Mass Movements
Figures

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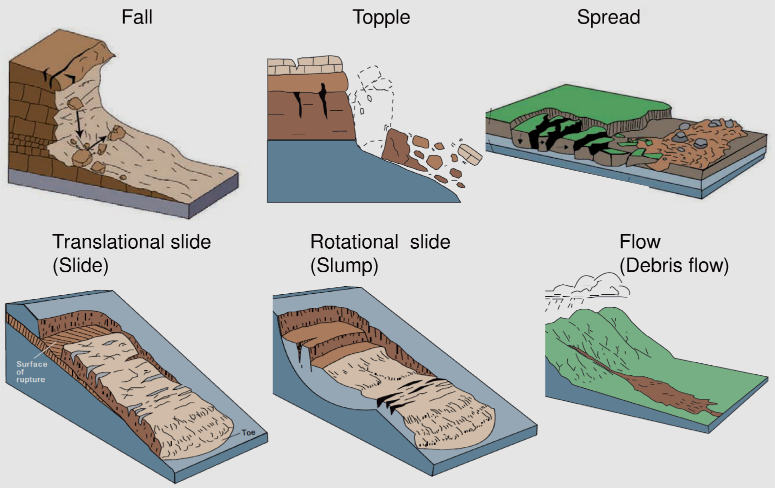
Classification of Mass Movements According to Varnes

Classification by the Type of Movement



Modified from: Shanmugam & Wang, Journal of Palaeogeography, 2015, doi: 10.3724/SP.J.1261.2015.00071

Classification of Mass Movements According to Varnes

Classification by the Material

Rock: Hard or firm mass that was intact and in its natural place before the initiation of movement.

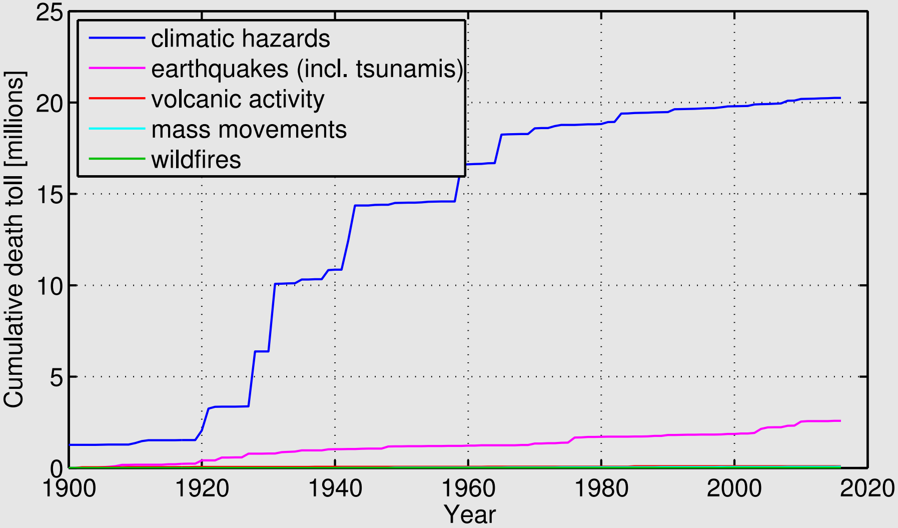
Soil: An aggregate of solid particles, generally of minerals and rocks, that either was transported or was formed by the weathering of rock in place. Gases or liquids filling the pores of the soil form part of the soil.

Earth: Material in which 80 % or more of the particles are smaller than 2 mm, the upper limit of sand sized particles.

Mud: Material in which 80 % or more of the particles are smaller than 0.06 mm, the upper limit of silt sized particles.

