Mass Movements Classifications and Landslides Activity

SLOPE STABILITY COURSE

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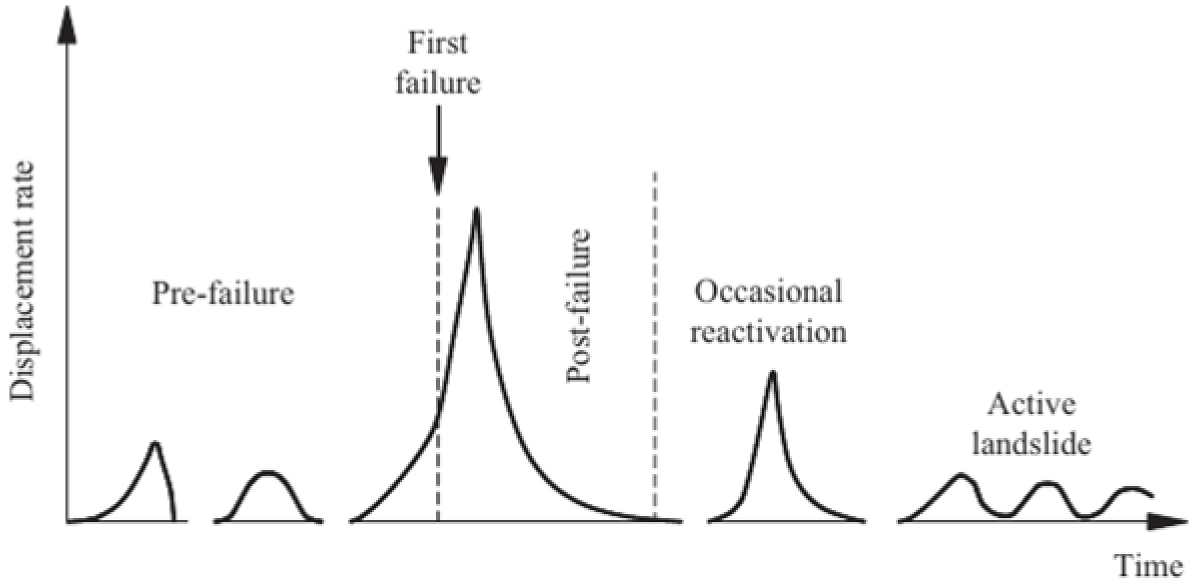
EPFL / ENAC / GC section – Master semester 2 and 4 – 2024-2025

EPFL

Stages of slope movements

- Leroueil, 1996



Stages of slope movements

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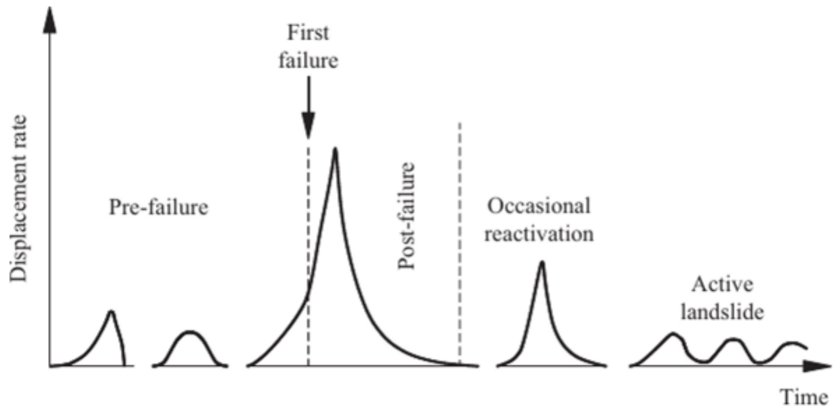


(*a*) The pre-failure stage, including all the deformation processes leading to failure. This stage is controlled mostly by deformations due to changes in stresses, creep and progressive failure.

(*b*) The onset of failure, characterised by the formation of a continuous shear surface through the entire soil mass.

(*c*) The post-failure stage, which includes movement of the soil mass involved in the landslide, from just after failure until it essentially stops. It is generally characterised by an increase of the displacement rate followed by a progressive decrease in velocity.

Classification of mass movements

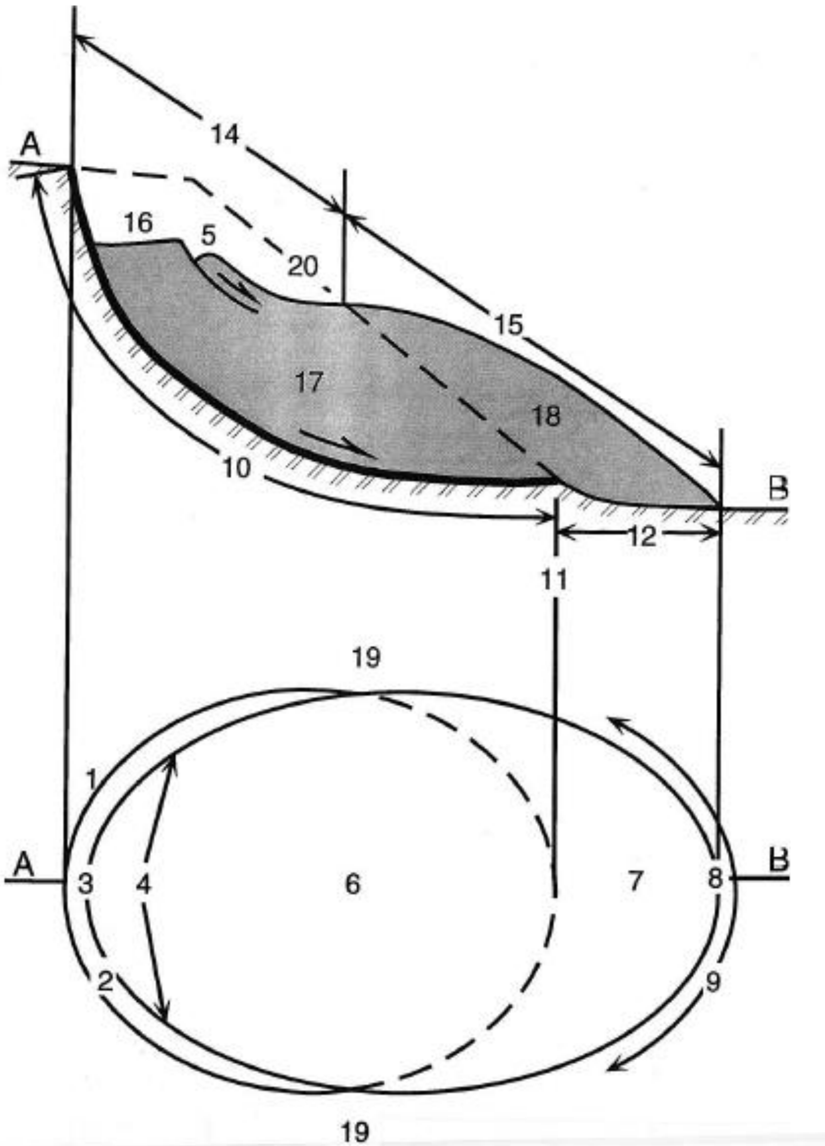
- Several landslide classifications have been proposed (e.g. Hutchinson (1967); Skempton & Hutchinson (1969); Varnes (1978)).

- We will refer to the classification proposed by "The International Geotechnical Societies' UNESCO Working Party for World Landslide Inventory WP/WLI, 1993" (*the complete document is available through the MOODLE – English and French version*).

- The work of the WP/WLI was initiated at the 5th Int. Symp. on Landslides in Lausanne (1988).

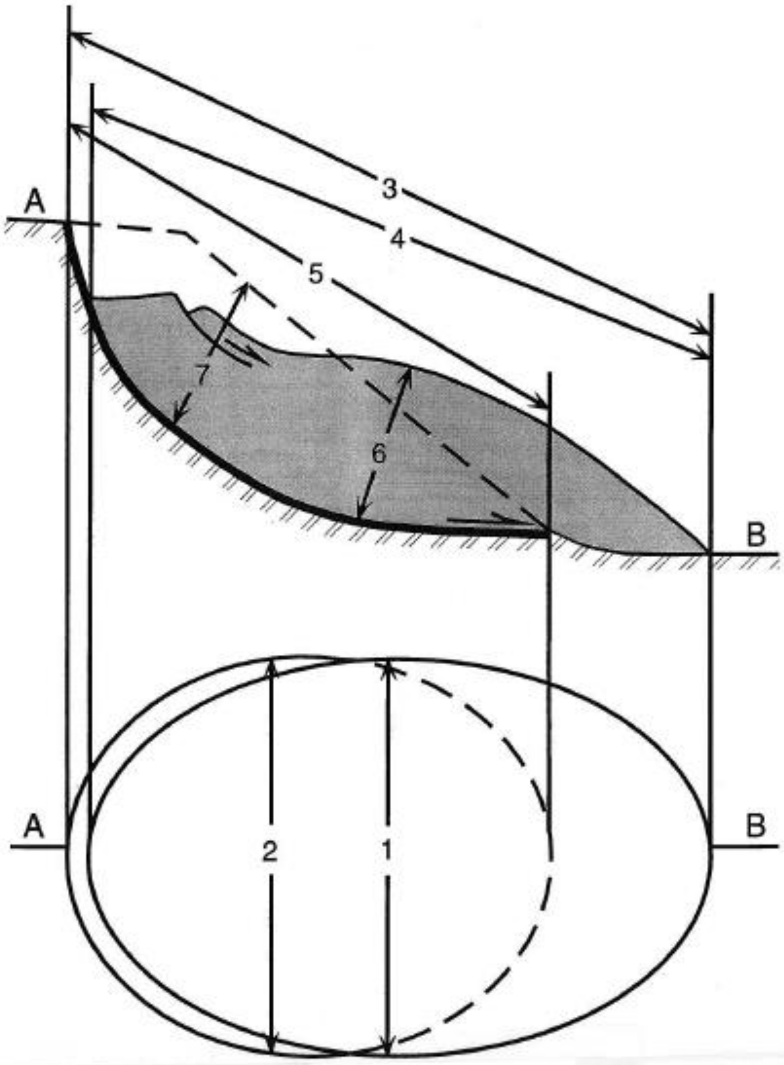
- The WP/WLI document provides a glossary for the main characteristics of the landslide (features and dimensions).

Landslide features (WP/WLI, 1993)



1)**Crown**: The practically undisplaced material still in place and adjacent to the highest parts of the main scarp (2).
2)**Main scarp**: A steep surface on the undisturbed ground at the upper edge of the landslide, caused by movement of the displaced material (13) away from the undisturbed ground. It is the visible part of the surface of rupture (10).
3)**Top**: The highest point of contact between the displaced material (13) and the main scarp (2).
4)**Head**: The upper parts of the landslide along the contact between the displaced material and the main scarp (2).
5)**Minor scarp**: A steep surface on the displaced material of the landslide produced by differential movements within the displaced material.
6)**Main body**: The part of the displaced material of the landslide that overlies the surface of rupture (10) between the main scarp (2) and the toe of the surface of rupture (11).
7)**Foot**: The portion of the landslide that has moved beyond the toe of the surface of rupture (11) and overlies the original ground surface (20).
8)**Tip**: The point on the toe (9) farthest from the top (3) of the landslide.
9)**Toe**: The lower, usually curved margin of the displaced material of a landslide, it is the most distant from the main scarp (2).
10)**Surface of rupture**: The surface which forms (or which has formed) the lower boundary of the displaced material (13) below the original ground surface (20).
11)**Toe of surface of rupture**: The intersection (usually buried) between the lower part of the surface of rupture (10) of a landslide and the original ground surface (20).
12)**Surface of separation**: The part of the original ground surface (20) overlain by the foot (7) of the landslide.
13)**Displaced material**: Material displaced from its original position on the slope by movement in the landslide. It forms both the depleted mass (17) and the accumulation (18).
14)**Zone of depletion**: The area of the landslide within which the displaced material lies below the original ground surface (20).
15)**Zone of accumulation**: The area of the landslide within which the displaced material lies above the original ground surface (20).
16)**Depletion**: The volume bounded by the main scarp (2), the depleted mass (17) and the original ground surface (20).
17)**Depleted mass**: The volume of the displaced material which overlies the rupture surface (10) but underlies the original ground surface (20).
18)**Accumulation**: The volume of the displaced material (13) which lies above the original ground surface (20).
19)**Flank**: The undisplaced material adjacent to the sides of the rupture surface. Compass directions are preferable in describing the flanks but if left and right are used, they refer to the flanks as viewed from the crown (1).
20)**Original ground surface**: The surface of the slope that existed before the landslide took place.

