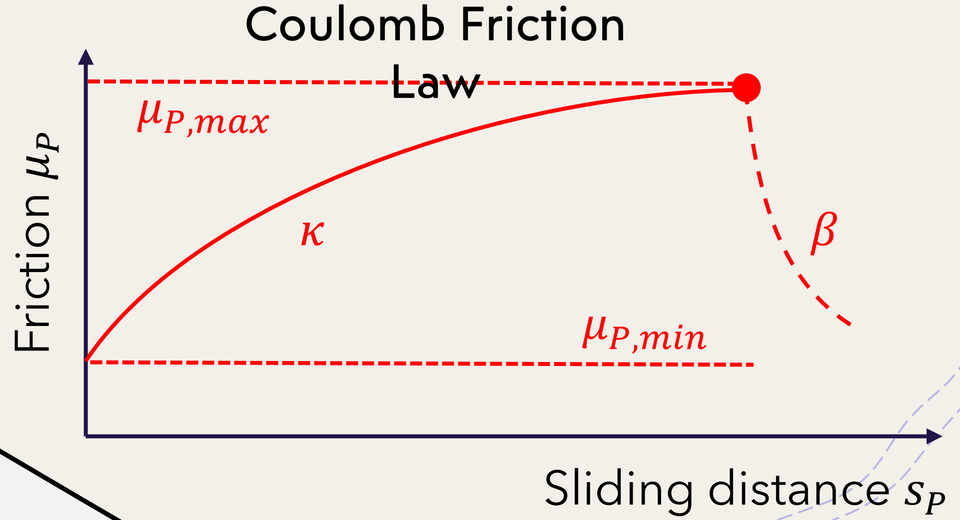
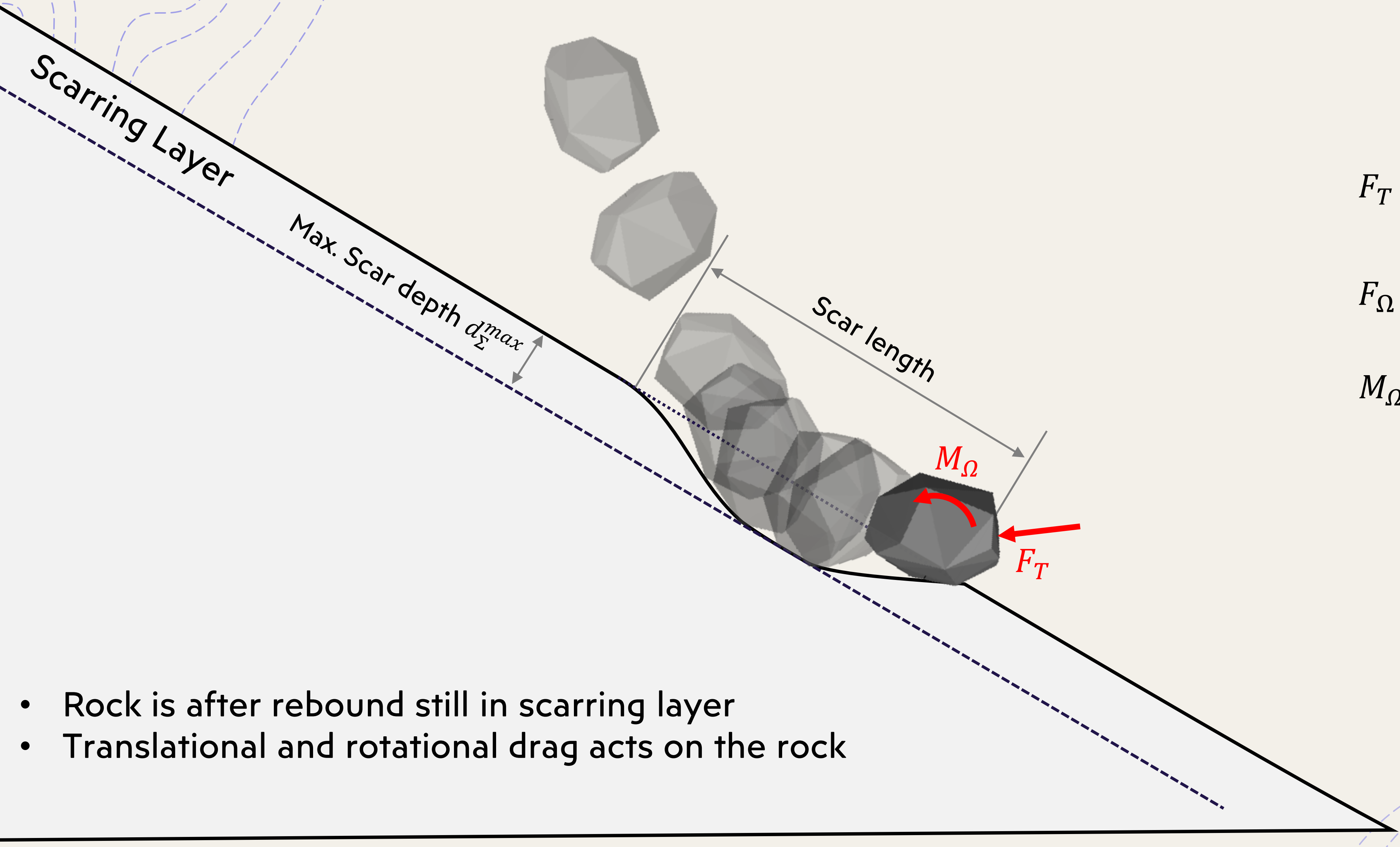


