



# Landslides and hydrogeological risk

## Part 1

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Mission 4 "Education and Research" - Component 2: "From research to business" - Investment  
3.1: "Fund for the realisation of an integrated system of research and innovation infrastructures"



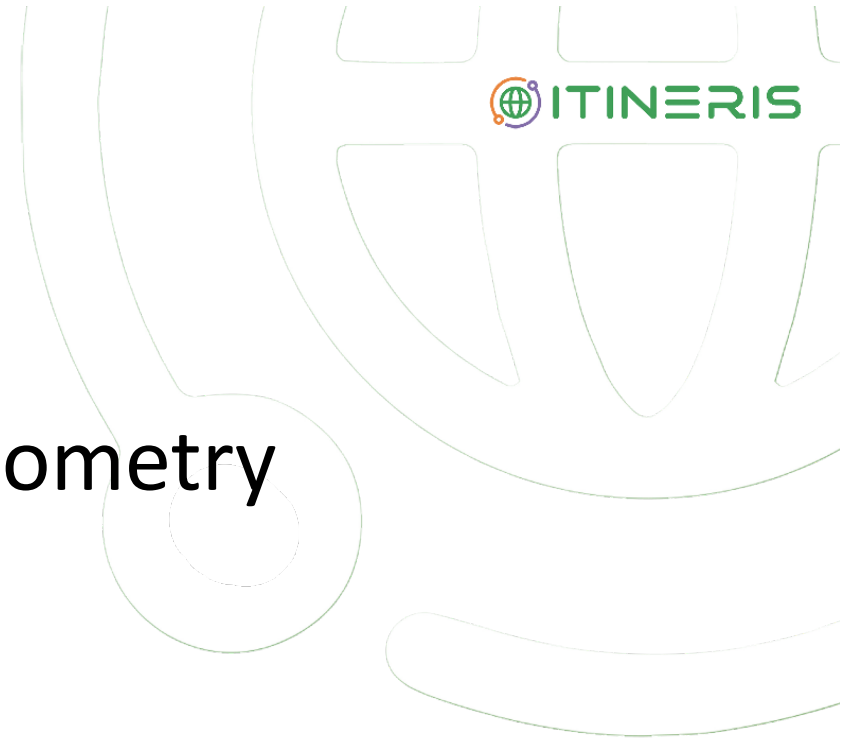
## Who I am



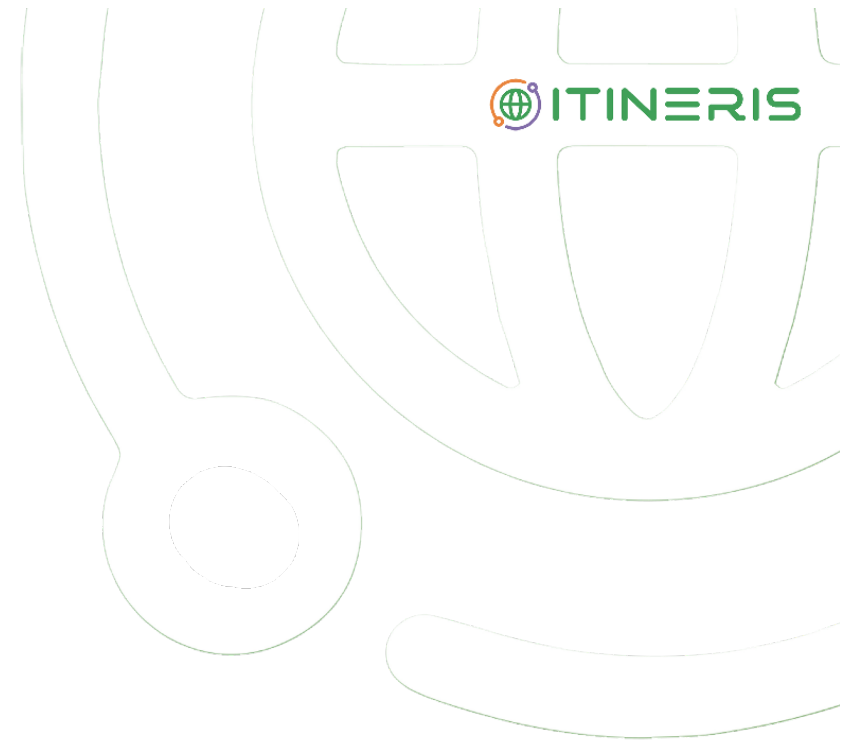
- **Associate Professor of Engineering geology**  
Department of Earth Sciences, University of Florence, Italy
- **Deputy Chairholder** Unesco Chair on Prevention and Sustainable Management of Geo-hydrological Hazards, University of Florence, Italy
- **Past Vice President** of International Consortium on Landslides (ICL)

## Outline

1. Introduction
2. Definitions, features and geometry
3. Classification
4. Causes
5. Effects



# Introduction



# Geological risk

## Seismic



## Volcanic



## Hydraulic



## Geo-hydrological

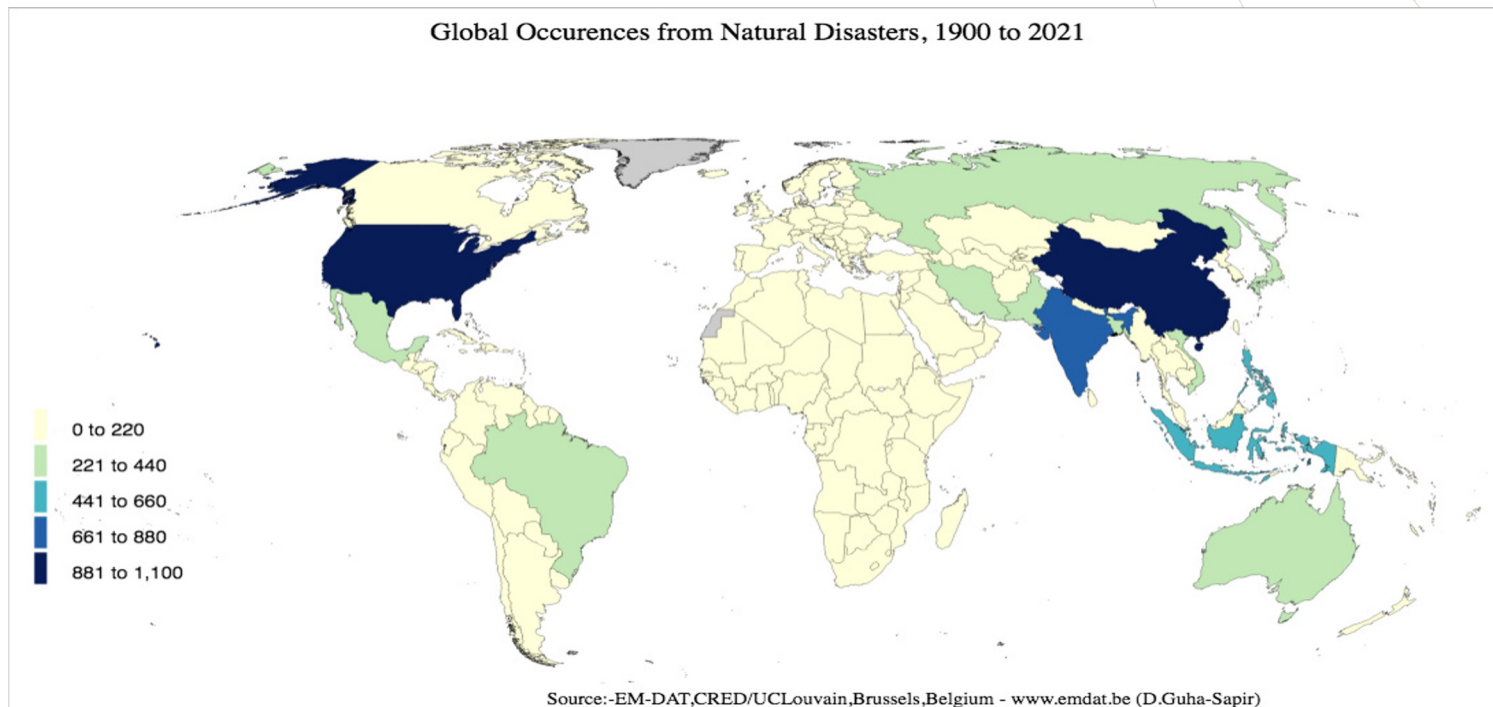
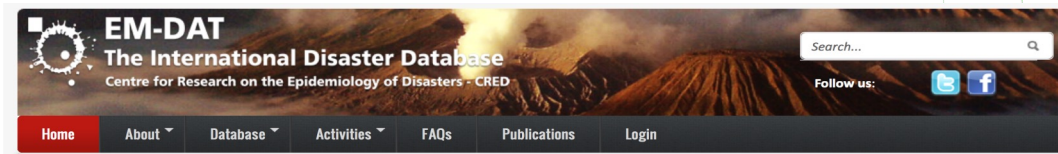