Landslide dimensions (WP/WLI, 1993)



1) The **width of the displaced mass, W_d**, is the maximum breadth of the displaced mass perpendicular to the length, L_d.

2) The **width of the rupture surface, W_r**, is the maximum width between the flanks of the landslide, perpendicular to the length, L_r.

3) The **total length, L**, is the minimum distance from the tip of the landslide to its crown.

4) The **length of the displaced mass, L_d**, is the minimum distance from the tip to the top.

5) The **length of the rupture surface, L_r**, is the minimum distance from the toe of the surface of rupture to the crown.

6) The **depth of the displaced mass, D_d**, is the maximum depth of the displaced mass, measured perpendicular to the plane containing W_d and L_d.

7) The **depth of the rupture surface, D_r**, is the maximum depth of the rupture surface below the original ground surface measured perpendicular to the plane containing W_r and L_r.

Classification of mass movements

- According to the WP/WLI document, a complete description of a landslide must include:
  - The type of landslide
  - The state of activity
  - The distribution of activity
  - The style of activity

Types of landslides (WP/WLI, 1993)

- The type of movement synthetizes the spatial distribution of the relative displacements of the moving landslide body with respect to the stable ground.

- The type of movement depends on the shape of the failure mechanism, the shape and extension of the landslide body, the geomechanical characteristics of the involved materials, the causes responsible of the failure.

- 5 types are listed:
  - Fall / Éboulement
  - Topple / Basculement
  - Slide / Gliseement
  - Spread / Étalement
  - Flow / Écoulement

Falls

- A fall starts with the detachment of soil or rock from a steep slope along a surface on which little or no shear displacement takes place. The material then descends mainly through the air by falling, bouncing, or rolling.

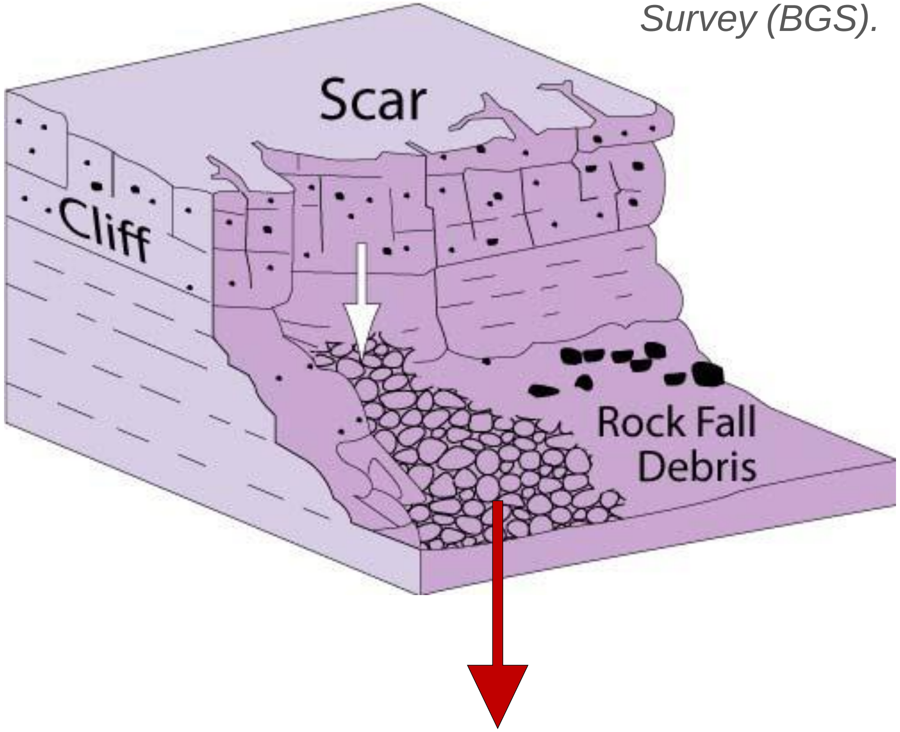
Rock fall at Pennington Point, Devon, UK. From British Geological Survey (BGS).

Falls

Inducing causes:

- Steep, sub-vertical slopes;
- Fractured rock joints;
- Freezing – warming cycles;
- Undermining at low level in the slope;
- Seismic shocks.

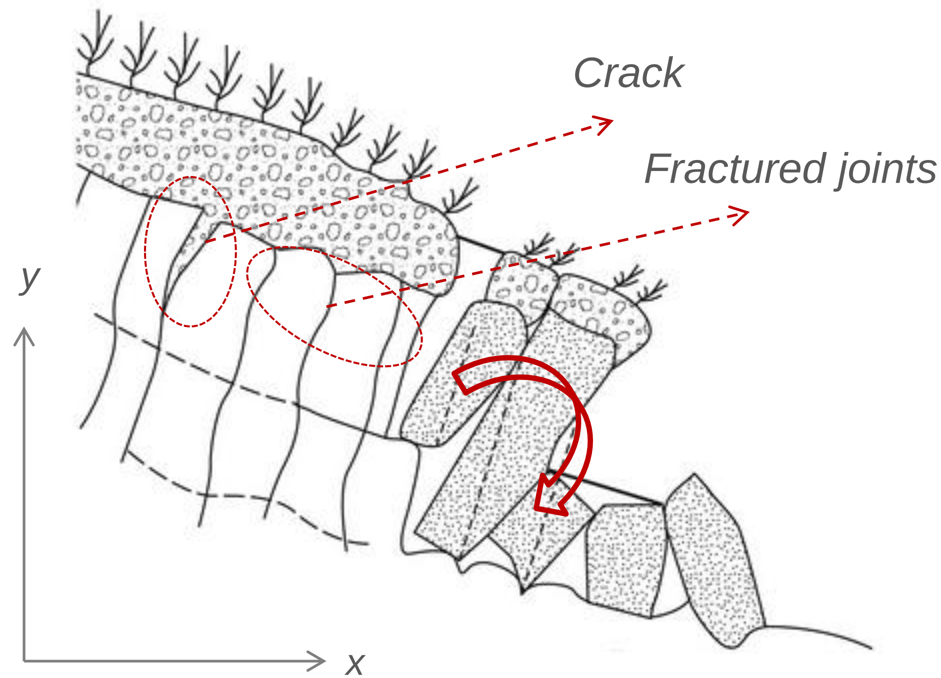
Fall scheme. Modified from British Geological Survey (BGS).



Debris cone of fractured material at the toe.

Topples

- Toppling is the forward rotation out of the slope of a mass of soil or rock about a point or axis below the centre of gravity of the displaced mass.



Scheme of a multiple toppling

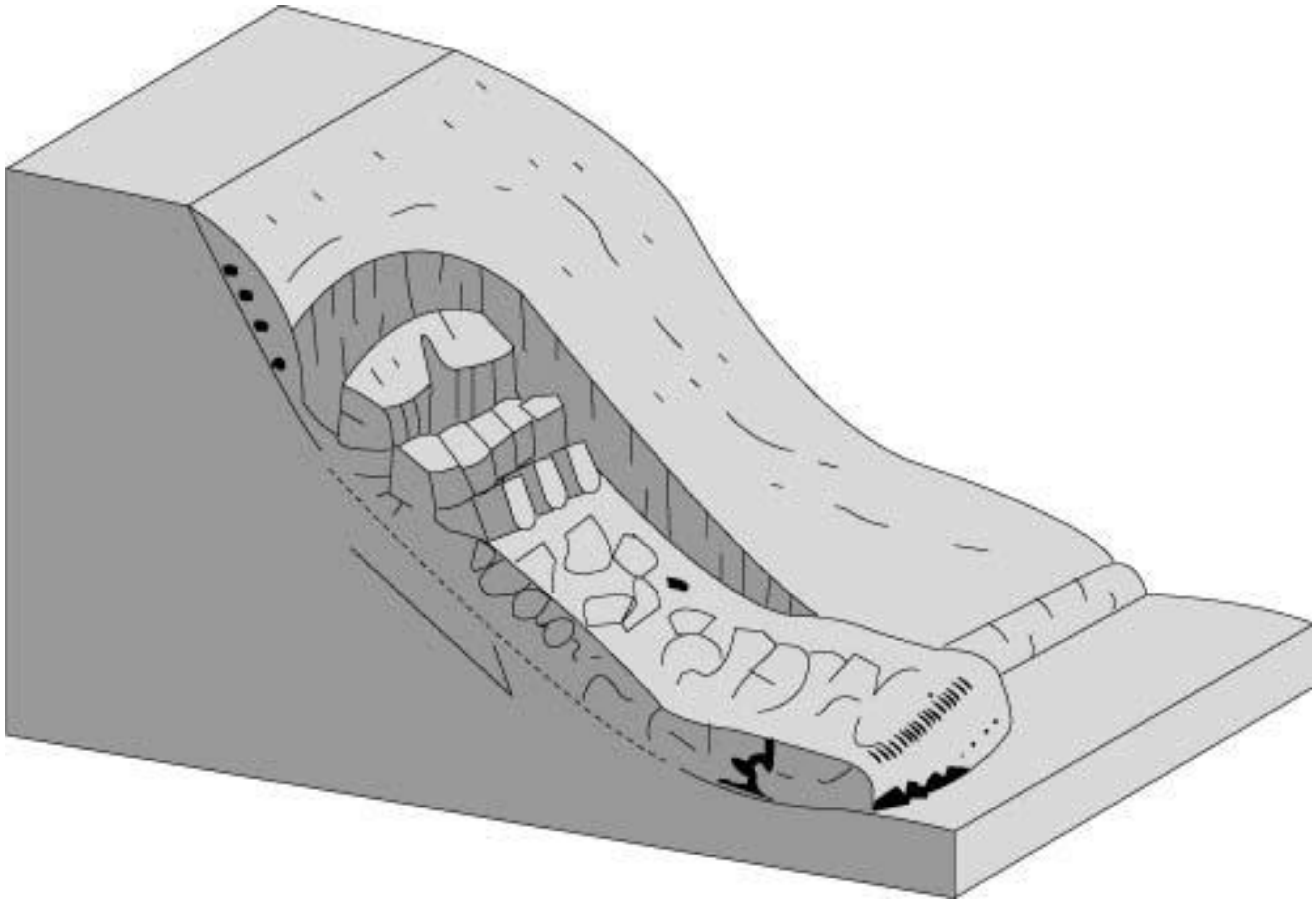
A displacement involving *fall* and *topple*

- Depending on the material involved, its quantity and trajectory, massive rock blocks moving with first topples and falls may evolve in sliding/rolling fractured debris; the topple of the biggest rock mass seems mostly 3D.

Rockfall during road construction.

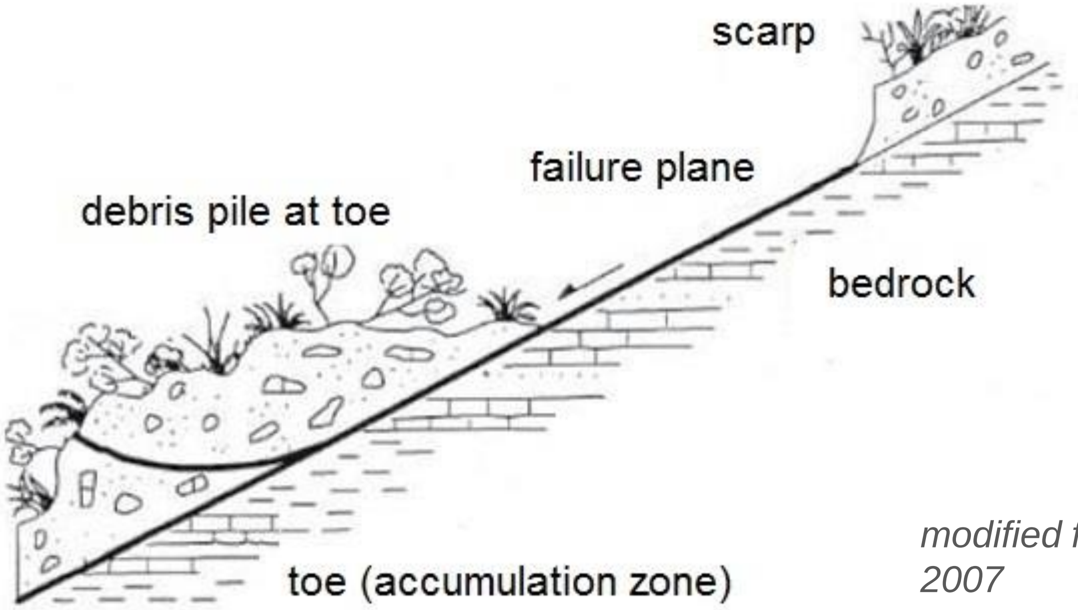
Slides

- A slide is a downslope movement of soil or rock mass occurring dominantly on the surface of rupture or on relatively thin zones of intense shear strain



Slides

- Shape of the shear surface plays a fundamental role in classifying sliding movements; apart from the material involved – intact block rock, incoherent coarse-grained debris or a fine clayey deposit - slides can be either *translational* or *rotational*.