- High friction causes rock to lose contact from rebound plane

Ground Interaction Model with Scarring



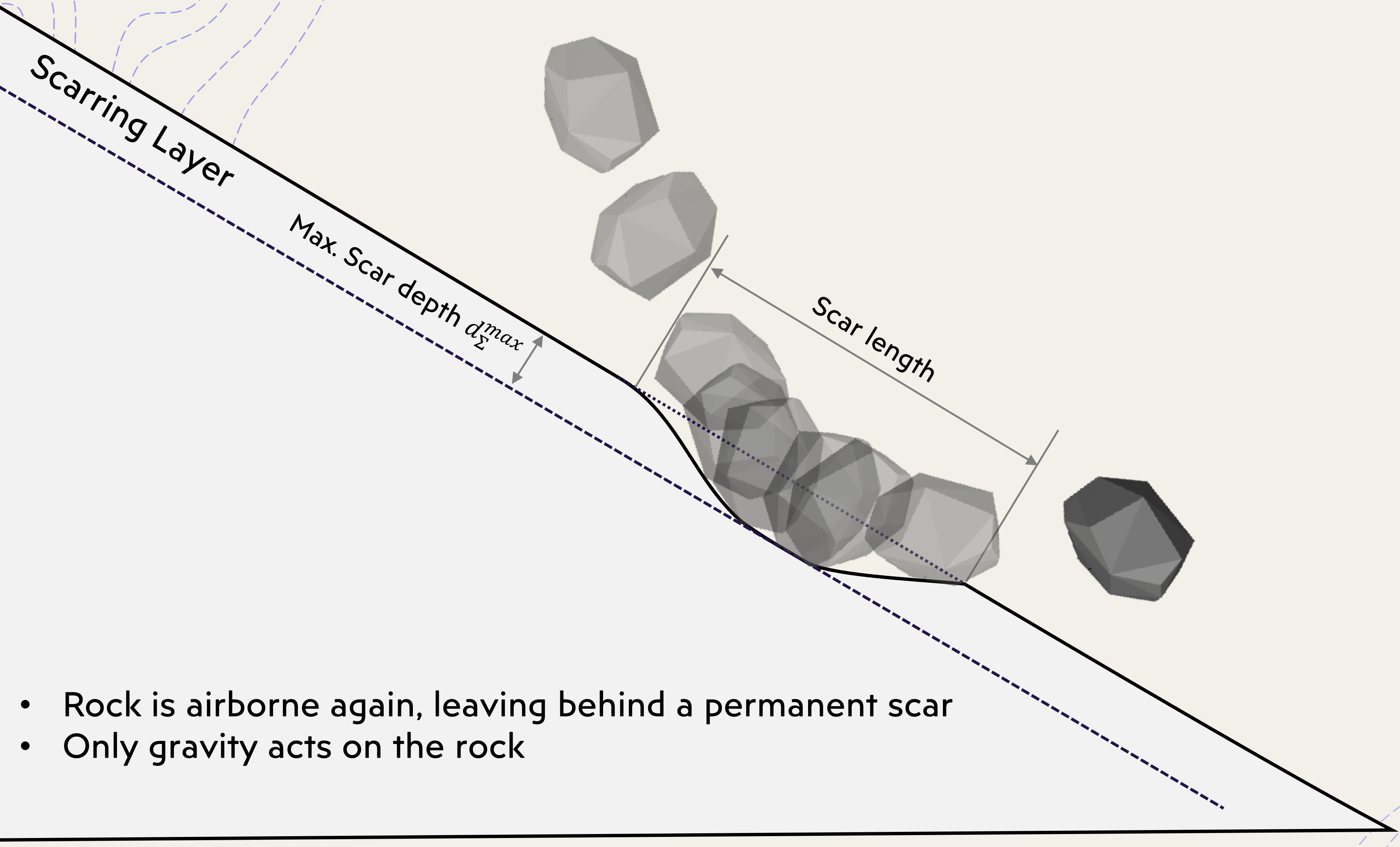
$$F_T = \frac{1}{2}\,\rho\, C_d\, A_T\, |v_T|^2$$