## Geo-hydrological risk

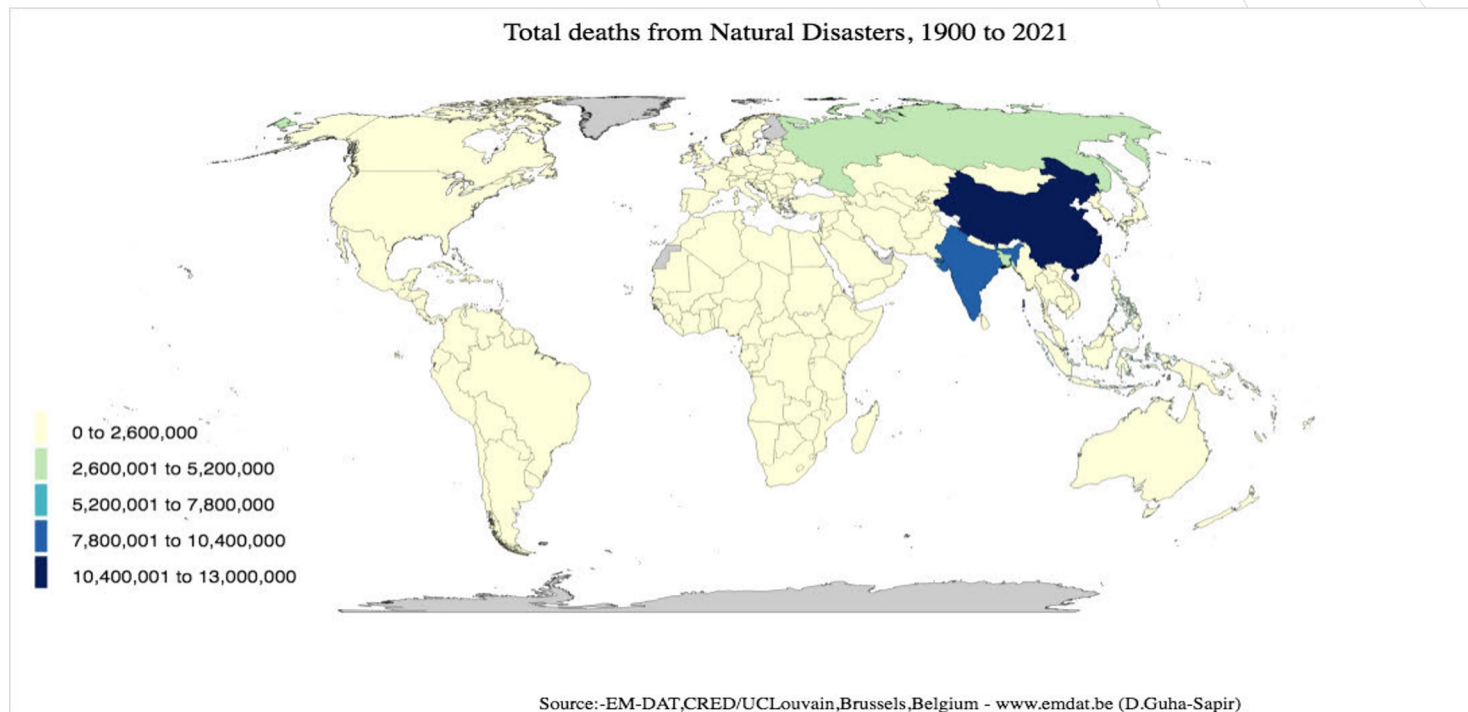
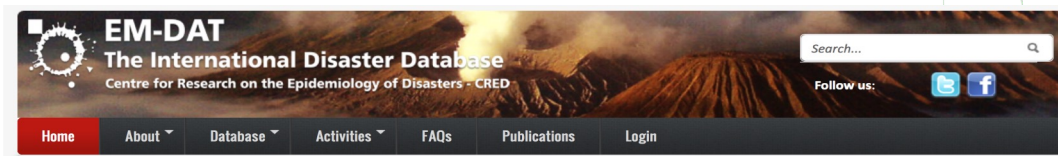
- Landslides
- Deep-seated slope deformation
- Subsidence and sinkholes
- Avalanches
- Submarine landslides



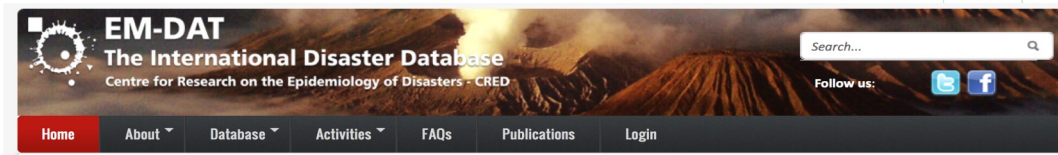
# Statistics on geological risks



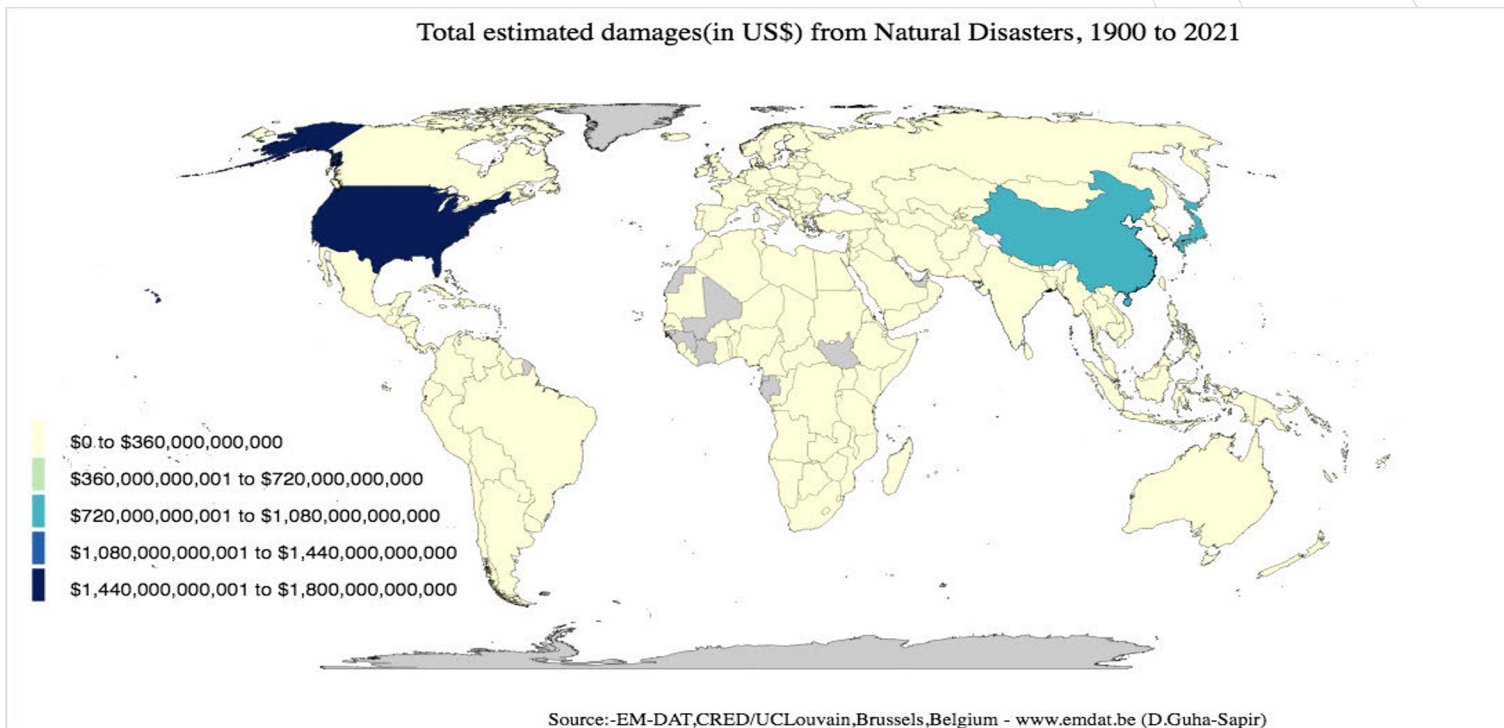
# Statistics on geological risks



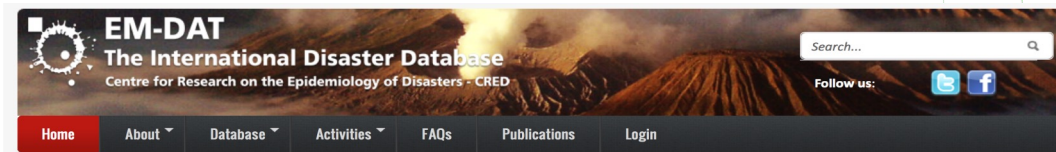
# Statistics on geological risks



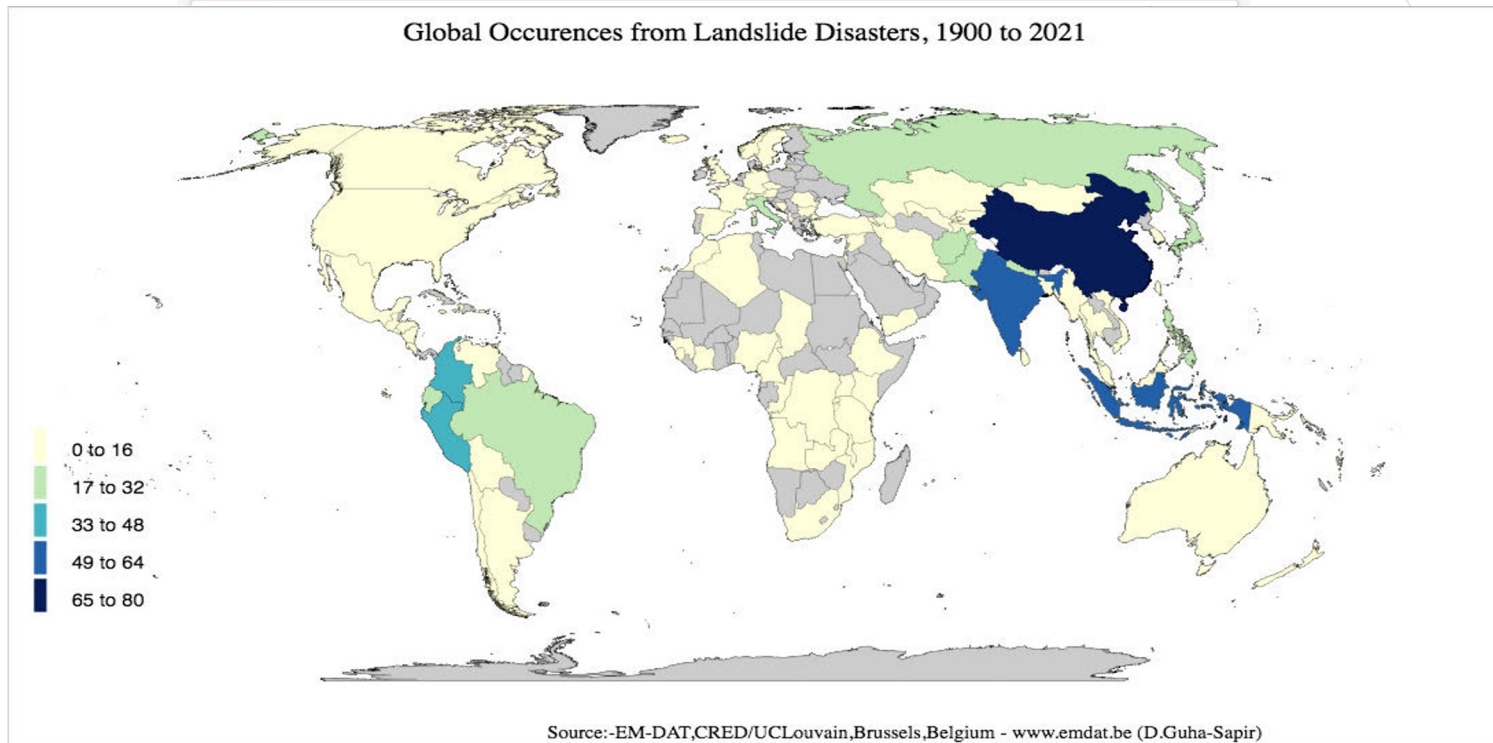
Total estimated damages(in US\$) from Natural Disasters, 1900 to 2021