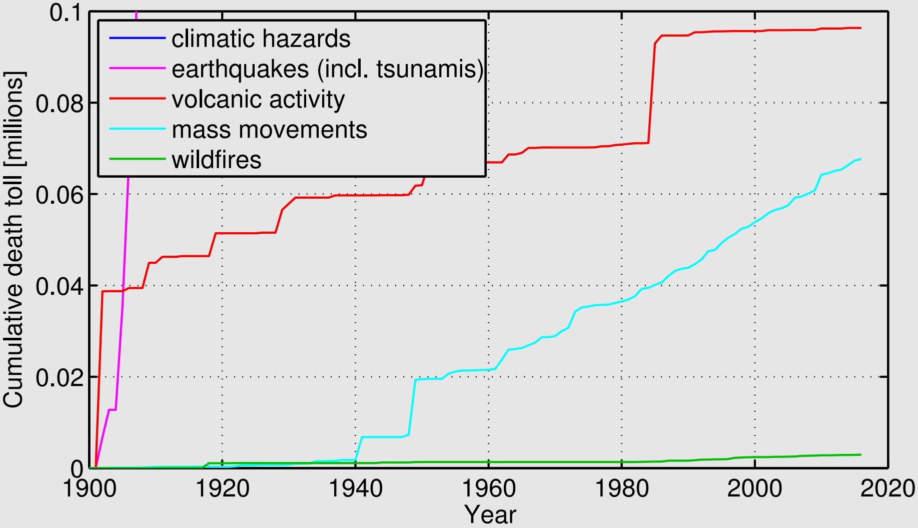
Debris: Contains a significant proportion of coarse material; 20 % to 80 % of the particles are larger than 2 mm.

Worldwide Death Toll Since 1900



Mass Movements as a Geohazard

Worldwide Death Toll Since 1900



Examples From the Alps

Rockslide at Randa (Matter Valley, 1991, $V \approx 30\,\text{mil.}\,\text{m}^3$)

Source: Wikipedia

Foto: S. Hergarten

Examples From the Alps

Flims Rockslide (9500 years b.p., $V \geq 8\ \mathrm{km}^3$)

Photo: K. Stüwe & R. Homberger (www.alpengeologie.org)

Wutach Gorge (2017)

Photo: M. Geyer (www.geotourist-freiburg.de)

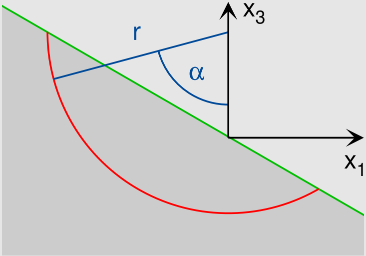
Freiburg, Main Railway Track (2016)

Photo: T. Kunz (Badische Zeitung)

Area Element

Size of an area element:

$$\delta A \;=\; w\, r\, \delta\alpha \;=\; w\, \frac{\delta x}{\cos\alpha}$$



with

$$\begin{aligned} w &= \text{width in } x_2 \text{ direction} \\ \delta\alpha &= \text{angle increment} \\ \delta x &= \text{increment in } x_1 \text{ direction} \end{aligned}$$

In integral form:

$$\int \dots\, dA \;=\; w\, r \int \dots\, d\alpha \;=\; w \int \frac{\dots}{\cos\alpha}\, dx$$

Overall Factor of Safety

Continuous form:

$$\mathrm{FoS} = \frac{\int \sigma_{\mathrm{s}}^{\mathrm{crit}} dA}{\int \sigma_{\mathrm{s}} dA} = \frac{\int \sigma_{\mathrm{s}}^{\mathrm{crit}} d\alpha}{\int \sigma_{\mathrm{s}} d\alpha} = \frac{\int \frac{\sigma_{\mathrm{s}}^{\mathrm{crit}}}{\cos\alpha} dx}{\int \frac{\sigma_{\mathrm{s}}}{\cos\alpha} dx}$$

As a discrete sum:

$$\mathrm{FoS} \approx \frac{\sum_i \sigma_{\mathrm{s}i}^{\mathrm{crit}} \delta A_i}{\sum_i \sigma_{\mathrm{s}i} \delta A_i} \approx \frac{\sum_i \sigma_{\mathrm{s}i}^{\mathrm{crit}} \delta \alpha_i}{\sum_i \sigma_{\mathrm{s}i} \delta \alpha_i} \approx \frac{\sum_i \frac{\sigma_{\mathrm{s}i}^{\mathrm{crit}}}{\cos\alpha_i} \delta x_i}{\sum_i \frac{\sigma_{\mathrm{s}i}}{\cos\alpha_i} \delta x_i}$$