$$F_{\Omega} = \frac{1}{2}\,\rho\, C_d\, A_{\Omega}\, |v_{\Omega}|^2$$

$$M_{\Omega} = F_{\Omega}\, d$$

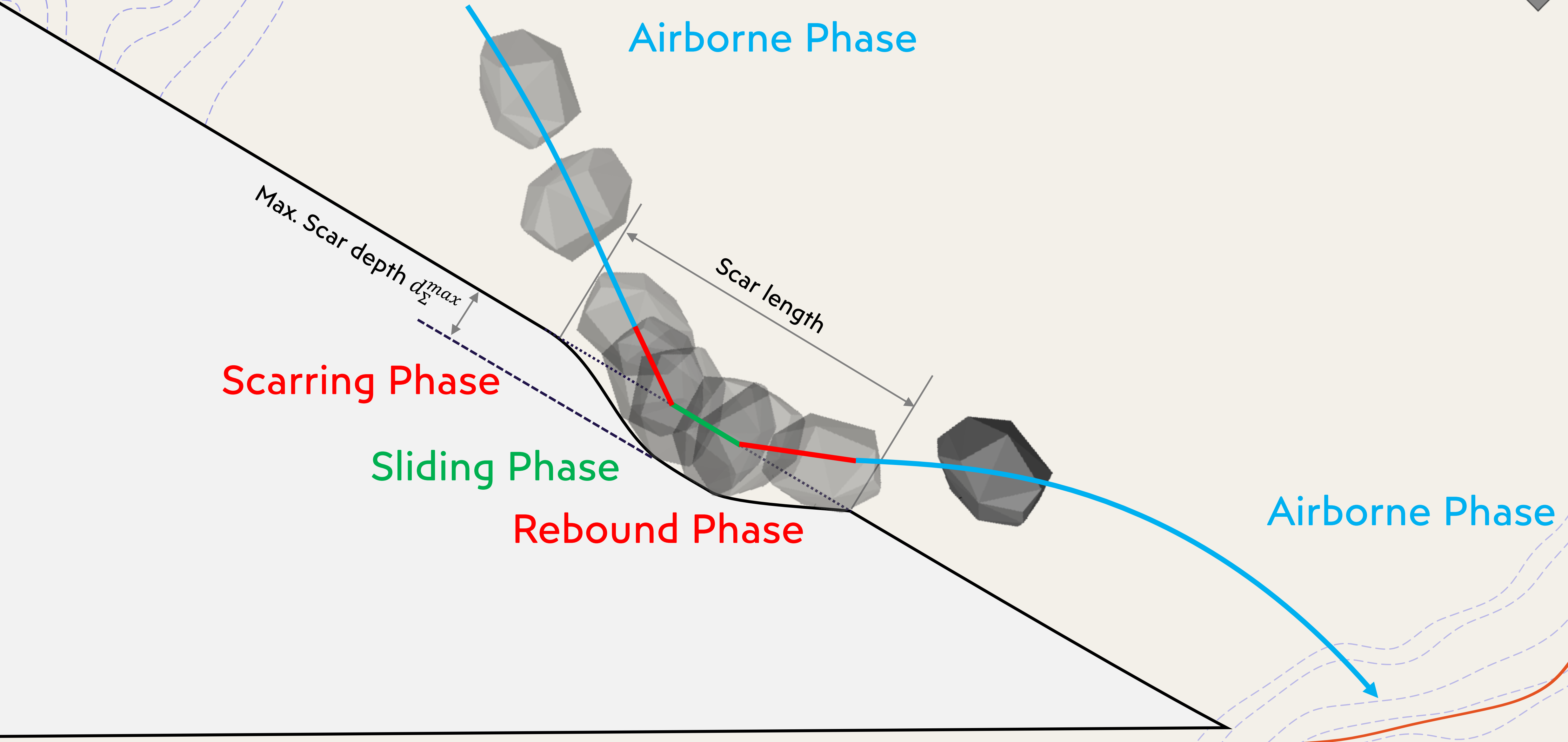
- Rock is after rebound still in scarring layer
- Translational and rotational drag acts on the rock