# Statistics on geological risks



Global Occurrences from Landslide Disasters, 1900 to 2021



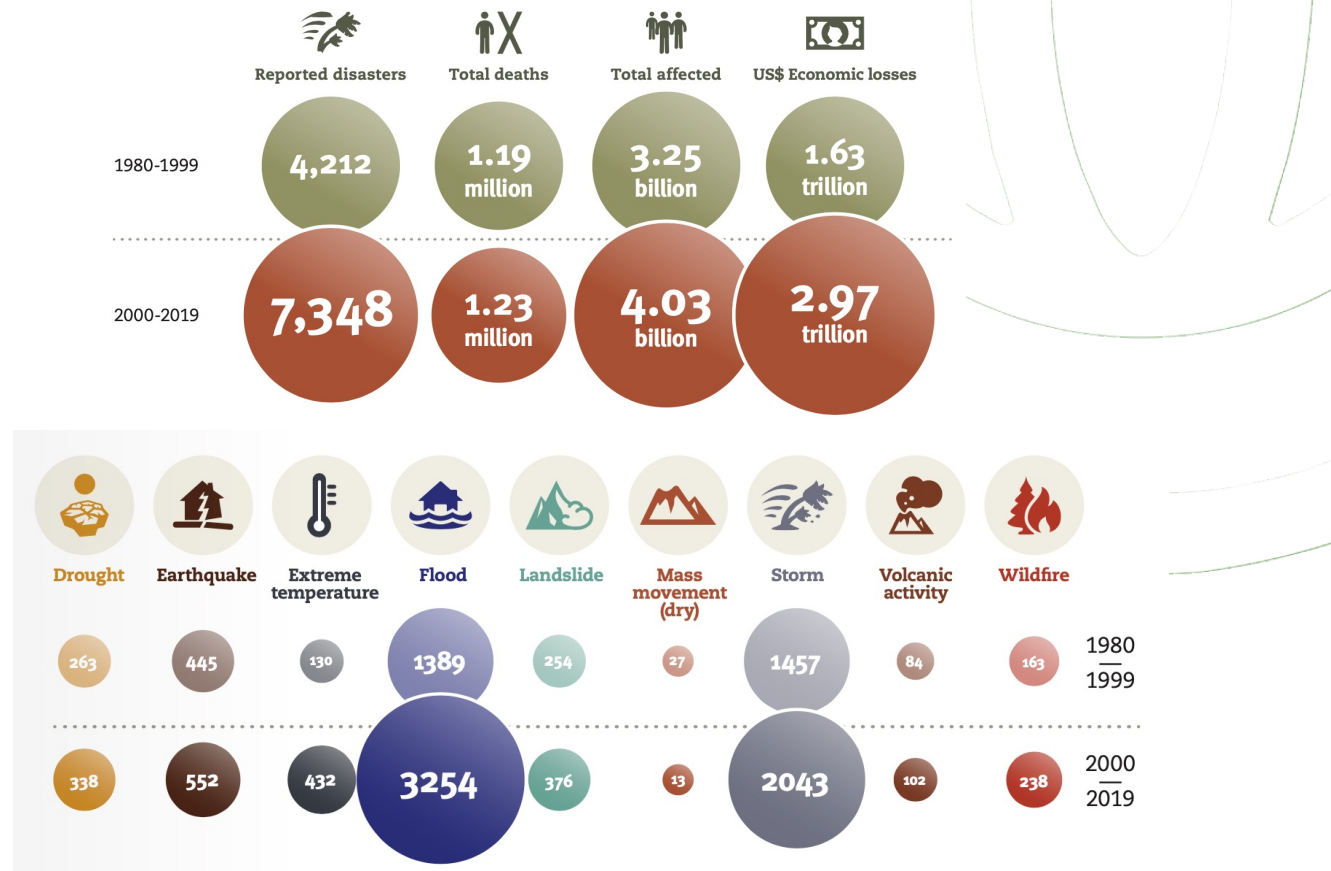
# Statistics on geological risks



**Human cost of disasters**  
An overview of the last 20 years  
**2000-2019**

Centre for Research on the Epidemiology of Disasters  
CREED

UNDRR  
UN Office for Disaster Risk Reduction

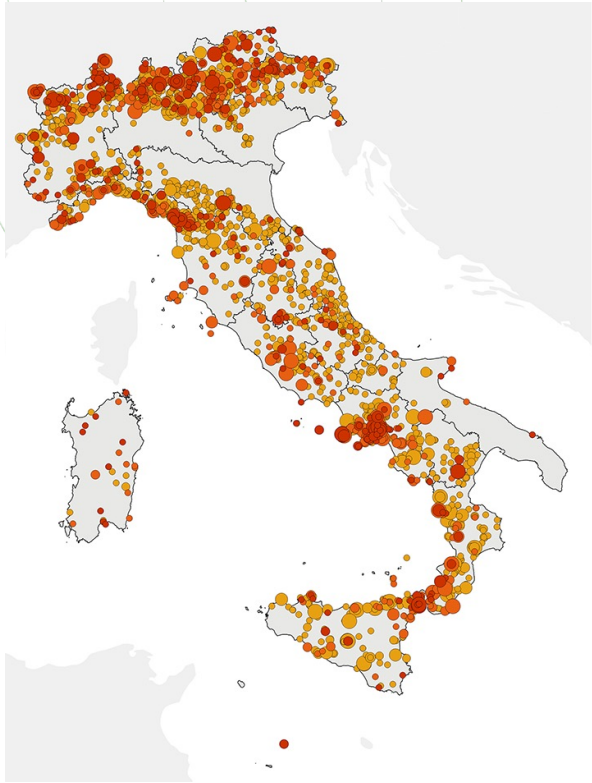


# What's going on in Italy

2 victims and 5 injuries due to landslides in Italy in the first semester of 2024



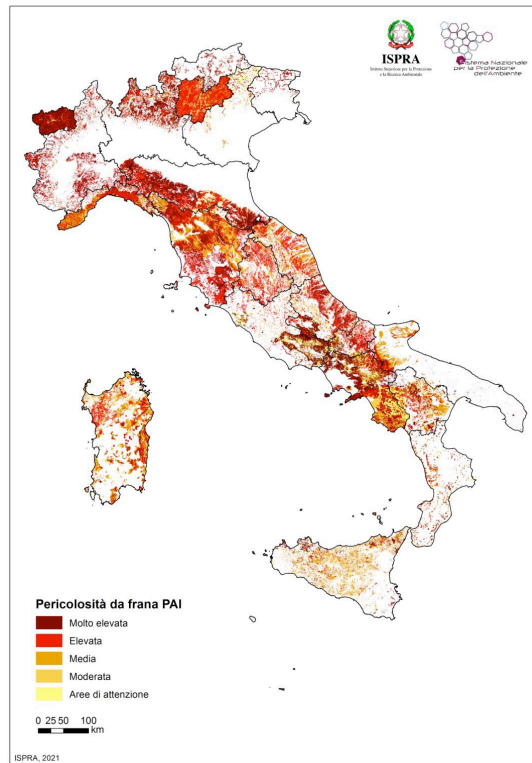
1060 victims and 1442 injuries due to landslides in Italy in the last 50 years



Source: IRPI Polaris

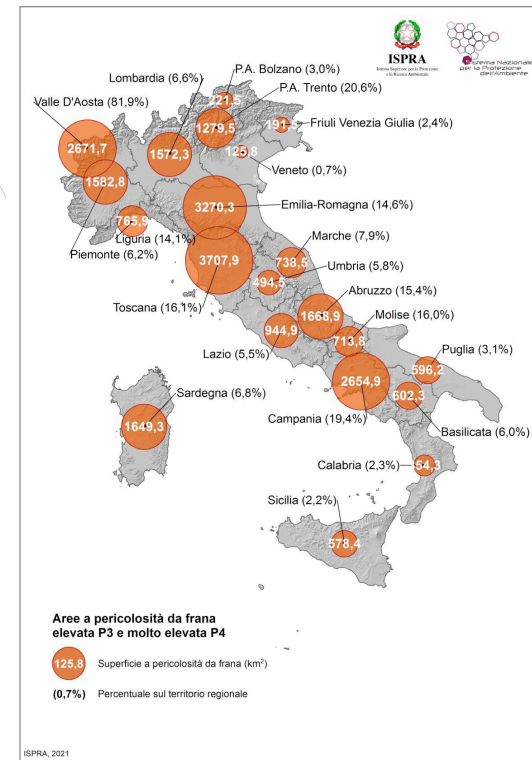
# What's going on in Italy

60'481 km<sup>2</sup> (20% of the national territory) is the total extent of hazardous areas in Italy



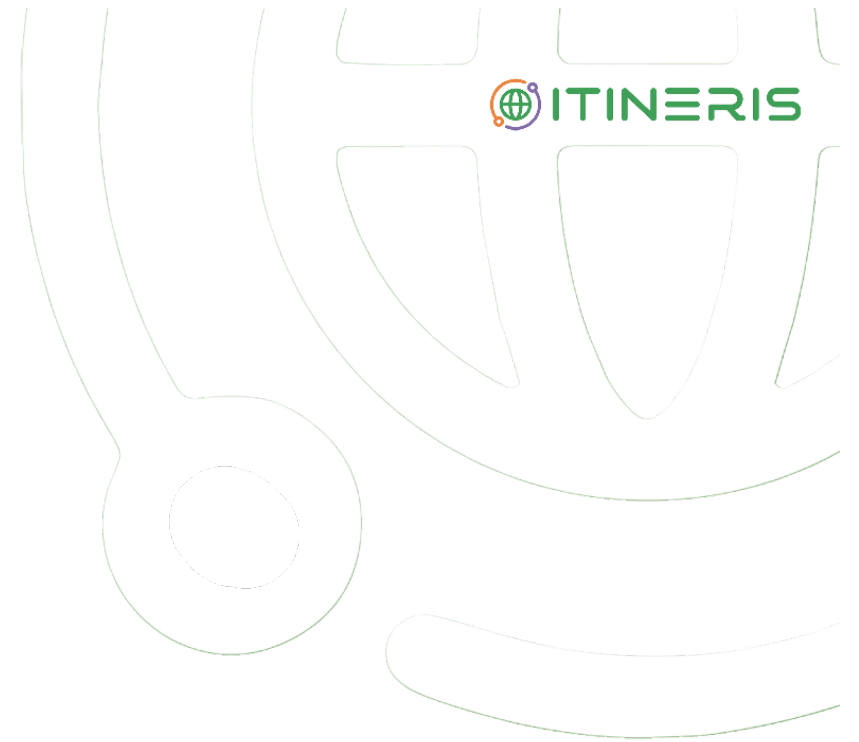
Tuscany, Emilia-Romagna, Valle d'Aosta, Campania regions have the higher extent of high and very high hazardous areas to landslides