Planar surface disposed with a unique dip angle.

modified from Potter, P.E., 2007

Slides

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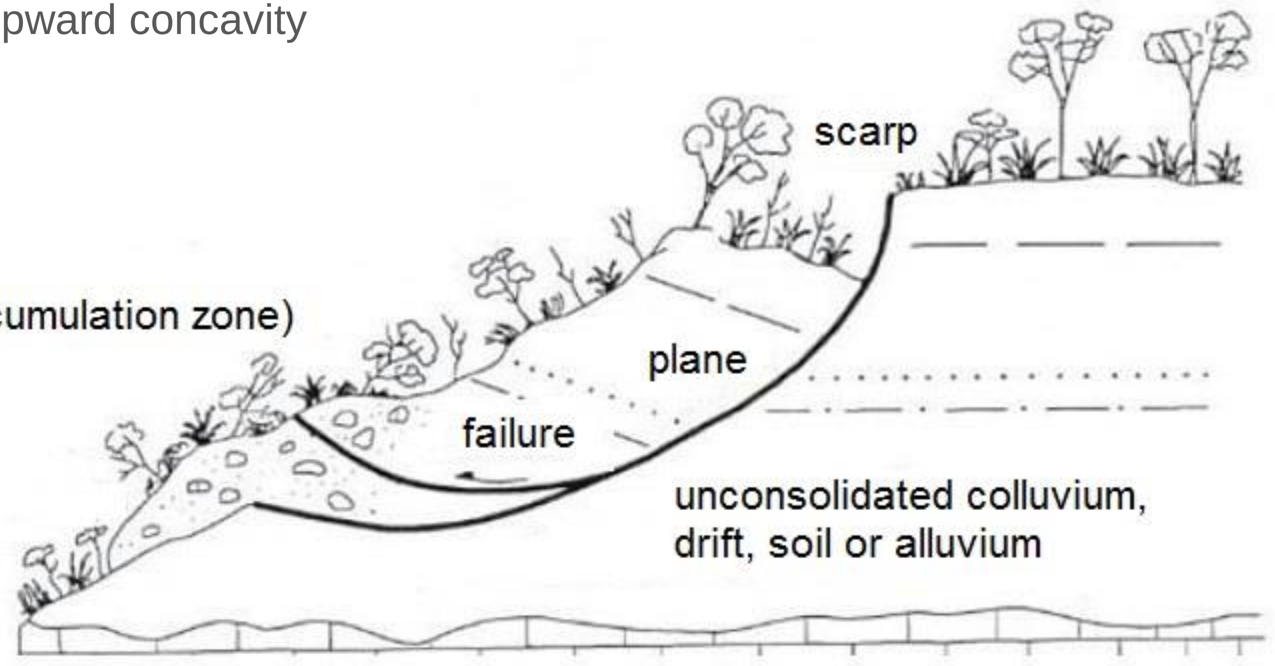
Curving surface with an upward concavity

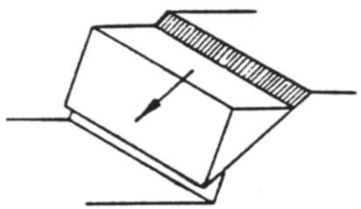


modified from Potter, P.E., 2007

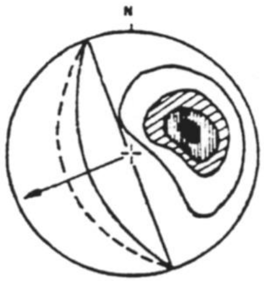
Translational slide

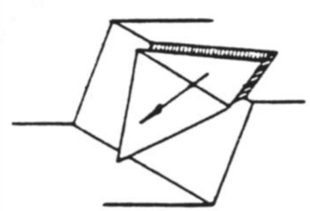
- Planar shift of the landslide mass relatively to the stable slope, along a flat shear surface constituted by :

1. faults;
2. weak joints;
3. lito- and stratigraphic discontinuities;
4. cracks.

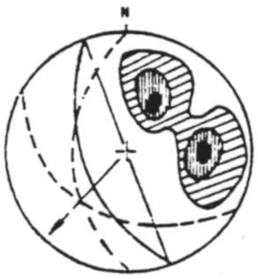


(a)





(b)



(a) → planar failure

(b) → wedge failures

Stereographic diagrams associated to possible translational sliding mechanisms (Hoek & Bray, 1981).

Translational slide

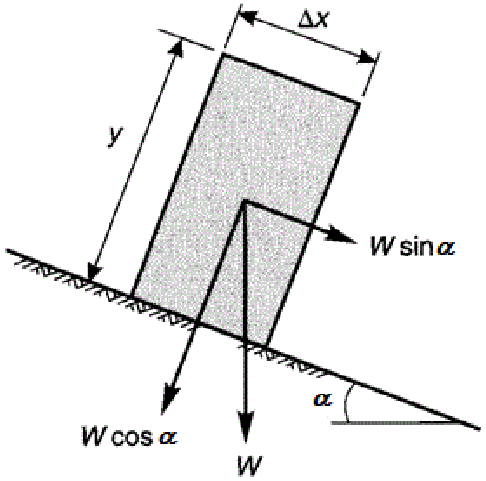
- The rigid displacement of the sliding mass is predominant compared to the internal deformation of the material, in particular for *rock slides.*

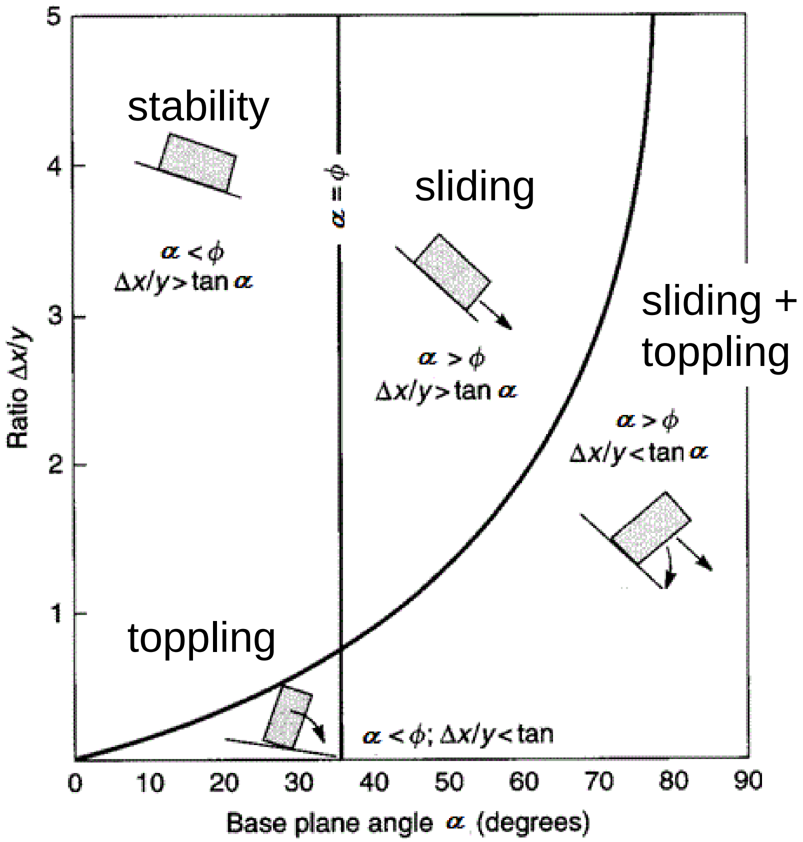
(a)

(b)

Translational slide - or topple?

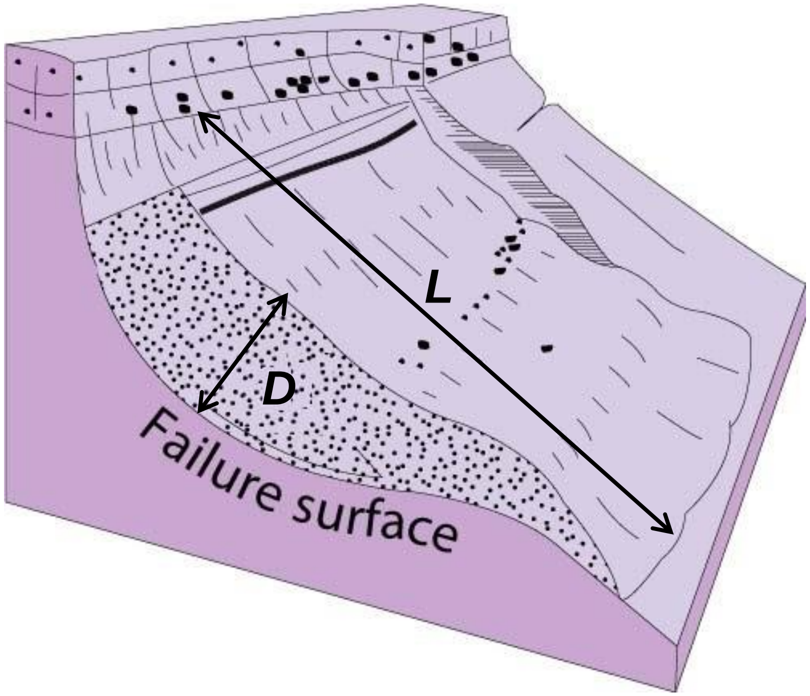
- Geometry has a fundamental role in the stability of a potential collapsing system; moreover, for a mass with limited longitudinal extension (e.g., rock block), slope inclination entity and dimensions determine a substantial difference concerning the kinematic mechanism:





Rotational slide

- The moving mass is usually constituted by relatively homogeneous soils; it can be either fine or coarse grained.



- Internal deformations have limited entity compared to the overall mass displacements; a coarse grained deposit may result more disturbed than a silty-clayey.

- It is a relatively deep mass movement, with *D/L* ratios between 0.15 and 0.33 (Skempton & Hutchinson, 1969).

Rotational slide scheme. Modified from British Geological Survey (BGS).

Rotational slide

- Geometry of the system can be simplified as planar if the transversal direction involves a long frontage: shear surface lays on a cylinder with the axes perpendicular to the motion direction.

Extended rotational slide at “London clay” interface, UK.

Rotational slide

- A “spoon-shaped” shear failure is otherwise defined for rotational slides with a limited width; anyway, the mechanism keeps bi-dimensional characteristics.

“Spoon-shaped” rotational slide adjacent to a stream river at Sheoaks, Australia. Multiple scarps can be noticed.

Erosion and Landslide Resources in the CCMA Region. AS Miner Geotechnical, 2007.

Compound slide

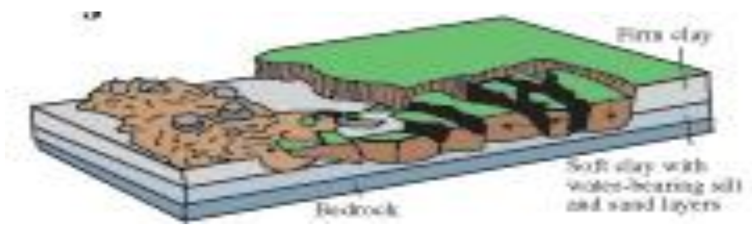
- Occurrence of landslide entirely translational or rotational may be anyway a rare event.
- Dislocating masses with a clearly non-circular shear surface, partially curving and partially flat, are defined as compound.
- It is an intermediary kind of dislocation among translational and rotational also in terms of *D/L* ratio.
- Because of the dual movement occurring, the material is subjected to more internal relative displacements: thus, the magnitude of disturbance within the landmass is relatively high compared to the initial conditions (landslide divided in block by shear sub-surfaces).