Ground Interaction Model with Scarring



- Rock is airborne again, leaving behind a permanent scar
- Only gravity acts on the rock

Ground Interaction Model with Scarring

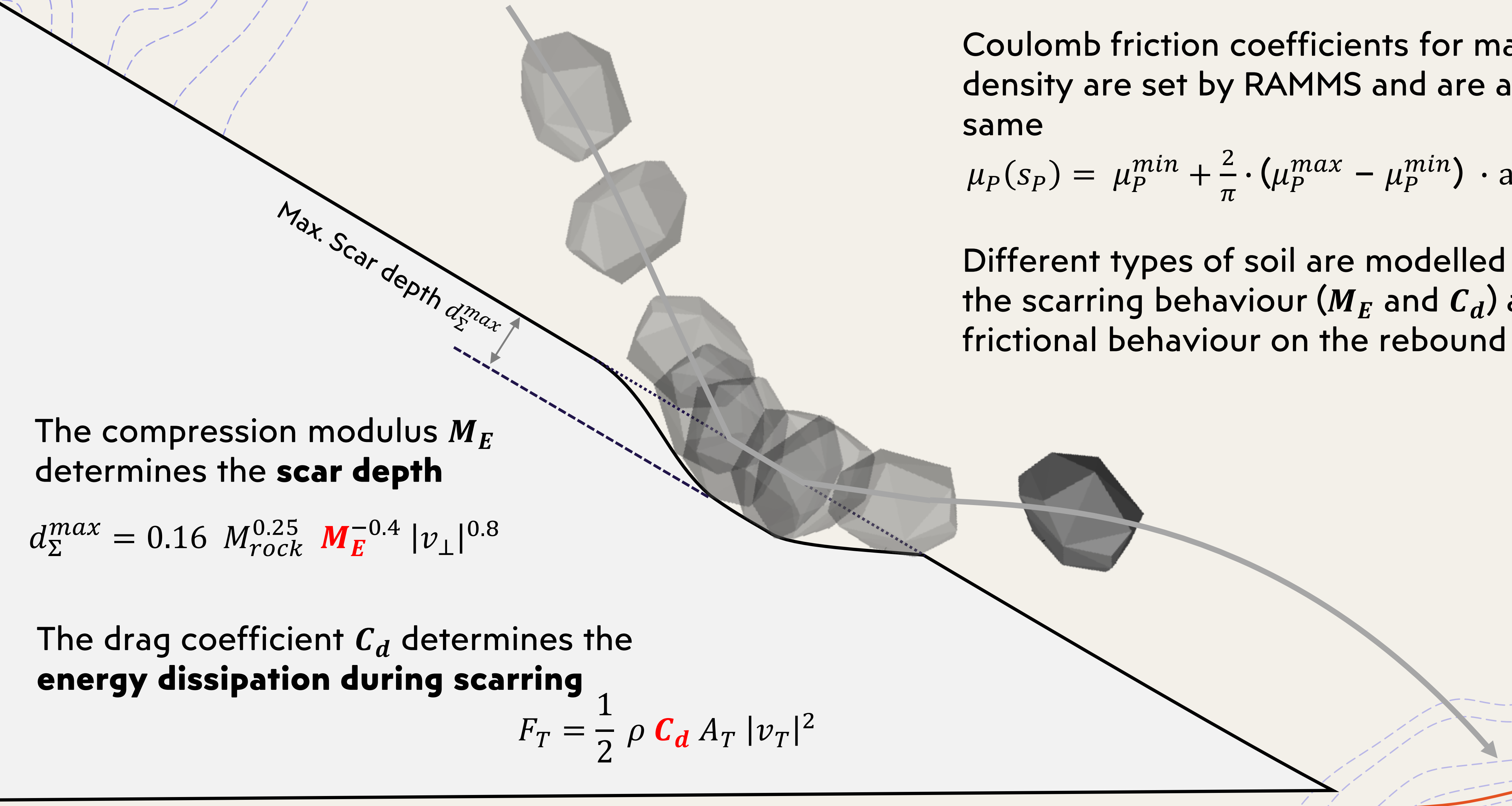


Ground Interaction Model with Scarring

Coulomb friction coefficients for maximal soil density are set by RAMMS and are always the same

$$\mu_P(s_P) = \mu_P^{min} + \frac{2}{\pi} \cdot (\mu_P^{max} - \mu_P^{min}) \cdot \arctan(\kappa \cdot s_P)$$