Fellenius' Method

- Introduced by W. Fellenius 1929
- Earliest and simplest model for rotational slope failure taking into account the variation in σ_n and thus $\sigma_\mathrm{s}^\mathrm{crit}$ along the slip circle
- Also called ordinary method of slices (OMS)
- Originally developed in terms of torques for a discrete set of vertical slices
- Can also be derived from a simplified stress tensor

$$\boldsymbol{\sigma} \;=\; \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\rho g h \end{pmatrix}$$

(in Cartesian coordinates ($\tilde{\boldsymbol{\sigma}}$ in assignment 1) where h is the depth below the surface

Fellenius' Method

$$
\begin{aligned}
\sigma_{\mathrm{n}} &= -\rho g h \cos^2\alpha \\
\sigma_{\mathrm{s}} &= \rho g h \cos\alpha \sin\alpha \\
\sigma_{\mathrm{s}}^{\mathrm{crit}} &= C - \sigma_{\mathrm{n}} \tan\phi = C + \rho g h \cos^2\alpha \tan\phi
\end{aligned}
$$

$$\Downarrow$$

Local

$$
\mathrm{FoS}_{\mathrm{loc}} = \frac{\sigma_{\mathrm{s}}^{\mathrm{crit}}}{\sigma_{\mathrm{s}}} = \frac{C + \tan\phi\,\rho g h \cos^2\alpha}{\rho g h \sin\alpha \cos\alpha} = \frac{\tan\phi}{\tan\alpha} + \frac{C}{\rho g h \cos\alpha \sin\alpha}.
$$

Fellenius' Method

Overall

$$
\begin{aligned}
\text{FoS} &= \frac{\int \left(C + \tan\phi\, \rho g h\, \cos^2\alpha\right)\, d\alpha}{\int \rho g h\, \cos\alpha \sin\alpha\, d\alpha} \\
&= \frac{\int \left(\frac{C}{\cos\alpha} + \tan\phi\, \rho g h\, \cos\alpha\right)\, dx}{\int \rho g h\, \sin\alpha\, dx} \\
&\approx \frac{\sum_i \left(\frac{C}{\cos\alpha_i} + \tan\phi\, \rho g h_i\, \cos\alpha_i\right)\delta x_i}{\sum_i \rho g h_i\, \sin\alpha_i\, \delta x_i}
\end{aligned}
$$

Bishop's Method

- Introduced by A. W. Bishop 1955
- Most widely used model for rotational slope failure
- Originally developed in terms of torques for a discrete set of vertical slices
- Can also be derived from a simplified, inconsistent stress tensor

$$\boldsymbol{\sigma} = \begin{pmatrix} 0 & 0 & \tau \\ 0 & 0 & 0 \\ 0 & 0 & -\rho g h \end{pmatrix}$$

with an arbitrary stress τ

Rotational Slides

Bishop's Method

$$
\begin{aligned}
\sigma_\mathrm{n} &= -\rho g h \cos^2\alpha + \tau \cos\alpha \sin\alpha \\
\sigma_\mathrm{s} &= \rho g h \cos\alpha \sin\alpha + \tau \cos^2\alpha \\
\sigma_\mathrm{s}^\mathrm{crit} &= C - \sigma_\mathrm{n} \tan\phi \;=\; C + \tan\phi \left(\rho g h \cos^2\alpha - \tau \cos\alpha \sin\alpha\right)
\end{aligned}
$$

$$\Downarrow$$

Local

$$
\mathrm{FoS}_\mathrm{loc} = \frac{\sigma_\mathrm{s}^\mathrm{crit}}{\sigma_\mathrm{s}} = \frac{C + \tan\phi \left(\rho g h \cos^2\alpha - \tau \cos\alpha \sin\alpha\right)}{\rho g h \cos\alpha \sin\alpha + \tau \cos^2\alpha}
$$

$$\Downarrow$$

$$
\tau = \frac{C + \tan\phi\, \rho g h \cos^2\alpha - \mathrm{FoS}_\mathrm{loc}\, \rho g h \cos\alpha \sin\alpha}{\mathrm{FoS}_\mathrm{loc} \cos^2\alpha + \tan\phi \cos\alpha \sin\alpha}
$$