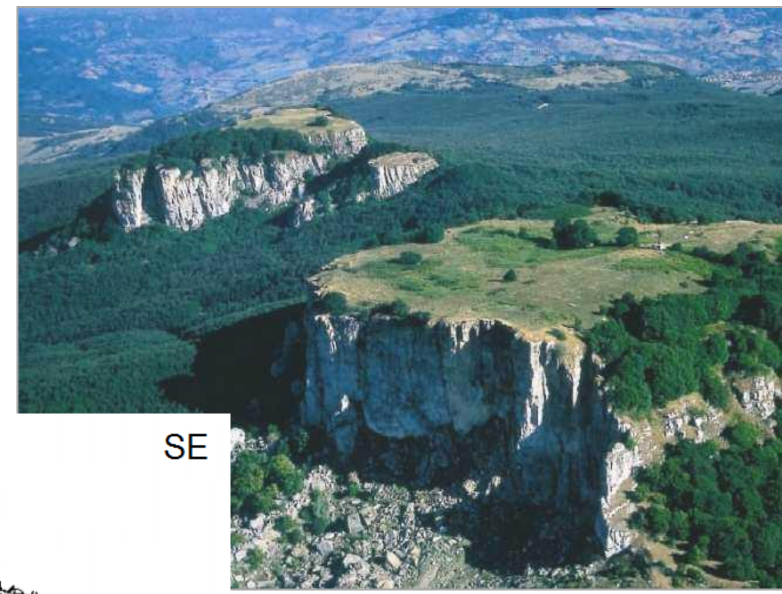
Compound slide

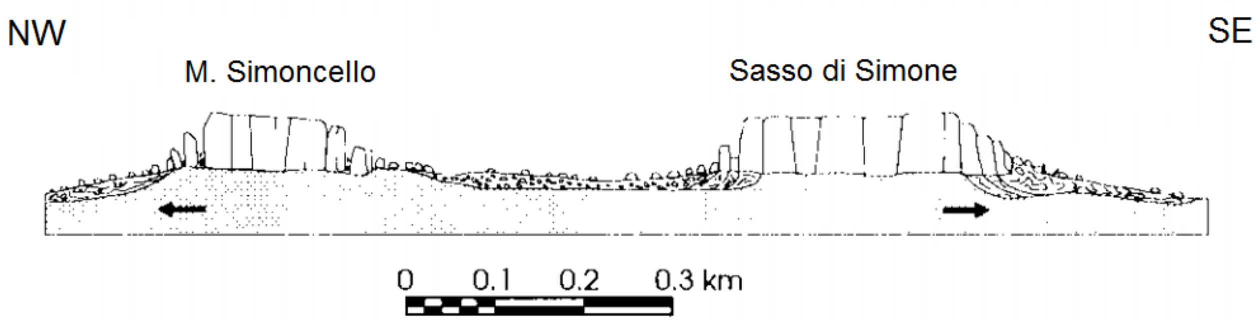
Cliff collapsed during drainage works to divert a floodwater at Sindangjaya Village in West Java.

Spreads

- A spread is an extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer underlying material. The rupture surface is not a surface of intense shear. Spreads may result from liquefaction or flow (and extrusion) of the softer material.







Schematic cross section for Monte Simoncello and Sasso di Simone formations, Italy. (modified after Casagli,1994).

Spreads

- Displacing land masses can be made of rock or soil, involving a great variety of geological deposit, with significant dimension: up to some kilometers from the tilted front to the discontinuities where dislocation takes place

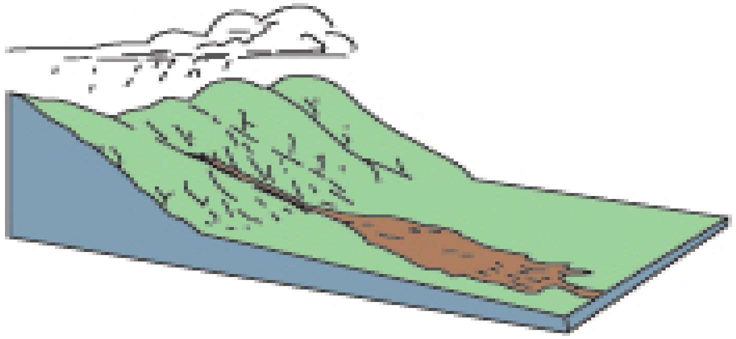
Lateral spread in **rocks**: slow or very slow displacements – almost constant rates, poorly affected by seasonal variations.

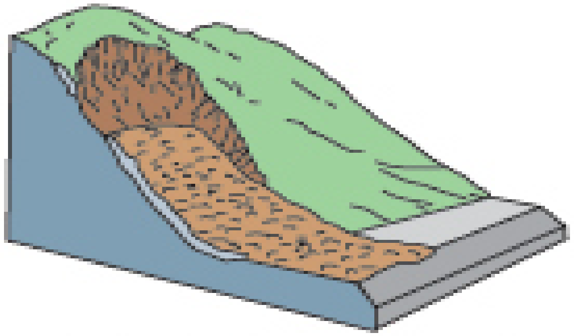
Lateral spread in **soils**: relatively quick displacements, which can be influenced by short term effects as climatic changes.

Flows

- A **flow** is a spatially continuous movement in which surfaces of shear are short-lived, closely spaced, and usually not preserved. The distribution of velocities in the displacing mass resembles that of a viscous liquid.

- Despite the fact that flows are commonly characterized by more or less elongated shapes similar to torrents, they cluster different typologies, and it's not easy to classify due to the amount of factors coming into play such as involved materials, water content, velocity and triggering and propagation mechanisms.





Flows

Classification of flows (Hungr et al. 2001)

Material	Water Content[1]	Special Condition	Velocity	Name
Silt, Sand, Gravel, Debris (talus)	dry, moist or saturated	- no excess pore-pressure, - limited volume	various	Non-liquefied sand (silt, gravel, debris) flow
Silt, Sand, Debris, Weak rock[2]	saturated at rupture surface content	- liquefiable material[3], - constant water	Ex. Rapid	Sand (silt, debris, rock) flow slide
Sensitive clay	at or above liquid limit	- liquefaction *in situ*,[3] - constant water content[4]	Ex. Rapid	Clay flow slide
Peat	saturated	- excess pore-pressure	Slow to very rapid	Peat flow
Clay or Earth	near plastic limit	- slow movements, - plug flow (sliding)	< Rapid	Earth flow
Debris	saturated	- established channel[5], - increased water content[4]	Ex. Rapid	Debris flow
Mud	at or above liquid limit	-fine-grained debris flow	> Very rapid	Mud flow
Debris	free water present	- flood[6]	Ex. Rapid	Debris flood
Debris	partly or fully saturated	- no established channel[5], - relatively shallow, steep source	Ex. Rapid	Debris avalanche
Fragmented Rock	various, mainly dry	- intact rock at source, - large volume[7]	Ex. Rapid	Rock avalanche

1 Water content of material in the vicinity of the rupture surface at the time of failure.
2 Highly porous, weak rock (examples: weak chalk, weathered tuff, pumice).
3 The presence of full or partial *in situ* liquefaction of the source material of the flow slide may be observed or implied.
4 Relative to *in situ* source material.
5 Presence or absence of a defined channel over a large part of the path, and an established deposition landform (fan). Debris flow is a recurrent phenomenon within its path, while debris avalanche is not.
6 Peak discharge of the same order as that of a major flood or an accidental flood. Significant tractive forces of free flowing water. Presence of floating debris.
7 Volume greater than 10,000 m^3 approximately. Mass flow, contrasting with fragmental rock fall.

Landslide velocity scale (Cruden and Varnes, 1996)

Velocity class	Description	Velocity (m/sec)	Typical velocity
7	Extremely Rapid	5	5 m/sec
6	Very Rapid	0.05	3 m/min
5	Rapid	$5x10^{-4}$	1.8 m/hr
4	Moderate	$5x10^{-6}$	13 m/month
3	Slow	$5x10^{-8}$	1.6 m/year
2	Very Slow	$5x10^{-10}$	16 mm/year
1	Extremely Slow		

Flows

- From an engineering point of view it’s important to focus on the mechanisms of generation and propagation taking into account the fluidizing effect of water which represents an important part of the process.

- Different types of triggering mechanisms allow us to distinghish between:
  - **Mud flows**
  - **Debris flows**
  - **Debris avalanche**

Mudflows

Mudflow from the Lower Jurassic shales, Black Ven Cliffs, Dorset.

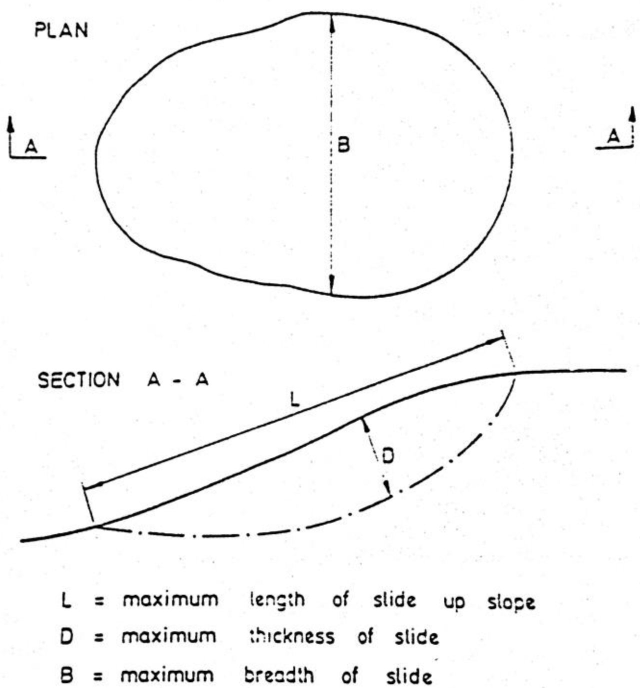
Mudflows

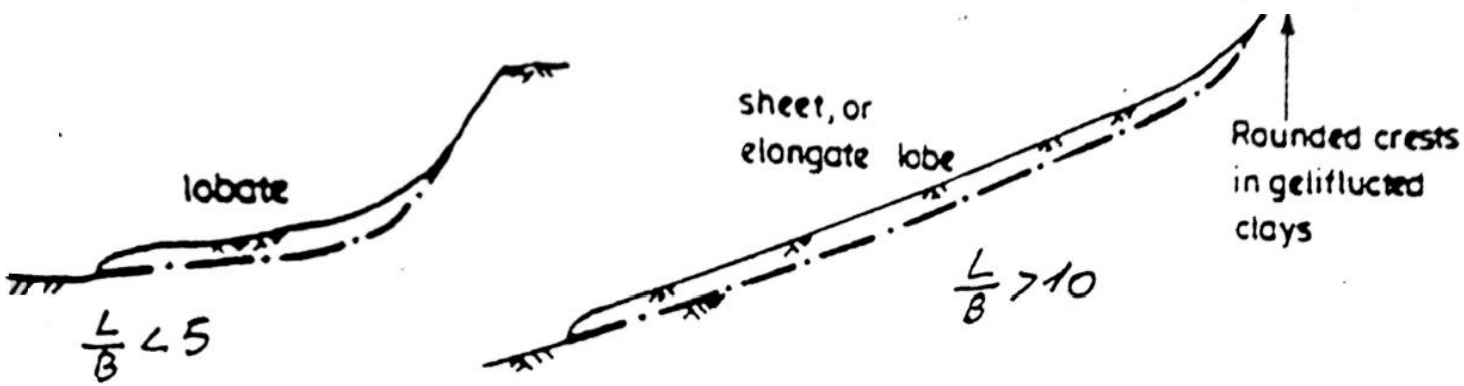
Geometry

- Mudflows have surface inclinations varying generally between about 5 and 15 degrees

- Mudflows can present two different type of shapes:
  - Elongated shapes
  - Lobate shapes

The first are developed mainly in length with the ratio L/B >10. The others are characterized by
a more squat form with a ratio L/B less then 5.





Mudflows

Involved materials

- Mudflows are characterized by soils having a clay-sized fraction more than 50% of the total mass weight.

- Rates of mudflow movement vary widely and can be highly seasonal. Mudflows commonly develop when a mass of clayey debris becomes softened by water and they consist of the ill-sorted remnants of this debris in a soft clayey matrix.