Different types of soil are modelled by changing the scarring behaviour ($\boldsymbol{M_E}$ and $\boldsymbol{C_d}$) and not the frictional behaviour on the rebound plane



The compression modulus $\boldsymbol{M_E}$ determines the **scar depth**

$$d_\Sigma^{max} = 0.16 \; M_{rock}^{0.25} \; \boldsymbol{M_E}^{-0.4} \; |v_\perp|^{0.8}$$

The drag coefficient $\boldsymbol{C_d}$ determines the **energy dissipation during scarring**

$$F_T = \frac{1}{2} \rho \, \boldsymbol{C_d} \, A_T \, |v_T|^2$$

Soil Parameter: M_E

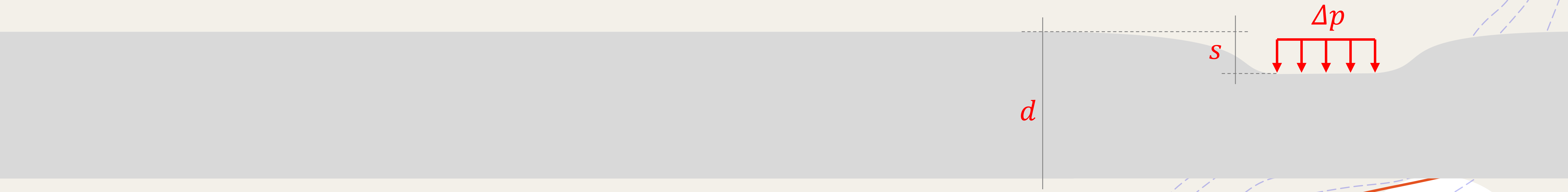
The compression modulus M_E is used in civil engineering practice for the calculation of settlements after consolidation. It stands for the amount of pressure that needs to be applied to achieve a certain amount of strain.

The compression modulus M_E can be derived with Oedometer tests and has the unit **N/m²**

$$M_E = \frac{\Delta p}{\epsilon} = \frac{\Delta p}{s}\, d$$

A higher M_E leads to stiffer soil behaviour. For a given rock energy (mass and velocity), the scar depth is smaller.