Source: ISPRA





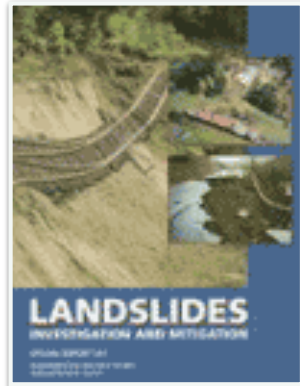
# Landslides: Features and geometry



## Landslide definition

*A landslide is the movement of a mass of rock, earth or debris down a slope*

Cruden (1991)  
UNESCO WP/WLI



## Mass movement vs mass transport

**Mass movement:** movement of masses of material on the slope that occur predominantly as a result of the action of gravity

- typically non-selective character
- reduced transport (zone of erosion and short-range deposition)
- Examples: landslides, subsidence, avalanches



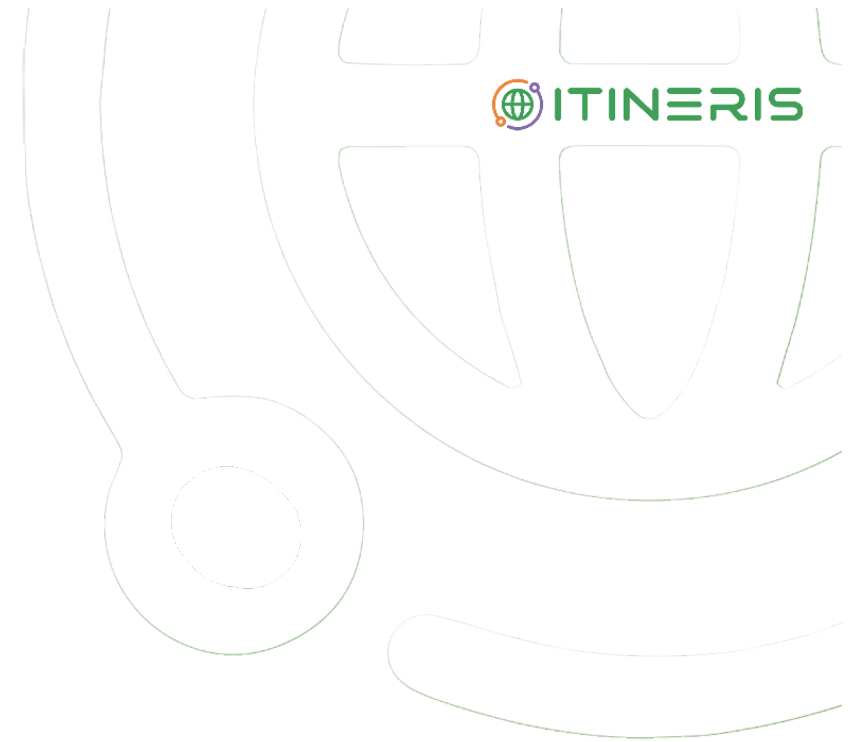
**Mass transport:** movement of material masses that occur mainly as result of the action of shallow water flows

- selective character (conditioned by grain size)
- transport over distances of up to several kilometers,
- Examples: river floods, debris flows.

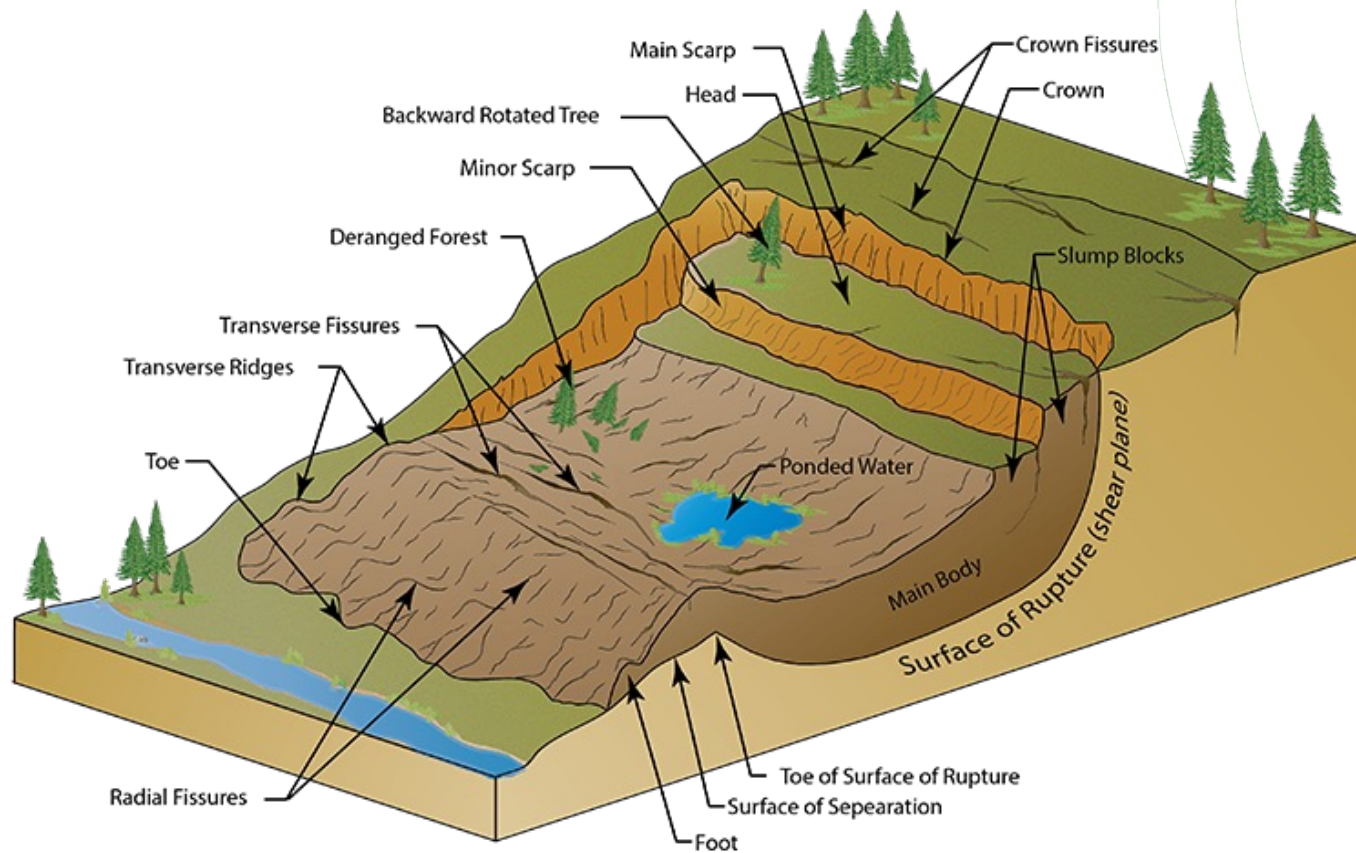


## Key features

1. Basic features
2. Dimensions
3. Type of movement
4. Type of material
5. Water content
6. Velocity
7. Activity



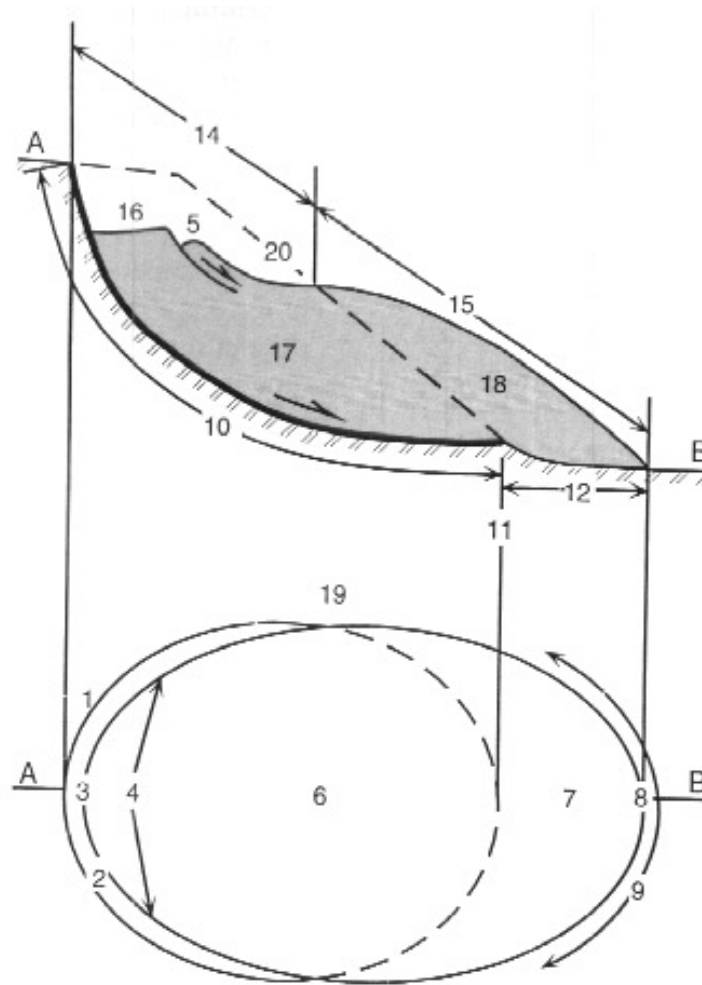
# Features



IAEG Commission on Landslides (1990)

# Features

1. crown
2. main scarp
3. top
4. head
5. minor scarp
6. main body
7. foot
8. tip
9. toe
10. surface of rupture
11. toe of surface of rupture
12. surface of separation
13. displaced material
14. zone of depletion
15. zone of accumulation
16. depletion
17. depleted mass
18. accumulation
19. flank
20. original ground surface



IAEG Commission on Landslides (1990)

## Features

# La Conchita, California March 1995



## Features

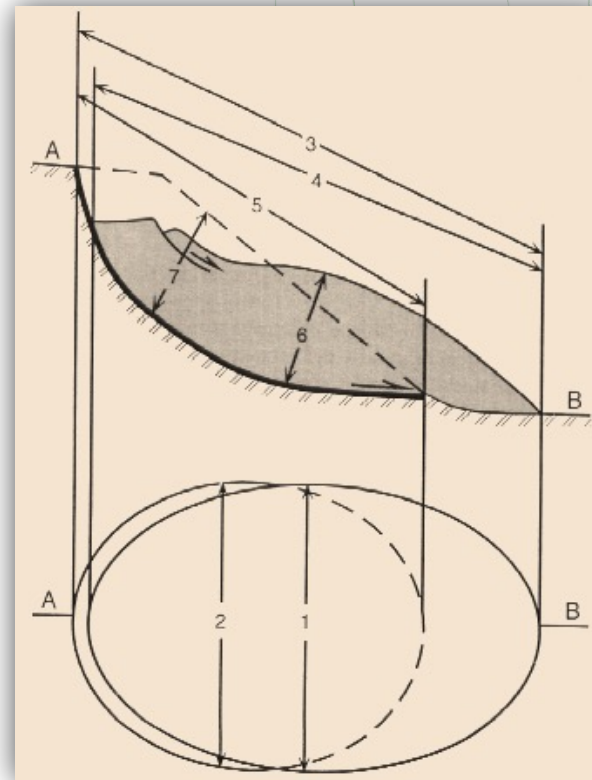
La  
Conchita,  
California  
1995



## Geometry

1. Width of the Displaced Mass  $W_d$
2. Width of the Rupture Surface  $W_r$
3. Total length  $L$
4. Length of the Displaced Mass  $L_d$
5. Length of the Rupture Surface  $L_r$
6. Depth of the Displaced Mass  $D_d$
7. Depth of the Rupture Surface  $D_r$
8. Length of center line  $L_{cl}$
9. Height  $H$