- It is possible to distinguish two main mechanisms of accumulation in the source zone:

  – In soils characterized by stiff fractured clay, the accumulation is due to previous slides or intense erosion phenomena.

  – In clayey soils with intrabedded sand layers, the water, flowing trought the sand, makes the clay softer. Consequently, clay is removed, forming clods and fragments.

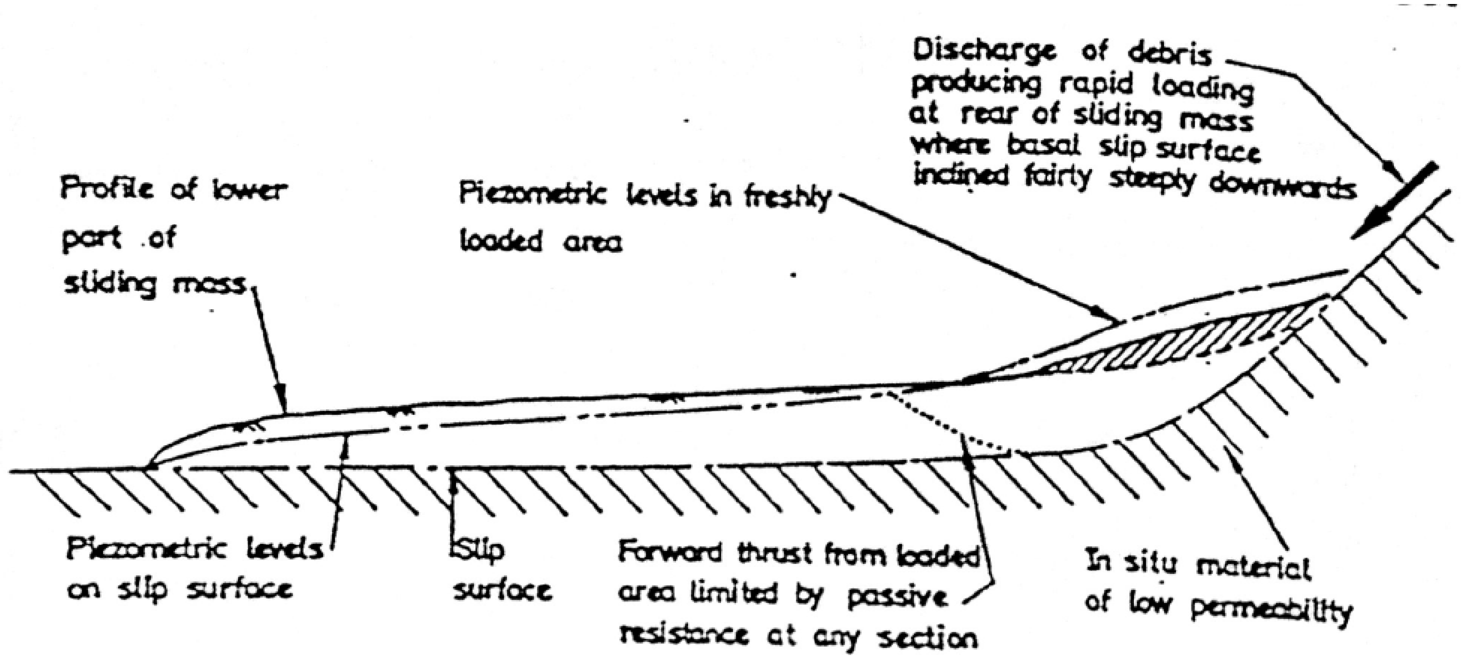
Skempton & Hutchinson (1969)

Mudflows

Triggering mechanism

- The material in the source zone, characterized by residual strength, starts to flow down due to discharge of debris which produces an undrained load.

Undrained Loading, a fundamental mechanism of mudflows.

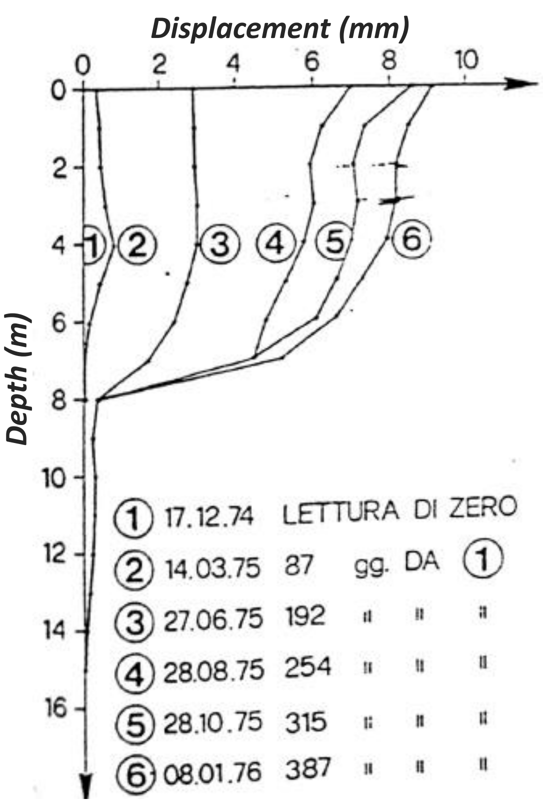


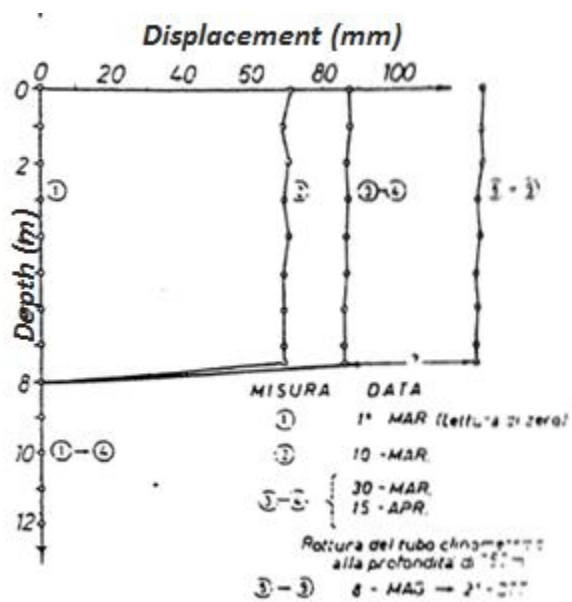
Mudflows

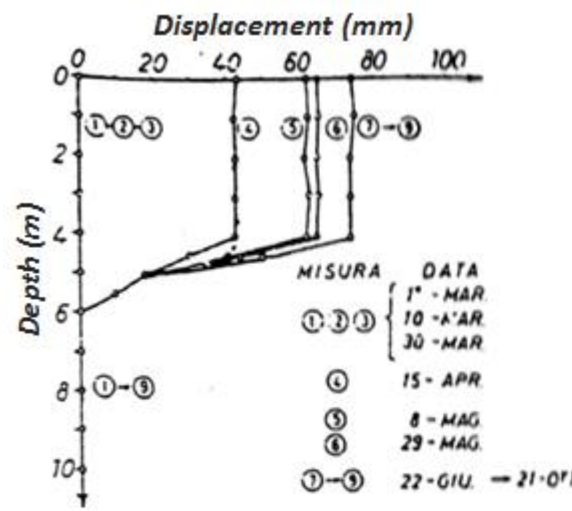
Kinematic features

- Mudflows flow down with avarage velocity ranging from 5 to 25 m/y

- Mudflows flow down mainly sliding on their boundary surfaces but very often creep displacements inside the mass of soil are relevant.







Mudflows

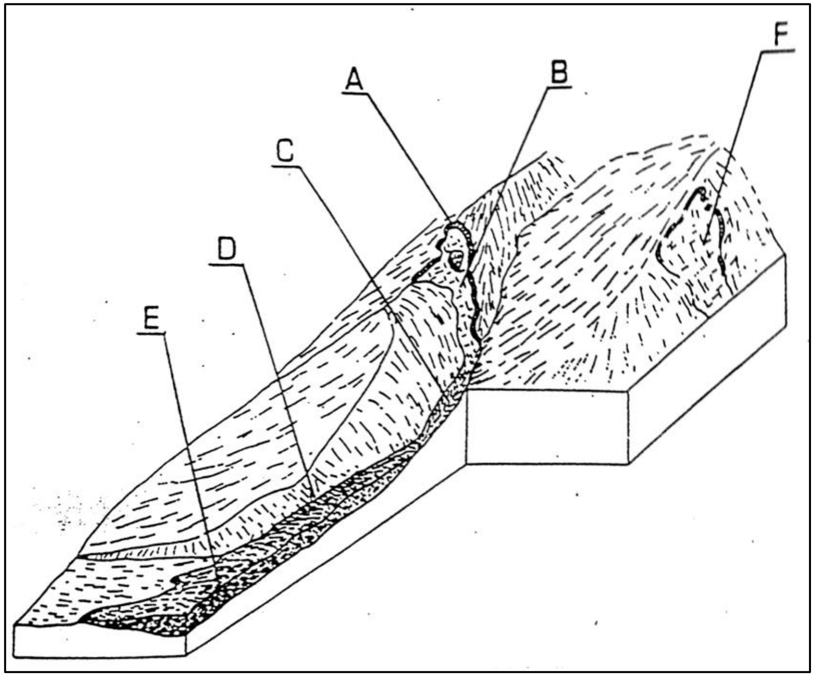
Redwoods torn down by mudslide in Northern California.

Debris flows

A debris flow is a form of rapid mass movement in which a combination of loose soil, rock, organic matter, air, and water mobilize as a slurry that flows downslope.

Geometry

Scars formed by debris flow outside Los Angeles during the winter of 1968-1969.



Morphological features of debris flow: A, scarp; B and F, surface of rupture; C, channel of erosion; D, levee; E, deposit.

Debris flows

Involved materials

- Debris flows include <50% fines (clay up to 5%), very coarse-grained sediments, and fragmented blocks, and rocks are involved too.

Debris flow and flood disaster in Lötschental (Switzerland), 2011.

Debris flows

Triggerig mechanism

- Debris flows are commonly caused by intense surface-water flow, due to heavy precipitation or rapid snowmelt, that erodes and mobilizes loose soil or rock on steep slopes.

- The triggering mechanism is identified in the sudden or very rapid saturation of material. The movement starts due to the collapse of the soil structures and the generation of high water pressure. The movement proceeds because of two possible hypotheses:

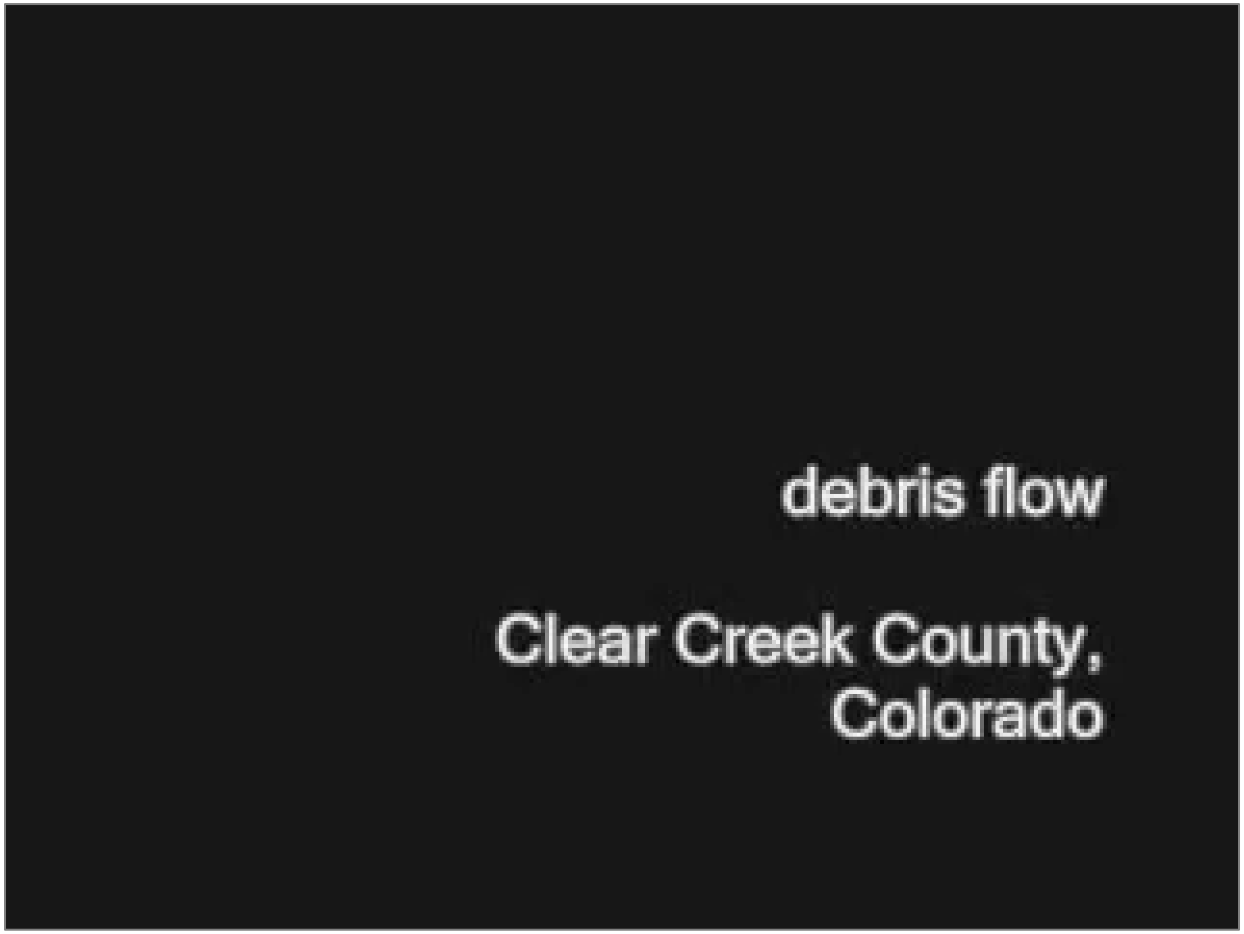
  – The front part of the flow is loaded in undrained conditions by the back part which starts moving.