Realistic values for M_E in alpine terrain are between **1 MPa** and **200 MPa**

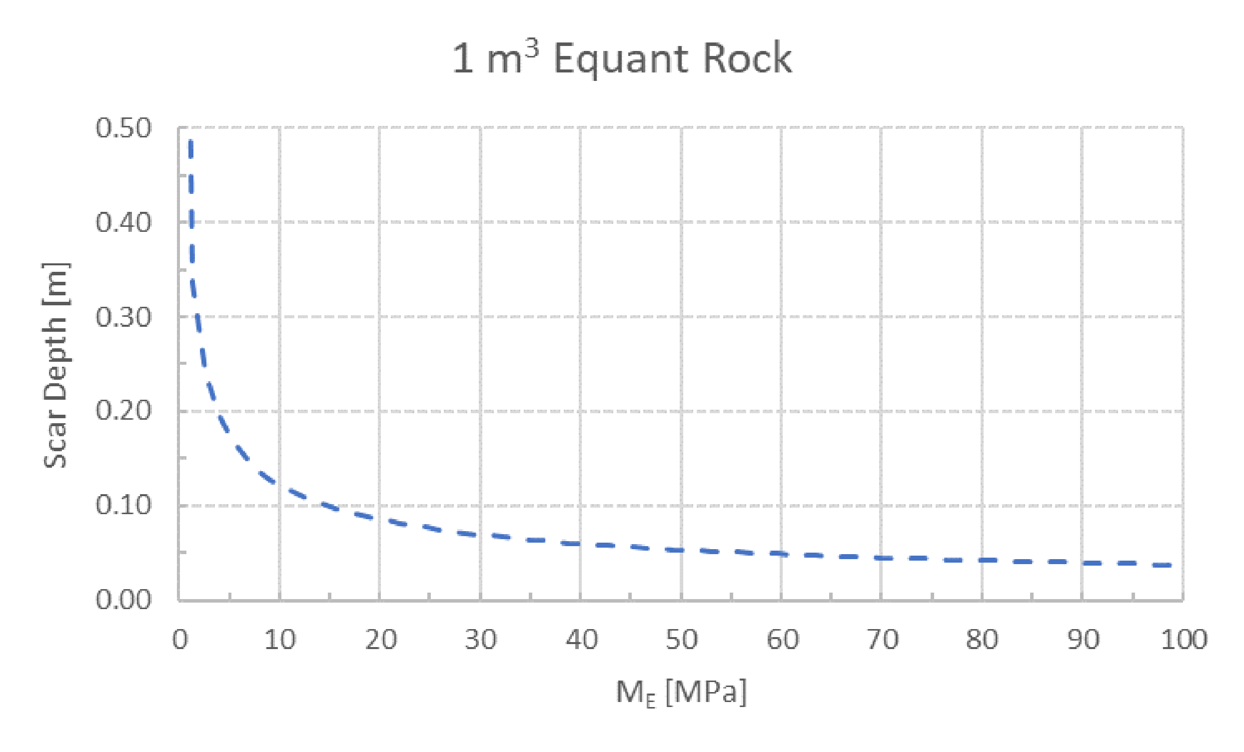


Soil Parameters

Scar Depth

$$d_{\Sigma}^{max} = 0.16\ M_{rock}^{0.25}\ \boldsymbol{M_E}^{-0.4}\ |v_{\perp}|^{0.8}\ \sim\propto \frac{1}{\sqrt{M_E}}$$

High scar depth	Low scar depth
Low M_E, (soft soil)	High M_E (hard soil)



Runout Distance – Kinetic Energy – Velocity

Jump Height

Soil Parameters

Scar Depth

$$d_{\Sigma}^{max} = 0.16\ M_{rock}^{0.25}\ \boldsymbol{M_E}^{-0.4}\ |v_{\perp}|^{0.8}\ \sim\propto \frac{1}{\sqrt{M_E}}$$

Low scar depth	High scar depth
High M_E, (hard soil)	Low M_E (soft soil)

Runout Distance – Kinetic Energy – Velocity

$$F_T = \frac{1}{2}\,\rho\,\boldsymbol{C_d}\,A_T\,|v_T|^2$$

Low Velocity	High Velocity
High C_D, (high drag)	Low C_D (low drag)

Jump Height

Soil Parameters

Scar Depth

$$d_{\Sigma}^{max} = 0.16 \; M_{rock}^{0.25} \; \boldsymbol{M_E}^{-0.4} \, |v_\perp|^{0.8} \; \sim\propto \frac{1}{\sqrt{M_E}}$$

Low scar depth	High scar depth
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Runout Distance – Kinetic Energy – Velocity

$$F_T = \frac{1}{2} \rho \, \boldsymbol{C_d} \, A_T \, |v_T|^2$$

Low Velocity	High Velocity
High C_D, (high drag)	Low C_D (low drag)

Jump Height

Low Jump Height	High Jump Height
Low C_D, Low M_E	High C_D, High M_E

Default Soil Parameters

Surface Soil

M_E = 3 Mpa
C_D = 1.55

Subsoil

M_E = 4 Mpa
C_D = 1.8

Talus Fine

M_E = 7 Mpa
C_D = 2.30

Talus Coarse

M_E = 10 Mpa
C_D = 2.70

Talus Blocs

M_E = 15 Mpa
C_D = 3.50

Moraine

M_E = 20 Mpa
C_D = 3.50

Bedrock

M_E = 100 Mpa
C_D = 4.00

Boulder Field

Alpine Spruce/ Beech Forest

Mountain Road

Asphalt

River/Swamp

Summary

1. **Rockfall impacts cannot be described by a single restitution coefficient.** Rock rebound depends on terrain roughness, rock shape, rotation, and ground deformation..

2. **RAMMS models rockfall using rigid-body mechanics.** Rocks are treated as polyhedral rigid bodies with **six degrees of freedom** (translation and rotation).

3. **Realistic rock geometry is essential.** Rock shapes are represented as **convex hull polyhedra derived from point clouds**, allowing realistic rotational dynamics.

Summary

4. **Impacts are solved using hard-contact mechanics.**
   Contact forces applied at rock vertices generate torques that naturally produce **rolling, sliding, jumping, and stopping**.

5. **Rock rotation strongly influences trajectories.**
   Rocks tend to rotate around the **axis with the largest moment of inertia**, producing stable wheel-like motion and potentially long runout distances.

6. **Energy dissipation is dominated by ground interaction (scarring).**
   Soil compaction, viscous drag forces, and slip-dependent friction control the transition from bouncing to rolling and stopping.