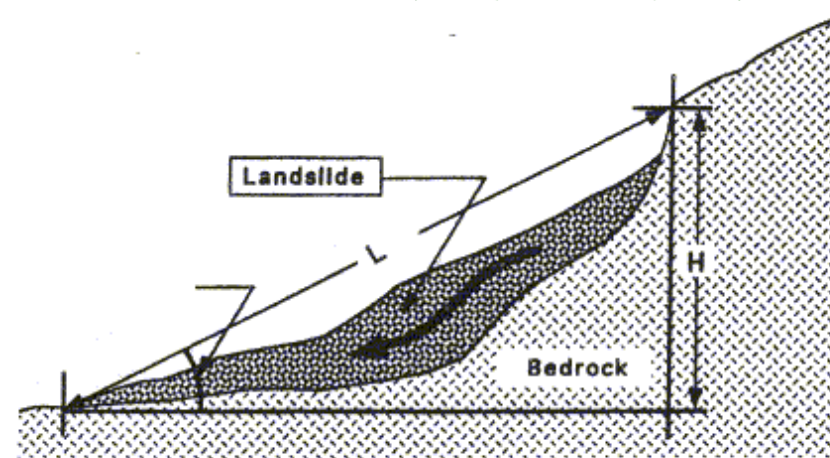
UNESCO WP/WLI (1990)



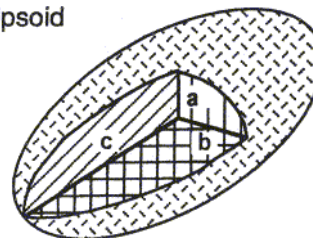
# Geometry

- **Travel angle:**  
 $\beta = \arcsin (H/L)$
- **Initial volume:**  
 $V_i = F \times L_r \times W_r \times D_r$
- **Final volume:**  
 $V_f = F \times L_d \times W_d \times D_d$
- **Shape factor:**  
 $F = \pi/6$  (semi-ellipsoid)
- **Swelling factor**  
 $SF = 100 \times (V_f - V_i) / V_i$

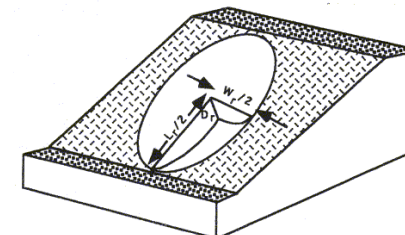
UNESCO WP/WLI (1990)



(a) Ellipsoid



(b) Landslide



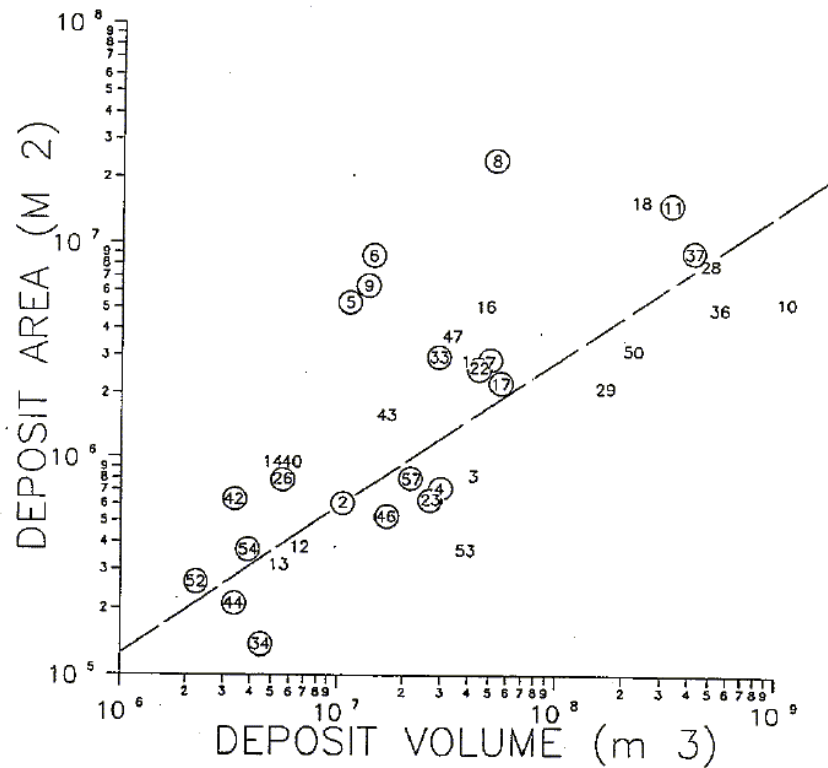
Mechanically excavated rock: SF=67%

Church (1981)

Rockslides: SF=33%

Nicoletti & Sorriso-Valvo (1991)

# Area-volume relationships



ID	Equation	Min $A_L$ (m <sup>2</sup> )	Max $A_L$ (m <sup>2</sup> )	N	Source
1	$V_L = 0.074 \times A_L^{1.450}$	$2 \times 10^0$	$1 \times 10^9$	677	This work (Eq. (1))
2	$V_L = 0.1479 \times A_L^{1.368}$	$2.3 \times 10^0$	$1.9 \times 10^5$	207	Simonett (1967)
3	$V_L = 0.234 \times A_L^{1.11}$	$2.1 \times 10^0$	$2 \times 10^2$	29	Rice et al. (1969)
4	$V_L = 0.0329 \times A_L^{1.3852}$	$3 \times 10^1$	$5 \times 10^2$	30	Innes (1983)
5	$V_L = 0.1549 \times A_L^{1.0905}$	$7 \times 10^2$	$1.2 \times 10^5$	124	Guthrie and Evans (2004a)
6	$V_L = 0.00004 \times A_L^{1.95}$	$> 1 \times 10^6$		23	Korup (2005b)
7	$V_L = 4.655 \times A_L^{1.292}$	$5 \times 10^5$	$2 \times 10^8$	160	ten Brink et al. (2006)
8	$V_L = 0.39 \times A_L^{1.31}$	$1 \times 10^1$	$3 \times 10^3$	51	Imaizumi and Sidle (2007)
9	$V_L = 0.0844 \times A_L^{1.4324}$	$1 \times 10^1$	$1 \times 10^9$	539	Guzzetti et al. (2008)
10	$V_L = 0.19 \times A_L^{1.19}$	$5 \times 10^1$	$4 \times 10^3$	11	Imaizumi et al. (2008)
11(*)	$V_L = 0.328 \times A_L^{1.104}$	$1.1 \times 10^1$	$1.5 \times 10^3$	37	Rice and Foggin (1971)
12(*)	$V_L = 0.242 \times A_L^{1.307}$	$2 \times 10^5$	$6 \times 10^7$	53	Abele (1974)
13(*)	$V_L = 0.769 \times A_L^{1.250}$	$5 \times 10^4$	$3.9 \times 10^6$	45	Whitehouse (1983)
14(*)	$V_L = 1.826 \times A_L^{0.898}$	$5 \times 10^1$	$1.6 \times 10^4$	1019	Larsen and Torres Sanchez (1998)
15(*)	$V_L = 1.0359 \times A_L^{0.880}$	$2 \times 10^2$	$5.2 \times 10^4$	615	Martin et al. (2002)
16(*)	$V_L = 12.273 \times A_L^{1.047}$	$3 \times 10^5$	$3.9 \times 10^{10}$	65	Hafidason et al. (2005)

# Landslide magnitude

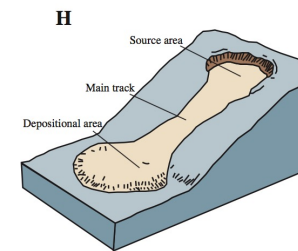
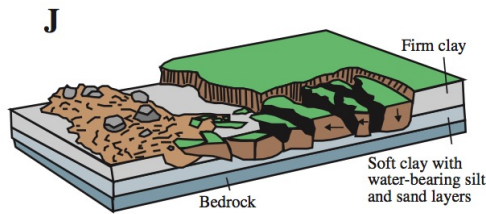
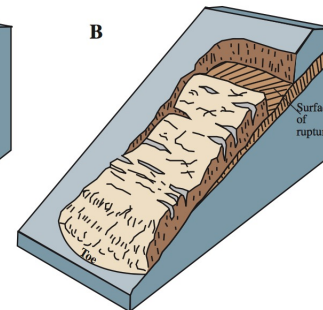
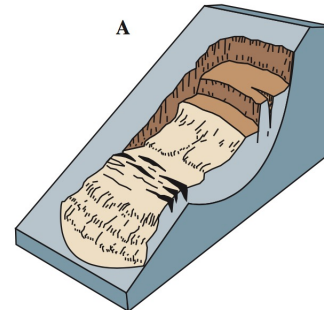
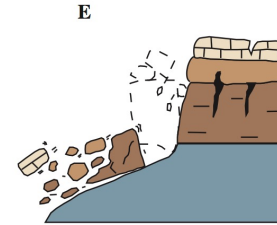
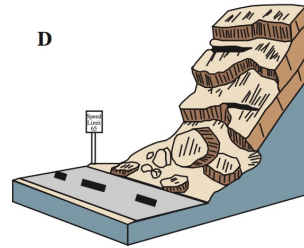
## Volume scale

Class	Description	Volume (m <sup>3</sup> )
1	Extremely small	$< 5 \cdot 10^2$
2	Very small	$5 \cdot 10^2 \div 5 \cdot 10^3$
3	Small	$5 \cdot 10^3 \div 5 \cdot 10^4$
4	Average	$5 \cdot 10^4 \div 2.5 \cdot 10^5$
5	Large	$2.5 \cdot 10^5 \div 1 \cdot 10^6$
6	Very large	$1 \cdot 10^6 \div 5 \cdot 10^6$
7	Extremely large	$> 5 \cdot 10^6$

Fell (1994)

# Types of movement

- 1.fall
- 2.topple
- 3.slide
  - a.rotational
  - b.translational
- 4.spread
- 5.flow