Rotational Slides

Bishop's Method

$$\Downarrow$$

$$\begin{aligned}
\sigma_\mathrm{n} &= \frac{C \tan\alpha - \mathrm{FoS_{loc}}\,\rho g h}{\mathrm{FoS_{loc}} + \tan\phi \tan\alpha} \\
\sigma_\mathrm{s} &= \frac{C + \tan\phi\,\rho g h}{\mathrm{FoS_{loc}} + \tan\phi \tan\alpha} \\
\sigma_\mathrm{s}^\mathrm{crit} &= \frac{C + \tan\phi\,\rho g h}{1 + \frac{\tan\phi \tan\alpha}{\mathrm{FoS_{loc}}}}
\end{aligned}$$

- σ_s is inconsistent.
- Even if it was correct, it would not be useful at this stage.

Rotational Slides

Bishop's Method

Assume that

- τ only affects σ_n and thus $\sigma_\mathrm{s}^\mathrm{crit}$, but not σ_s.
- FoS in the expression for $\sigma_\mathrm{s}^\mathrm{crit}$ is the overall FoS.

Overall

$$
\begin{aligned}
\mathrm{FoS} &= \frac{\int \frac{\sigma_\mathrm{s}^\mathrm{crit}}{\cos\alpha}\,dx}{\int \frac{\sigma_\mathrm{s}}{\cos\alpha}\,dx} = \frac{\int \frac{C+\tan\phi\,\rho g h}{\cos\alpha+\frac{\tan\phi\,\sin\alpha}{\mathrm{FoS}}}\,dx}{\int \rho g h\,\sin\alpha\,dx} \\
&\approx \frac{\sum_i \frac{C+\tan\phi\,\rho g h_i}{\cos\alpha_i+\frac{\tan\phi\,\sin\alpha_i}{\mathrm{FoS}}}\,\delta x_i}{\sum_i \rho g h_i\,\sin\alpha_i\,\delta x_i}
\end{aligned}
$$

Bishop's Method

Occurrence of FoS at the right-hand side can be treated using a fixed-point iteration.

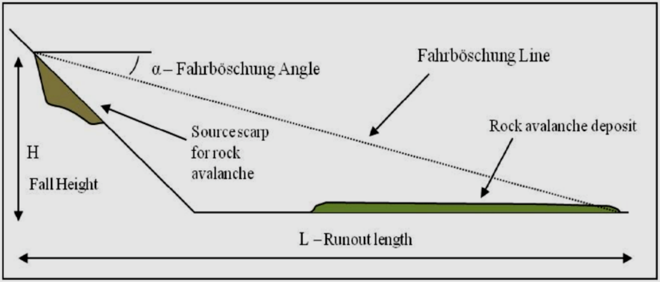
- Converges rapidly
- Useful initial guess: FoS of Fellenius method

Local

$$\mathrm{FoS}_{\mathrm{loc}} = \frac{\sigma_{\mathrm{s}}^{\mathrm{crit}}}{\sigma_{\mathrm{s}}} = \frac{\frac{C + \tan\phi\, \rho g h}{1 + \frac{\tan\phi\ \tan\alpha}{\mathrm{FoS}}}}{\rho g h\ \cos\alpha \sin\alpha} = \frac{\frac{C}{\rho g h} + \tan\phi}{\left(\cos\alpha + \frac{\tan\phi\ \sin\alpha}{\mathrm{FoS}}\right)\sin\alpha}$$