  – The high values of overpressure are due to the ongoing mixing of blocks during the flowing downslope.

Kinematic features

- Debris flows show avarage velocities ranging from 30 to 50 km/h.

Debris flow



Debris flow with very coarse-grained material and block rocks, Colorado.

Debris avalanche

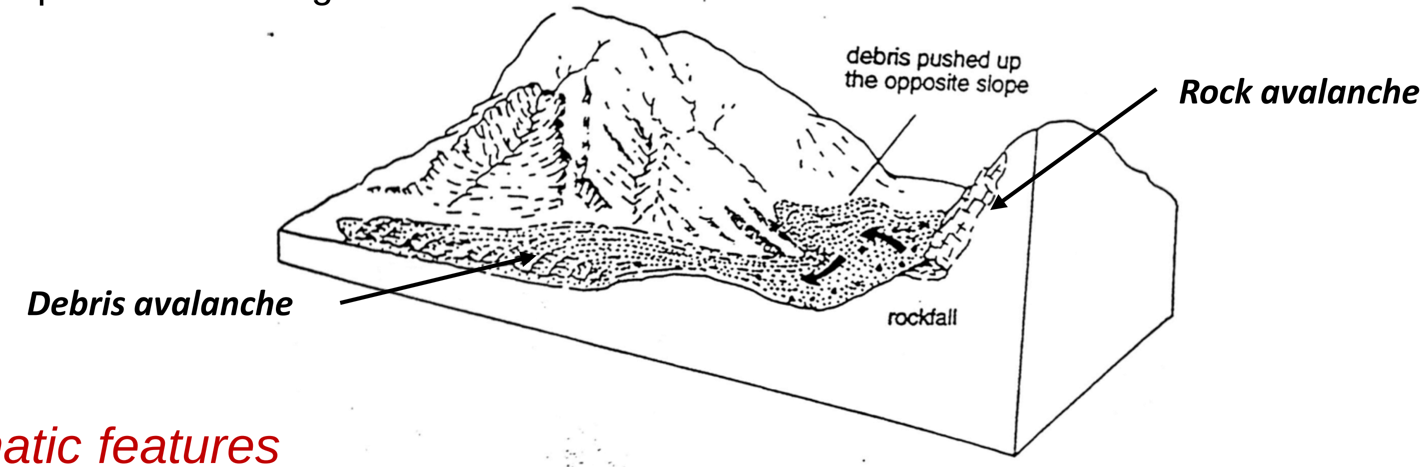
- Debris avalanches are particular types of debris flows which differ in mechanism of generation and flow velocity.

Involved materials

- Debris avalanches include very coarse-grained sediments, fragmented blocks and rocks

Triggering mechanism

- The flows arise from violent impacts of a large volume of rocks (million of m^3), that were involved in a previous collapse or slide, with the soil surface. This mechanism does not depend on the presence of water porosity but is associated with a turbulent movement of the grains which remain in suspension colliding.



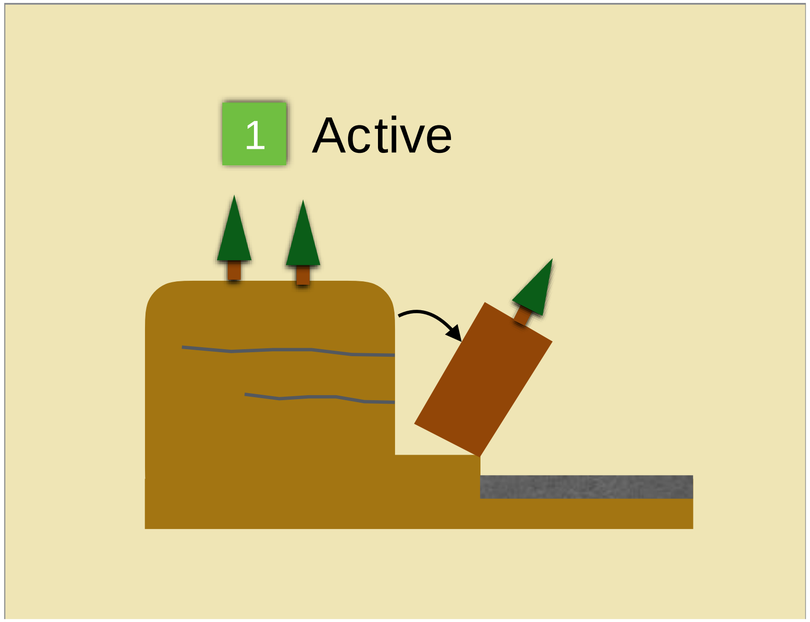
Kinematic features

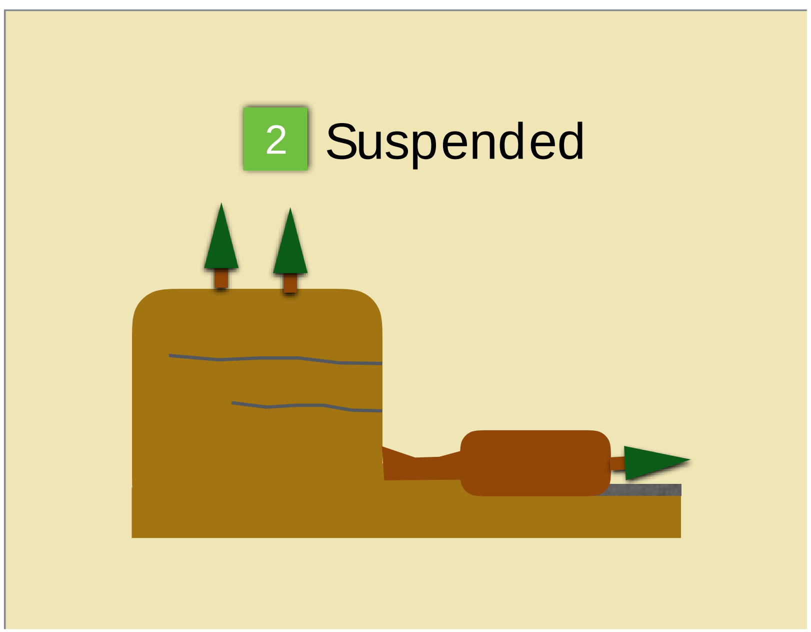
- Debris avalanches show avarage velocities ranging from 100 to 180 km/h

Rock avalanche

Two rock avalanches with a total volume of 30 million m³. Andreas Götz PLANAT 1991.

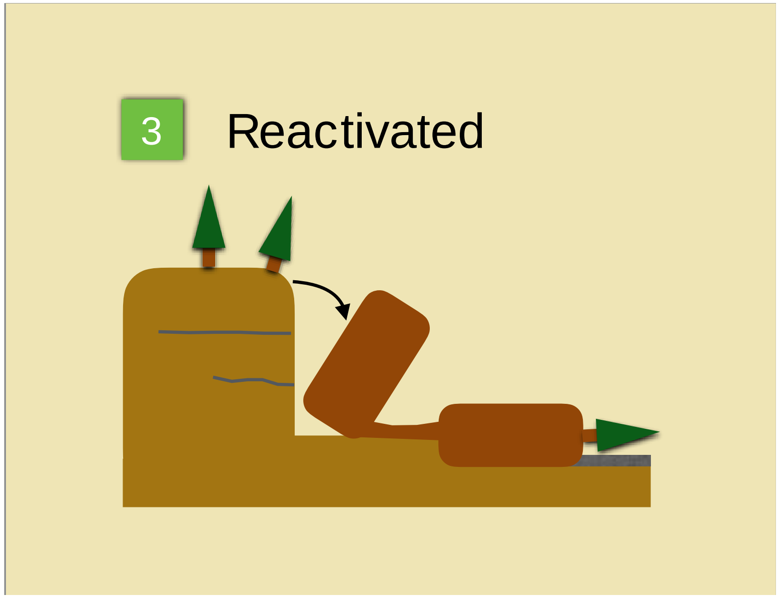
State of activities (WP/WLI, 1993)

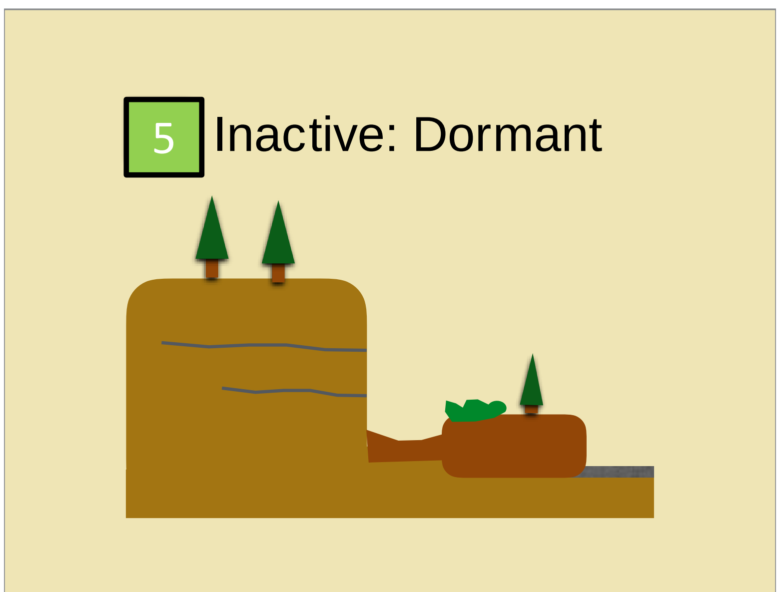




1. **Active**: An active landslide is currently moving.
2. **Suspended**: A suspended landslide has moved within the last 12 months, but is not active at present.