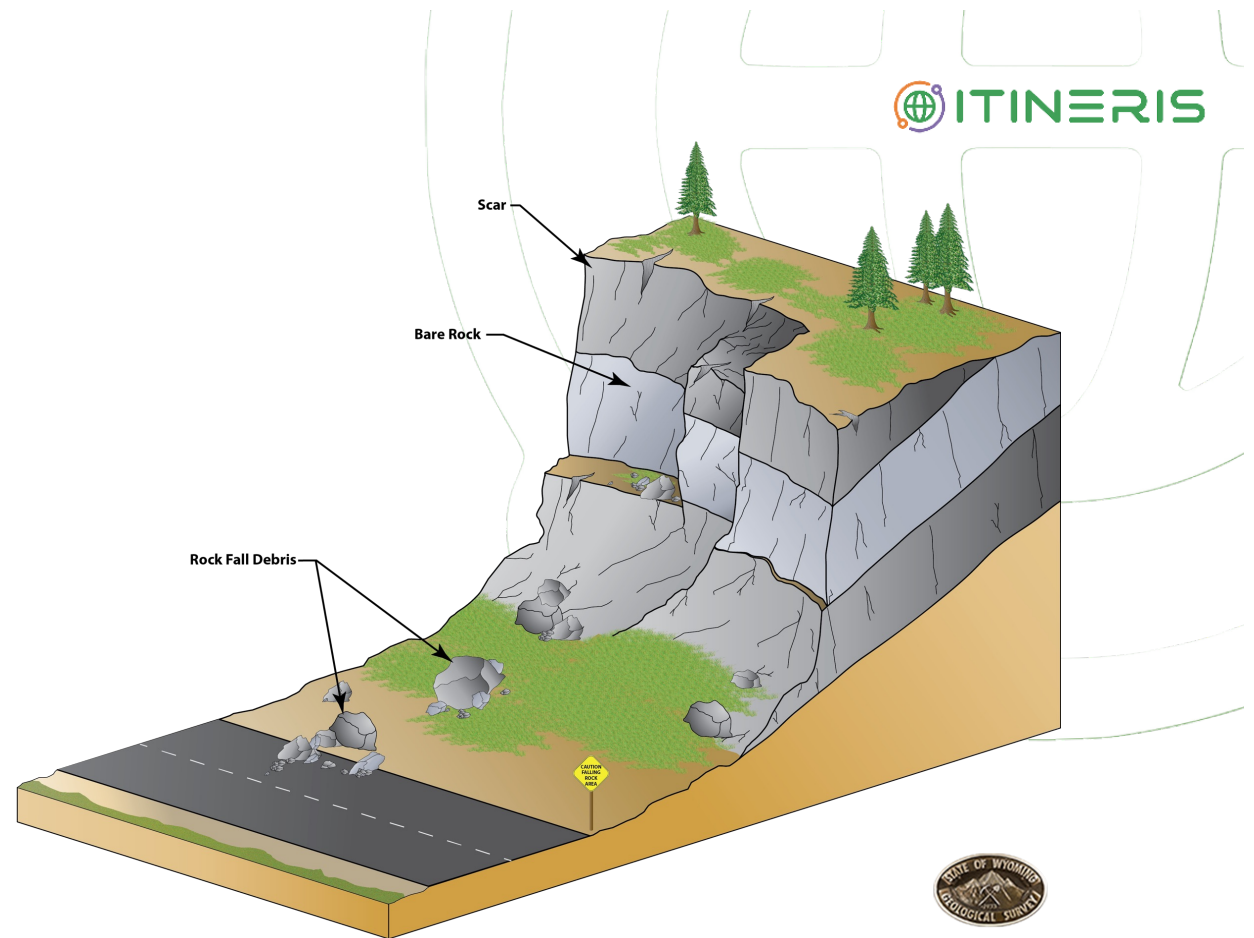


# Fall

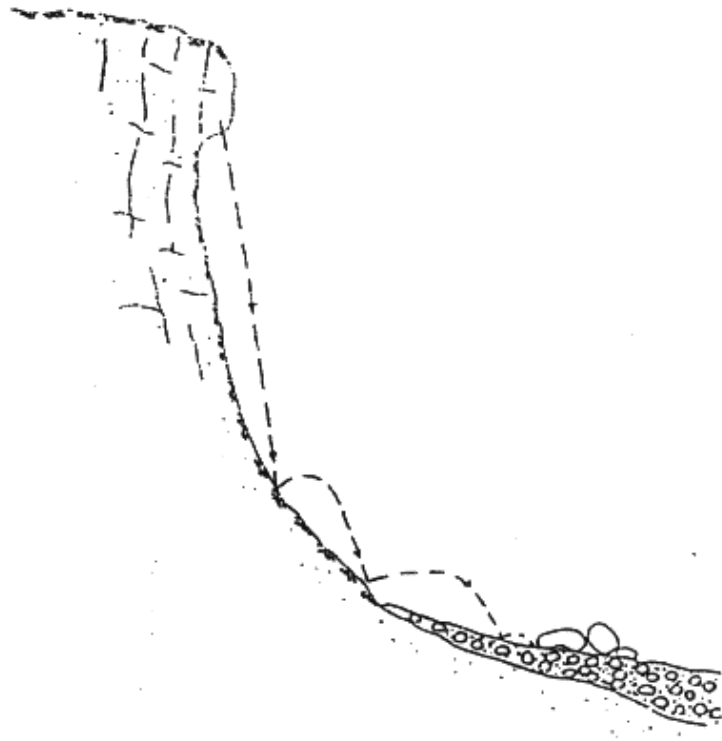
Mass detached from a very steep slope, then moves by free fall, bouncing, rolling.

Detachment can occur by:

- shear or tensile failure of intact rock/soil
- along pre-existing discontinuities



## Fall



**free fall:** first phase after detachment, when the slope inclination exceeds  $76^\circ$

**bouncing:** rebound from the impact will depend on:

- material properties (rebound coefficients)
- angle between the slope and the mass trajectory (morphology of the slope)
- fragmentation of the boulder in the impact

**rolling:** predominates on long slopes inclined less than  $45^\circ$ , gradual transition between bouncing and rolling

## Fall

### **OCCURRENCE:**

Common worldwide on steep or vertical slopes, also in coastal areas, and along rocky banks of rivers.

### **VELOCITY:**

Very rapid to extremely rapid, free-fall; Velocity of bouncing and rolling of detached material depends on slope steepness.

### **TRIGGERS:**

Undercutting of slope by natural processes such as streams or differential weathering (e.g. freeze/thaw cycle), human activities, earthquake shaking or other intense vibration.

### **MATERIAL:**

Rock, earth or debris

### **VOLUME:**

The volume of material in a fall can vary substantially, from individual rocks and clumps of soil to massive blocks thousands of cubic meters in size.

Fall

## San Leo (RM, Italy) rockfall



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Fall

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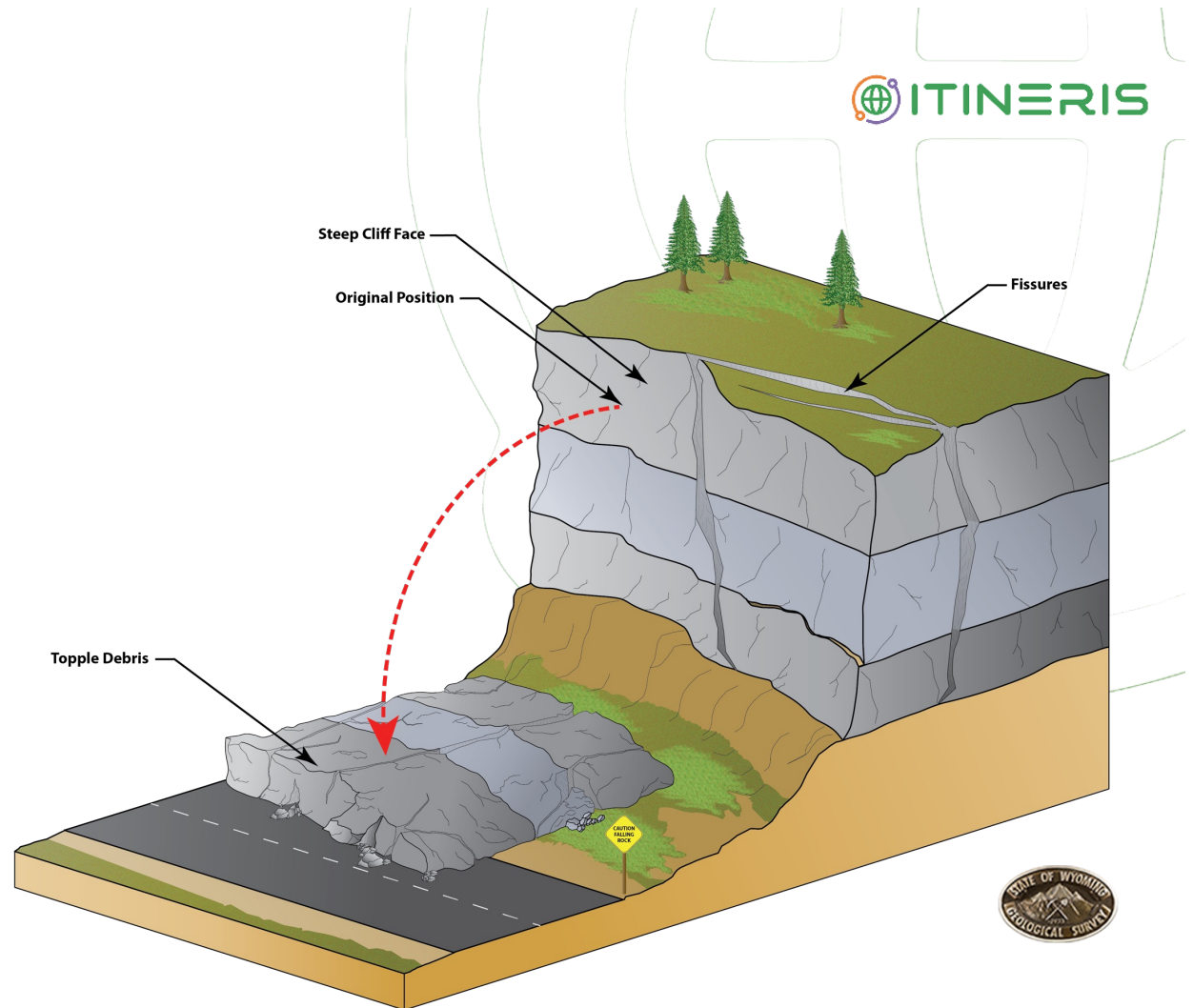
rock and earth  
fall

Taiwan, 31  
august 2013



# Topple

Forward rotation out of the slope of a mass of soil or rock about a point or axis below the center of gravity of the displaced mass



## Topple

**OCCURRENCE:** Common in rocky fractured masses, in columnar-jointed volcanic terrain. May evolve into fall or slide

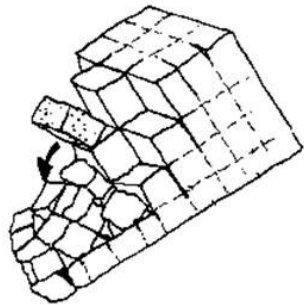
**VELOCITY:** They are extremely slow to extremely rapid, sometimes accelerating throughout the movement depending on distance of travel