The Fahrboeschung Concept

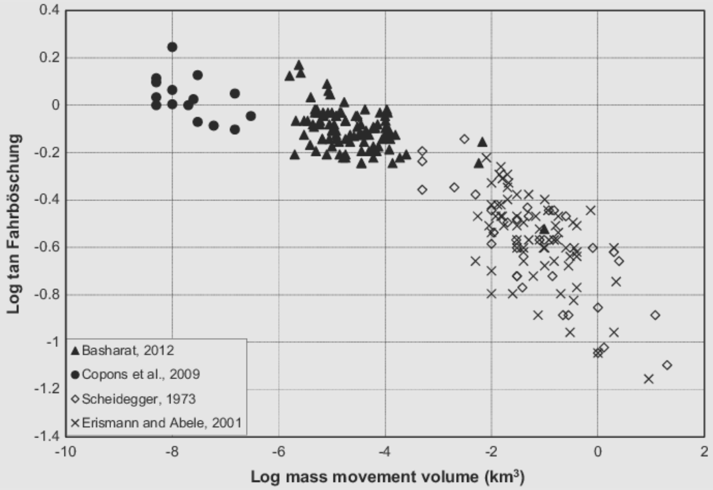
- Dates back to Albert Heim (1932).
- Mostly applied to rockfalls and rock avalanches, but also to mud flows and debris flows.
- Ratio of fall height H and runout length L.



Source: de Graaf & Bowman, 12th International Symposium on Landslides, 2016

Fahrboeschung and Talweg

Dependence of Fahrboeschung on Volume



Source: Basharat & Rohn, Nat. Hazards, 2015

Physical Interpretation of Fahrboeschung

Consider a particle moving on a 1D topography $H(x)$ with a given coefficient of kinetic (dynamic, sliding) friction ξ.

Friction force:

$$F_f \;=\; \xi\, mg \cos\beta$$

if dynamic effects are neglected with the slope angle β according to

$$\tan\beta \;=\; -\frac{\partial H}{\partial x}$$

Energy consumed by friction:

$$E_f \;=\; \int F_f\, v\, dt \;=\; \xi\, mg \int v \cos\beta\, dt \;=\; \xi\, mg\, L$$

with $L =$ traveled distance in x direction (horizontally measured)

Physical Interpretation of Fahrboeschung

Converted potential energy:

$$E_p \;=\; mg\,H$$

with $H =$ height drop

Particle comes to rest when $E_f = E_p$.

$$\Downarrow$$

$$\frac{H}{L} \;=\; \xi$$

Fahrboeschung and Talweg

Definition and Mathematical Description of the Talweg

Consider a given topography $H(x_1, x_2)$. The talweg (also thalweg) is the line (from a given point) following the direction of the steepest descent.

Talweg line $\vec{s}(t) = \binom{s_1(t)}{s_2(t)}$ (in map view) can be described by the ordinary differential equation

$$\frac{d}{dt}\vec{s}(t) \;\sim\; -\nabla H(\vec{s}(t))$$

where t is the curve parameter (not necessariliy time).

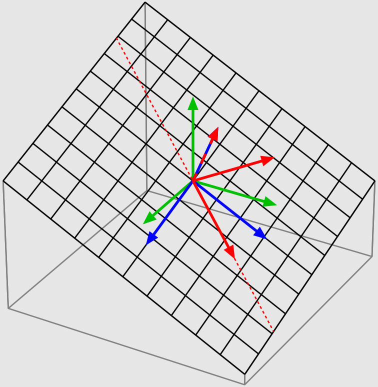
The factor of proportionality does not affect the talweg line, but only the meaning of t; any positive (not necessarily constant) value can be used.

Convenient choice:

$$\frac{d}{dt}\vec{s}(t) \;=\; -\frac{\nabla H(\vec{s}(t))}{|\nabla H(\vec{s}(t))|}$$

Applications of the Talweg Concept to Mass Movements

- Simplest "realistic" path of downward movement; relation $\frac{H}{L} = \xi$ remains valid with $L =$ track length (not a straight line).
- Construction of locally aligned coordinate systems for granular flow models based on continuum mechanics



Savage-Hutter model (1989)
avalanche model RAMMS
Cartesian coordinate system
(Hergarten & Robl, NHESS, 2015)