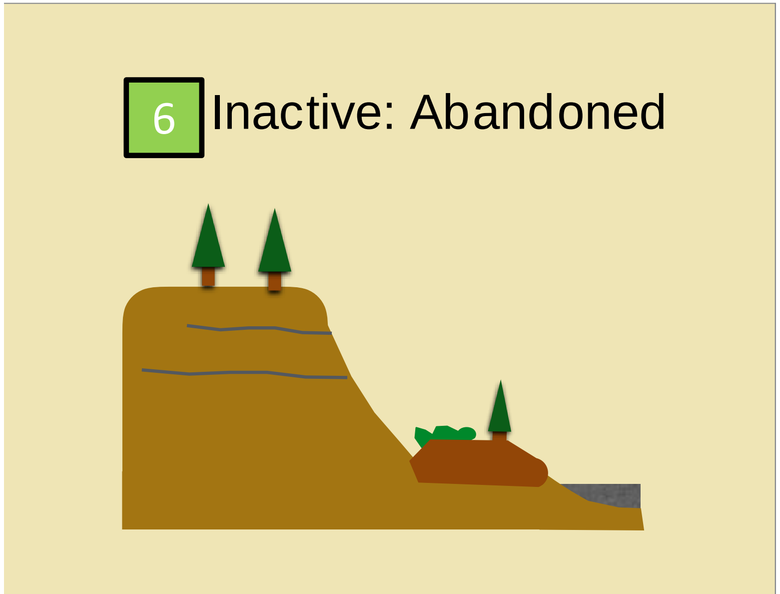
State of activities (WP/WLI, 1993)

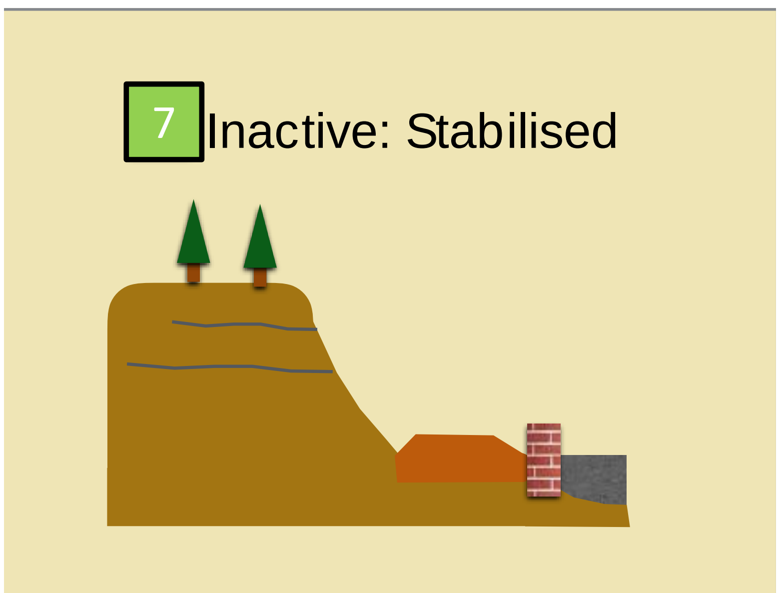




1. **Active**: An active landslide is currently moving.
2. **Suspended**: A suspended landslide has moved within the last 12 months, but is not active at present.
3. **Reactivated**: A reactivated landslide is an active landslide which has been inactive.
4. **Inactive**: An inactive landslide has not moved within the last 12 months and can be divided into 4 states: Dormant, Abandoned, Stabilised and Relict.
5. **Dormant**: A dormant landslide is an inactive landslide which can be reactivated by its original causes or other causes. In the example shown the displaced mass begins to regain its tree cover and scarps are modified by weathering.

State of activities (WP/WLI, 1993)





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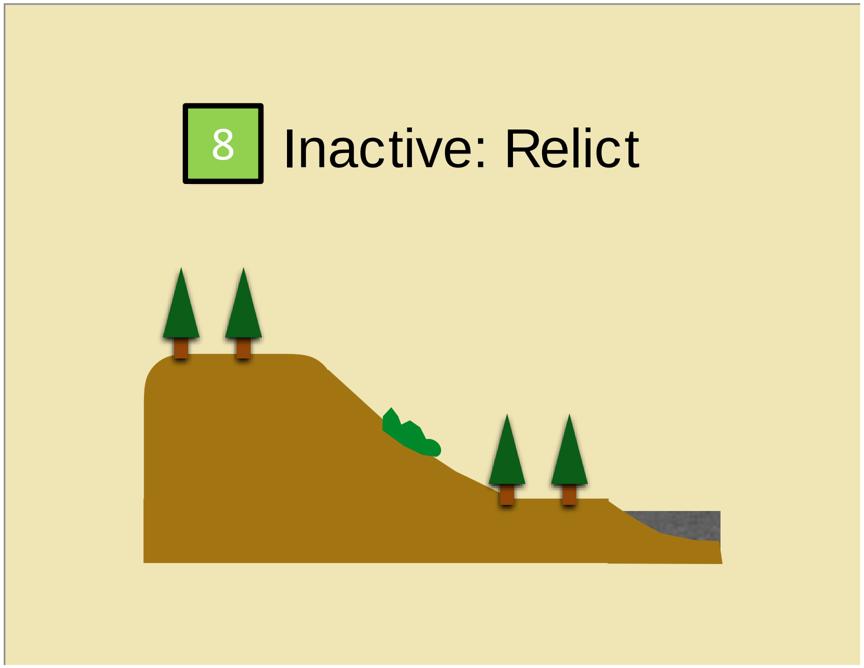
5. **Dormant**: A dormant landslide is an inactive landslide which can be reactivated by its original causes or other causes. In the example shown the displaced mass begins to regain its tree cover and scarps are modified by weathering.
6. **Abandoned**: An abandoned landslide is an inactive landslide which is no longer affected by its original causes.
7. **Stabilised**: A stabilised landslide is an inactive landslide which has been protected from its original causes by remedial measures.

State of activities (WP/WLI, 1993)



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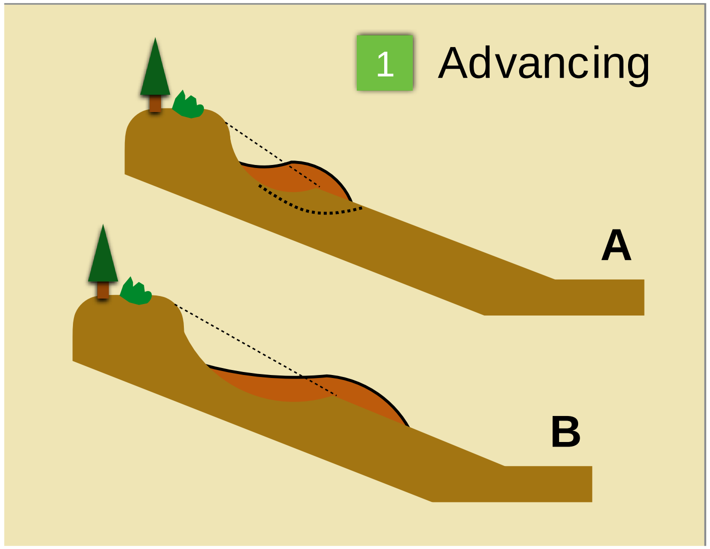
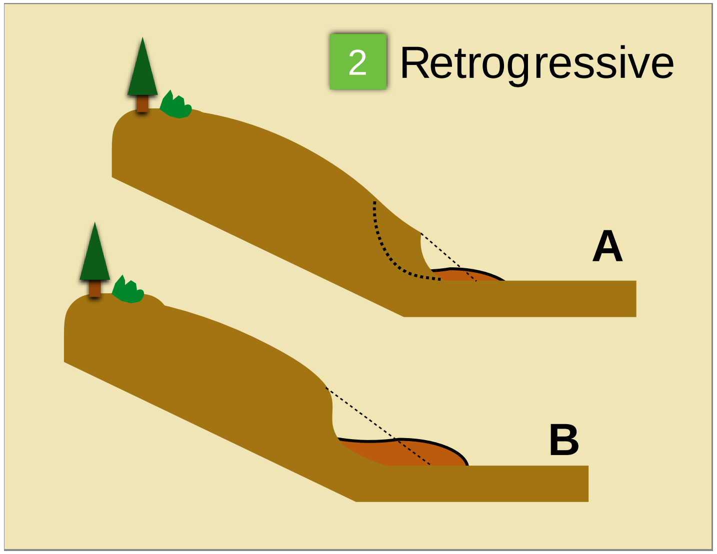
6. **Abandoned**: An abandoned landslide is an inactive landslide which is no longer affected by its original causes.
7. **Stabilised**: A stabilised landslide is an inactive landslide which has been protected from its original causes by remedial measures.
8. **Relict**: A relict landslide is an inactive landslide which developed under climatic or geomorphological conditions considerably different from those at present

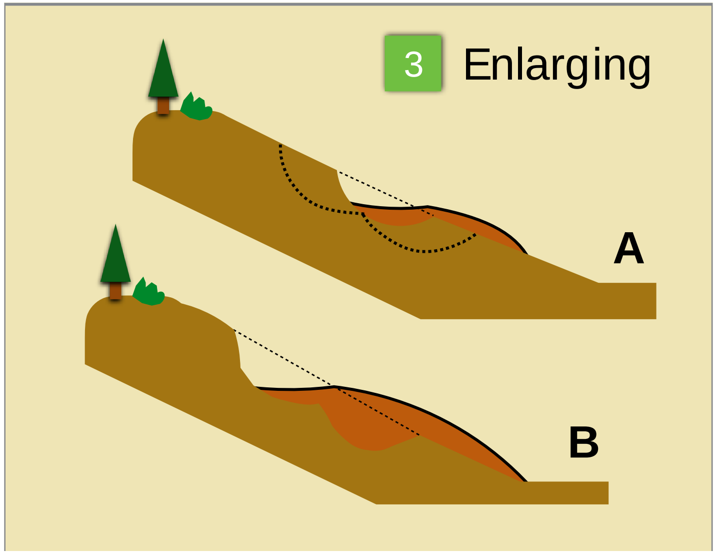
Distribution of activities (WP/WLI, 1993)

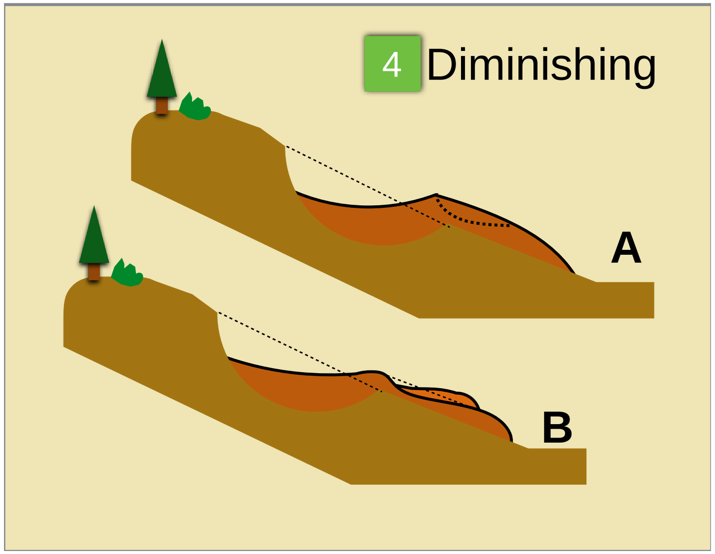




1. **Advancing**: In an advancing landslide the rupture surface is extending in the direction of movement.
2. **Retrogressive**: In a retrogressive landslide the rupture surface is extending in the direction opposite to the movement of the displaced material.

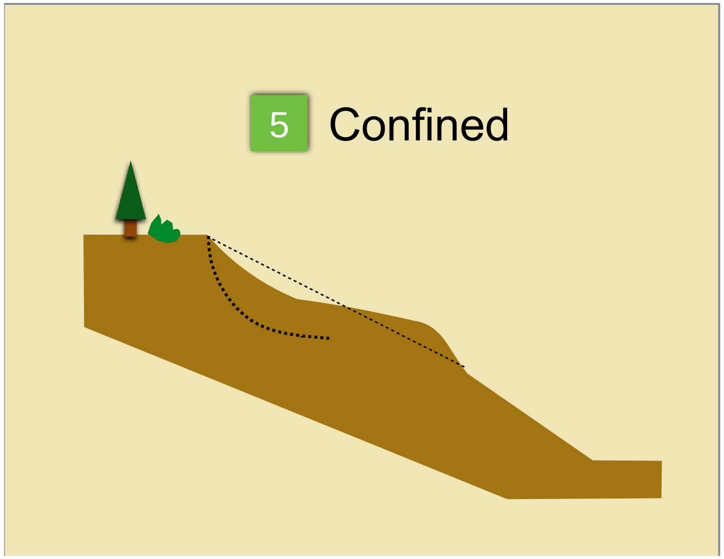
Distribution of activities (WP/WLI, 1993)

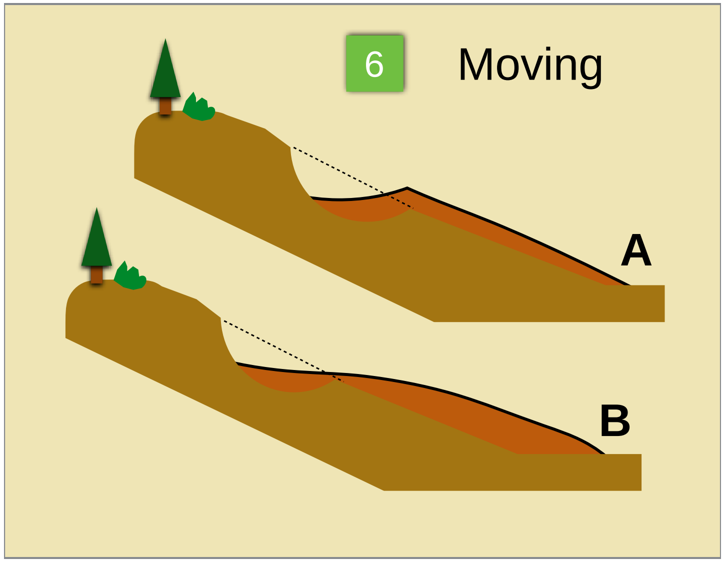




1. **Advancing**: In an advancing landslide the rupture surface is extending in the direction of movement.
2. **Retrogressive**: In a retrogressive landslide the rupture surface is extending in the direction opposite to the movement of the displaced material.
3. **Enlarging**: in an enlarging landslide the rupture surface of the landslide is extending in two or more directions.
4. **Diminishing**: In a diminishing landslide the volume of displaced material is decreasing.