**TRIGGERS:** Topples are sometimes driven by gravity exerted by material located upslope from the displaced mass and sometimes by water or ice occurring in cracks within the mass; also, vibration, undercutting, differential weathering, excavation

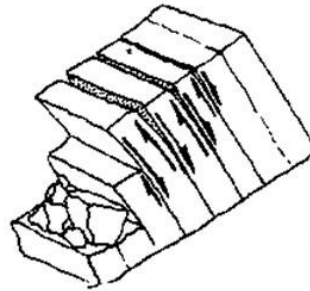
**MATERIAL:** Topples can consist of rock, debris (coarse material), or earth material (fine-grained material)

**MECHANISM:** It can be flexural topple or block topple

# Topple



**a) Block topple**



**b) Flexural topple**



It may evolve in fall or slide

The accumulation is similar to that of falls

## Topple

### Rock topple



### Earth topple

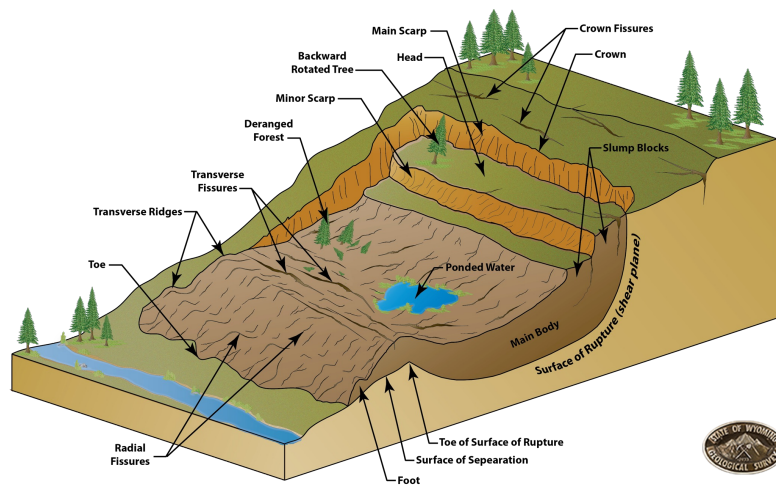


# Topple

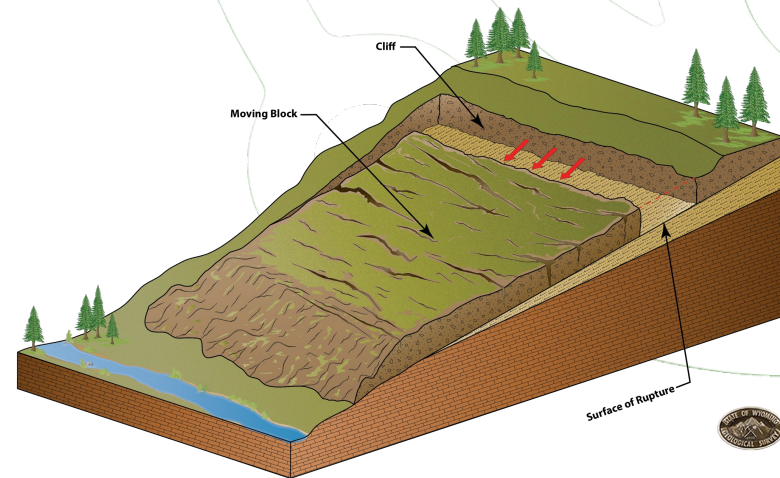


# Slide

Downslope movement of a soil or rock mass occurring dominantly on surfaces of rupture on relatively thin zones of intense shear strain



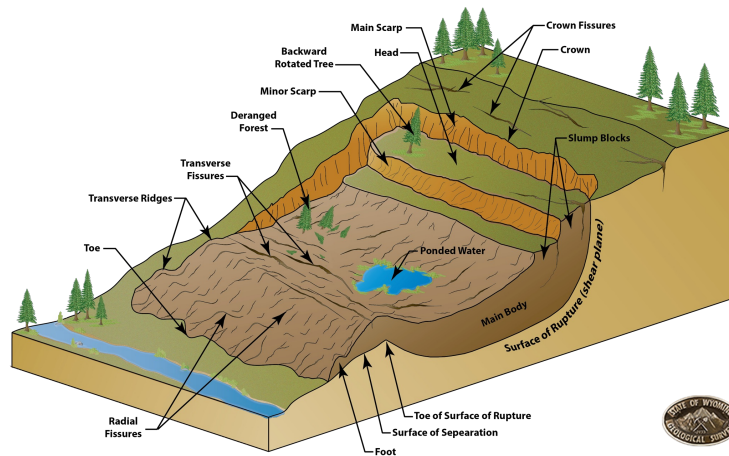
Rotational



Translational

# Slide

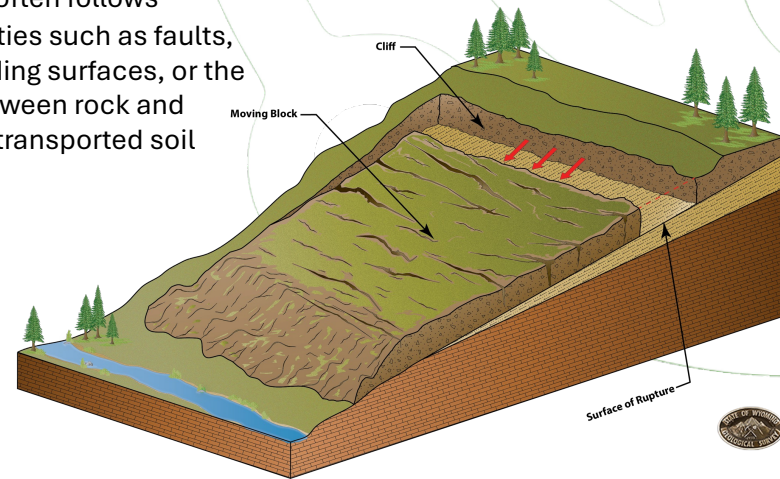
Movement along a surface of rupture that is curved and concave  
 Occur most frequently in homogeneous and continuous materials



**Rotational**

Movement along a planar or undulating surface of rupture  
 Occur most frequently in layered or discontinuous materials

Movement often follows discontinuities such as faults, joints, bedding surfaces, or the contact between rock and residual or transported soil



**Translational**

## Rotational slide



Tessina, 1992  
(Veneto)

## Rotational slide

Rotational slide,  
Sheppey island, UK



## Traslational slide



Alba, Langhe, 1992  
(Piemonte)

## Traslational slide

Borgo Tassignano,  
Bologna, Italy

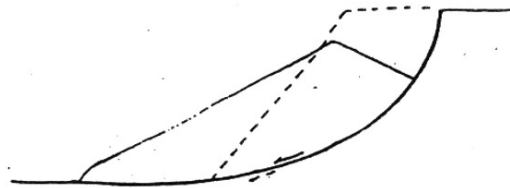


# Modes of sliding

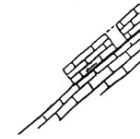
## 1) ROTATIONAL

$$D_r/L_r = 0.15 - 0.33$$

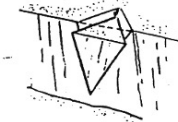
(Skempton & Hutchinson, 1969)



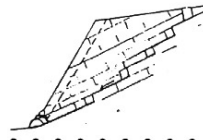
## 2a) planar



## 2b) wedge



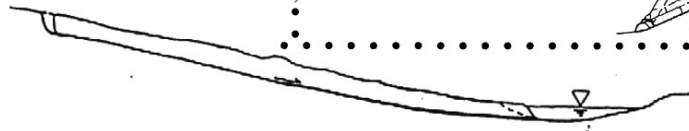
## 2c) stepped



## 2) TRANSLATIONAL

$$D_r/L_r < 0.05$$

(Skempton & Hutchinson, 1969)



## 3) COMPOUND

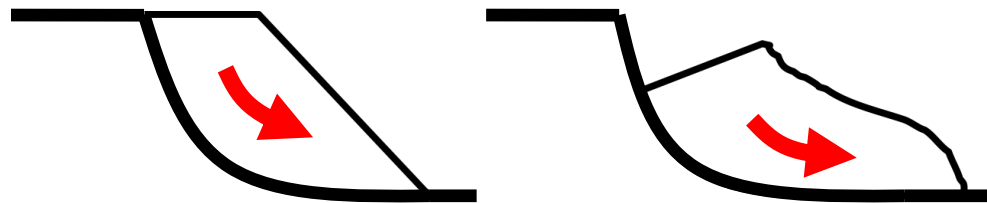
$$D_r/L_r \text{ intermediate}$$

(Skempton & Hutchinson, 1969)



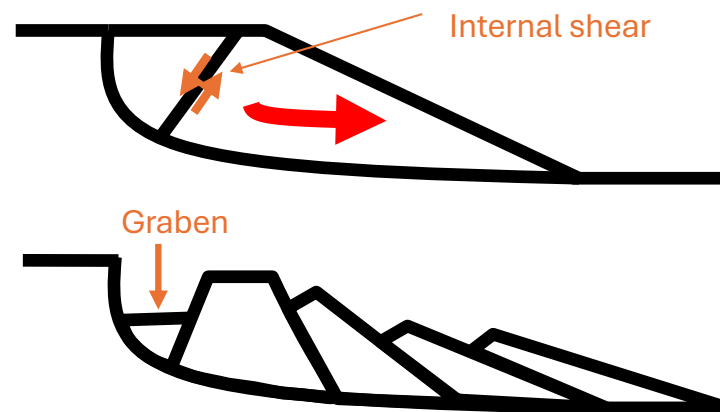
## Mechanism of sliding

- In rotational slides the mass moves along a curved sliding surface
- the movement involves the backward rotation of the sliding block
- the mechanism is **kinematically admissible** only if the sliding surface is circular or planar
- only in these cases the mass can slide without significant internal shear or deformation



## Mechanism of sliding

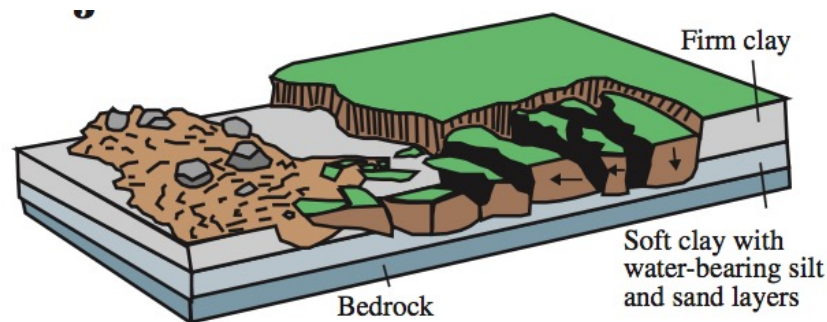
- movement occurs on a surface composed of planar and curved elements
- the sliding surface follows pre-existing
- the failure mechanism is **not kinematically admissible**
- the sliding of the mass can occur only with internal shear and deformation (formation of trenches, graben, counterscarps)