Falling

Particle Motion

Neglect air drag and interactions between particles

$$\Downarrow$$

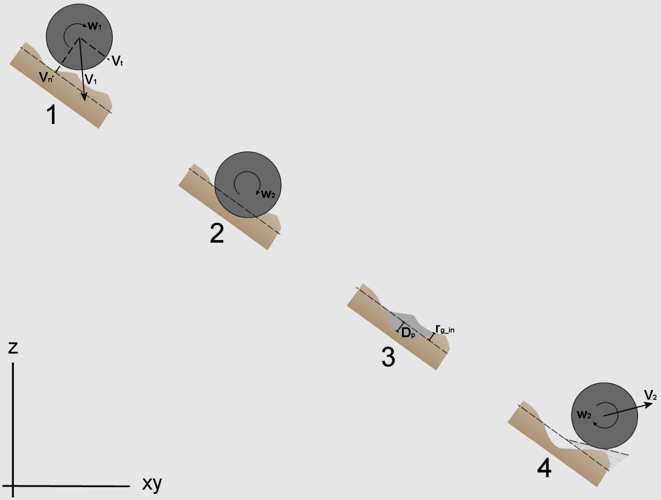
parabolic traces

$$
\begin{aligned}
\vec{v}(t+\delta t) &= \vec{v}(t) + \delta t \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix} \\
\vec{x}(t+\delta t) &= \vec{x}(t) + \delta t\, \vec{v}(t) + \frac{1}{2}\delta t^2 \begin{pmatrix} 0 \\ 0 \\ -g \end{pmatrix}
\end{aligned}
$$

valid for any t and δt

Falling

Rebound at the Surface



Source: Dorren, Rockyfor3D (v5.2) revealed, ecorisQ paper, 2016

Rebound at the Surface

Simplest approach: normal and tangential components of the velocity are reduced by different factors

$$
\begin{aligned}
v_n &\rightarrow -R_n\, v_n \\
v_t &\rightarrow R_t\, v_t
\end{aligned}
$$

where

$$
\begin{aligned}
R_n &= \text{coefficient of restitution normal to the surface,} \\
& \quad\ \text{depends on the material} \\
R_t &= \text{coefficient of restitution parallel to the surface,} \\
& \quad\ \text{mainly depends on the roughness of the surface}
\end{aligned}
$$

Falling

Coefficient of Restitution Normal to the Slope

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

Source: Dorren, Rockyfor3D (v5.2) revealed, ecorisQ paper, 2016

Coefficient of Restitution Parallel to the Slope

Difficult to estimate, e. g.,

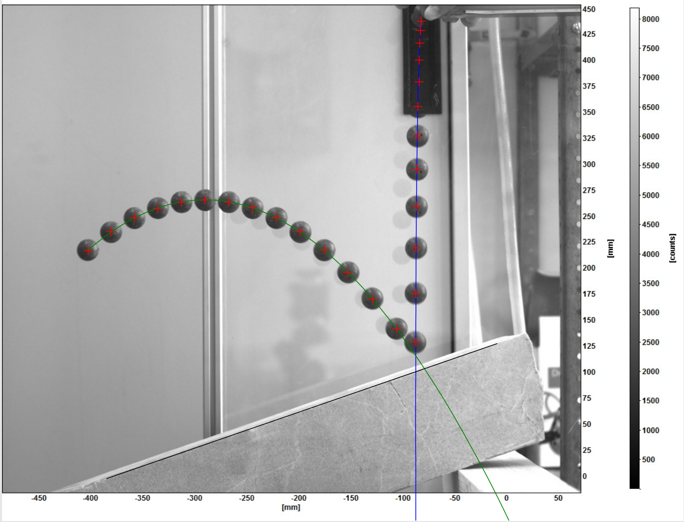
$$R_t = \frac{1}{1 + \frac{MOH + D_p}{R}}$$

with

$$\begin{aligned} MOH &= \text{representative obstacle height} \\ D_p &= \text{depth of penetration} \\ R &= \text{radius of the particle} \end{aligned}$$

Falling

Measuring Coefficients of Restitution in Laboratory



Explanation of the Quadratic Friction Law