Distribution of activities (WP/WLI, 1993)





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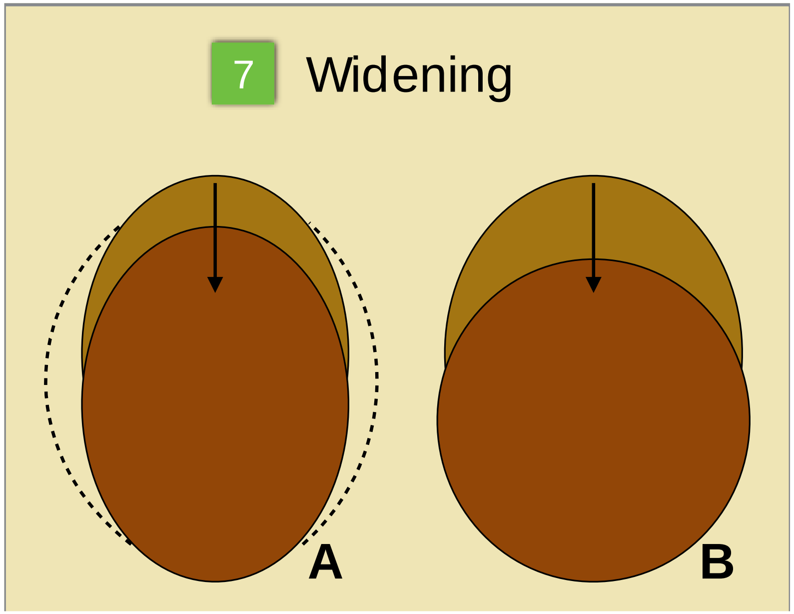
2. **Retrogressive**: In a retrogressive landslide the rupture surface is extending in the direction opposite to the movement of the displaced material.
3. **Enlarging**: in an enlarging landslide the rupture surface of the landslide is extending in two or more directions.
4. **Diminishing**: In a diminishing landslide the volume of displaced material is decreasing.
5. **Confined**: In a confined landslide there is a scarp but no rupture surface visible at the foot of the displaced mass.
6. **Moving**: In a moving landslide the displaced material continues to move without any visible change in the rupture surface and the volume of the displaced material.

Distribution of activities (WP/WLI, 1993)



1. **Advancing**: In an advancing landslide the rupture surface is extending in the direction of movement.
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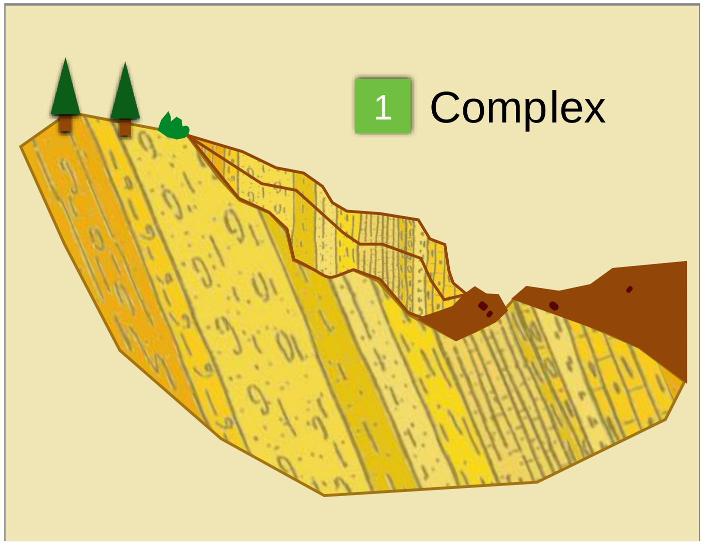
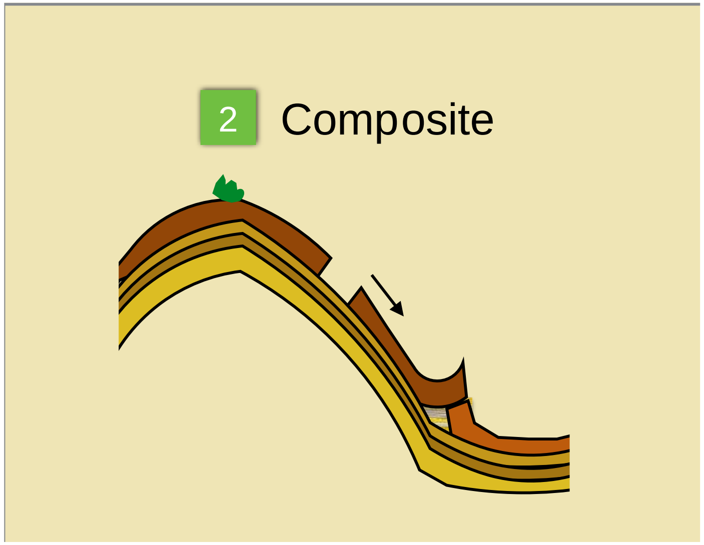
4. **Diminishing**: In a diminishing landslide the volume of displaced material is decreasing.
5. **Confined**: In a confined landslide there is a scarp but no rupture surface visible at the foot of the displaced mass.
6. **Moving**: In a moving landslide the displaced material continues to move without any visible change in the rupture surface and the volume of the displaced material.
7. **Widening**: In a widening landslide the rupture surface is extending into one or both flanks of the landslide.

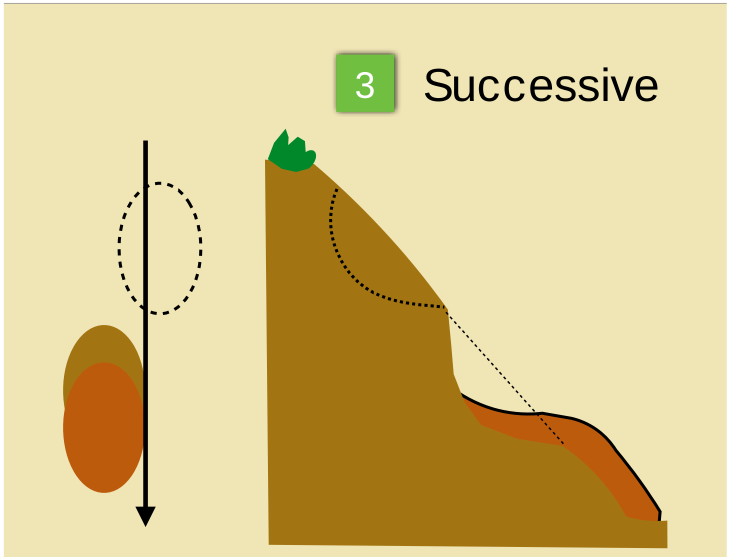
Style of activities (WP/WLI, 1993)

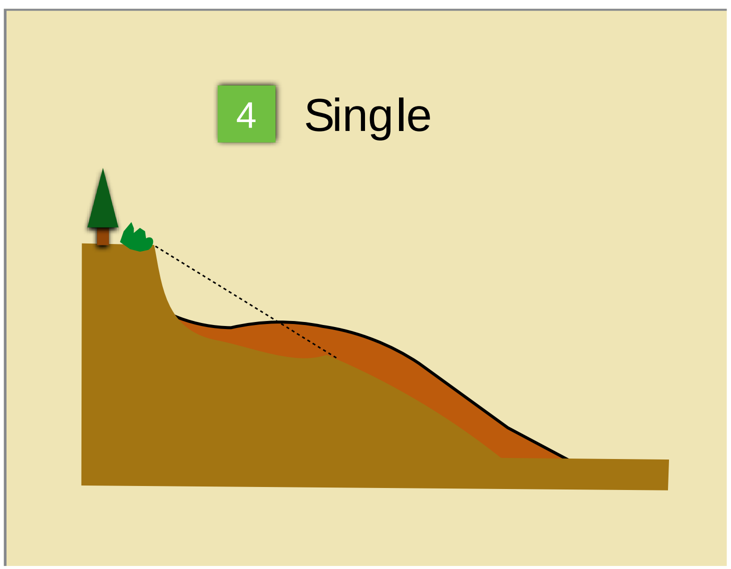




1. **Complex**: A complex landslide exhibits at least two types of movement (falling, toppling, sliding, spreading and flowing) in sequence.
2. **Composite**: A composite landslide exhibits at least two types of movement simultaneously in different parts of the displacing mass.

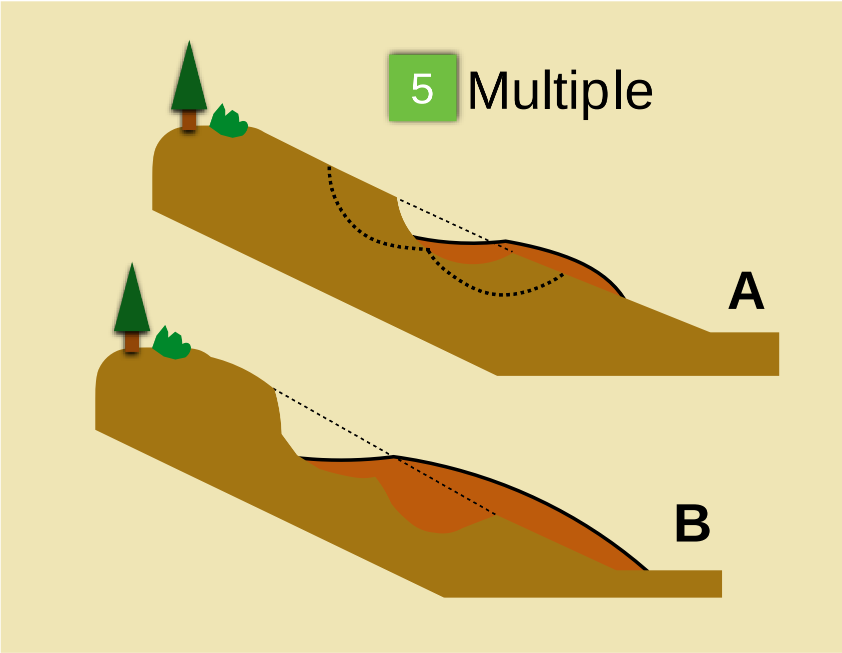
Style of activities (WP/WLI, 1993)





1. **Complex**: A complex landslide exhibits at least two types of movement (falling, toppling, sliding, spreading and flowing) in sequence.
2. **Composite**: A composite landslide exhibits at least two types of movement simultaneously in different parts of the displacing mass.
3. **Successive**: A successive landslide is the same type as a nearby, earlier landslide, but does not share displaced material or rupture surface with it.
4. **Single**: A single landslide is a single movement of displaced material.

Style of activities (WP/WLI, 1993)



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3. **Successive**: A successive landslide is the same type as a nearby, earlier landslide, but does not share displaced material or rupture surface with it.
4. **Single**: A single landslide is a single movement of displaced material.
5. **Multiple**: A multiple landslide shows repeated development of the same type of movement.

Complex & composite movements

Composite landslide based on a deep translational slide, developed as an earth/debris flow in conditions of high moisture. Maierato, (2010) Italy.