# 168号線地すべり

## Spread

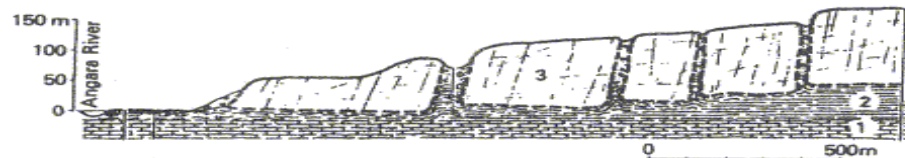
- Extension of a cohesive soil or rock mass combined with a general subsidence of the fractured mass of cohesive material into softer, underlying material
- The surface of rupture is not a surface of intense shear
- It may result from liquefaction or flow (and extrusion) of the softer material



## Modes of spreading

- **Block spreading:**

- a thick layer of rock overlies softer materials
- the strong upper layer may fracture and separate into strips
- the soft underlying material is squeezed into the cracks between the strips



Zaruba & Mencl (1969)

## Block spreading



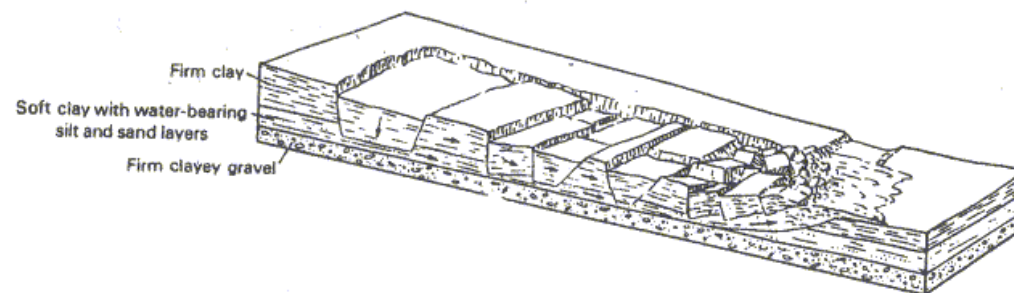
**Sasso di Simone  
e Simoncello  
(Arezzo)**

 **ITINERIS**

## Modes of spreading

- **Liquefaction spreading:**

- form in sensitive clays and silts that lose strength with disturbances that damage their texture
- movement is translational, if the underlying flowing layer is thick, clock may sink in it forming grabbers
- movement is often retrogressive

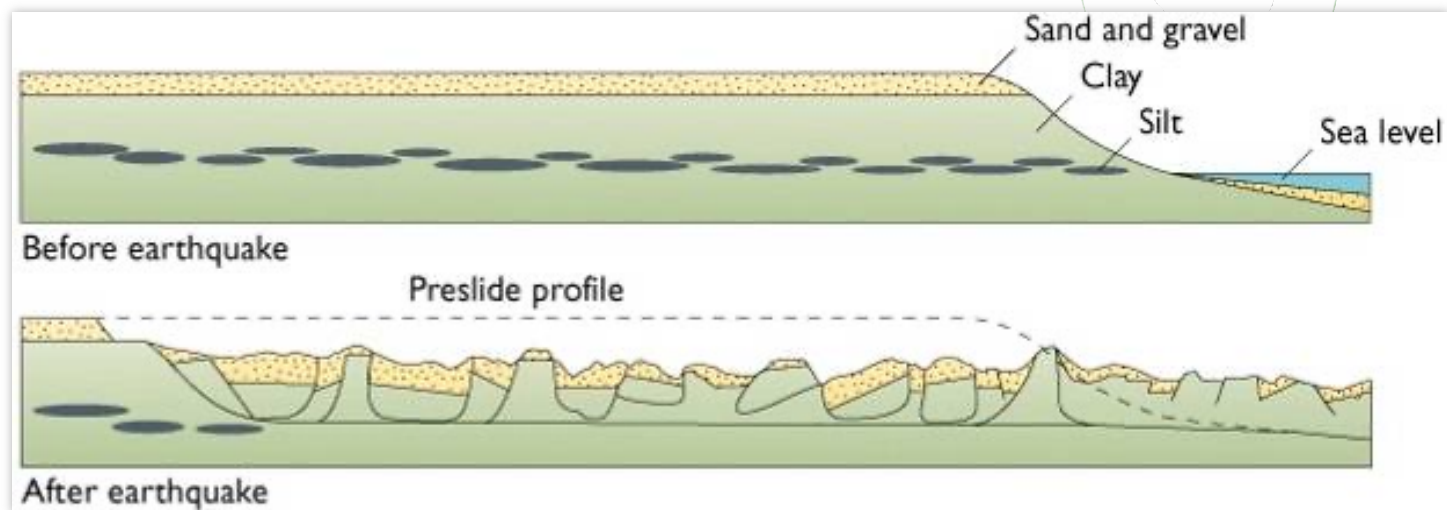


Varnes (1978)

# Liquefaction spreading



Anchorage, Alaska  
(1964)



## Liquefaction spreading



Rissa,  
Norway(1978)

Liquefaction  
of quick-clays



## Flow

Continuous movement in which surfaces of shear are short-lived, closely spaced and not usually preserved

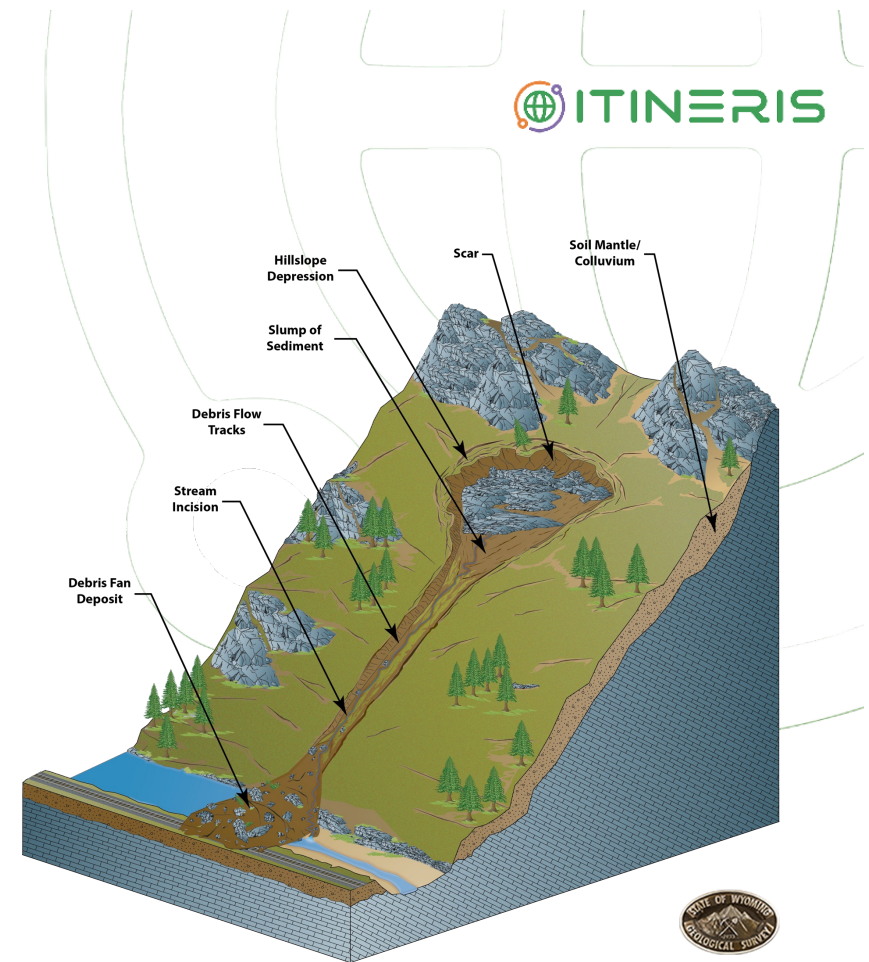
The distribution of velocities in the displacing mass resembles that in a viscous liquid

The lower boundary of the displaced mass may be:

- a surface along which appreciable differential movement has taken place
- a thick zone of distributed shear

There is a gradation from slides to flows depending on:

- water content
- mobility
- evolution of movement



## Open-slope debris flow (debris avalanches)



Sarno (NA), 1998

## Channelized debris flows



## Earth flow



**1983 Thistle  
landslide, Utah,  
U.S.A.**

## Earth flow



 ITINERIS

Montaguto (AV)

## Materials

### Rock

- hard rock: uniaxial compressive strength  $>25\text{MPa}$
- weak rock: uniaxial compressive strength  $<25\text{MPa}$

### Debris

20% to 80% of the particles with  $d > 2\text{mm}$  (gravel, pebbles, boulders)

### Earth

80% or more of the particles with  $d < 2\text{mm}$

- granular: most particles with  $d > 0.06\text{ mm}$  (sand)
- cohesive: most particles with  $d < 0.06\text{ mm}$  (silt and clay)
- organic: most particles made by organic matter (peat)

# Materials

**Table 3** Landslide-forming material types

Material name	Character descriptors (if important)	Simplified field description for the purposes of classification	Corresponding unified soil classes	Laboratory indices (if available)
Rock	Strong	Strong—broken with a hammer		UCS>25 MPa
	Weak	Weak—peeled with a knife		2<UCS<25 MPa
Clay	Stiff	Plastic, can be molded into standard thread when moist, has dry strength	GC, SC, CL, MH, CH, OL, and OH	$I_p > 0.05$
	Soft			
	Sensitive			
Mud	Liquid	Plastic, unsorted remolded, and close to Liquid Limit	CL, CH, and CM	$I_p > 0.05$ and $I_l > 0.5$
Silt, sand, gravel, and boulders	Dry	Nonplastic (or very low plasticity), granular, sorted. Silt particles cannot be seen by eye	ML	$I_p < 0.05$
	Saturated		SW, SP, and SM	
	Partly saturated		GW, GP, and GM	
Debris	Dry	Low plasticity, unsorted and mixed	SW-GW	$I_p < 0.05$
	Saturated		SM-GM	
	Partly saturated		CL, CH, and CM	
Peat		Organic		
Ice		Glacier		

**Hungr et al. (2014)**

## Water content

- **Dry:** no moisture visible
- **Moist:** contains some water but no free water. The material may behave as a plastic soil but does not flow
- **Wet:** contains enough water to behave in part as liquid, has water flowing from it, or supports significant bodies of standing water
- **Very wet:** contains enough water to flow as a liquid under low gradients

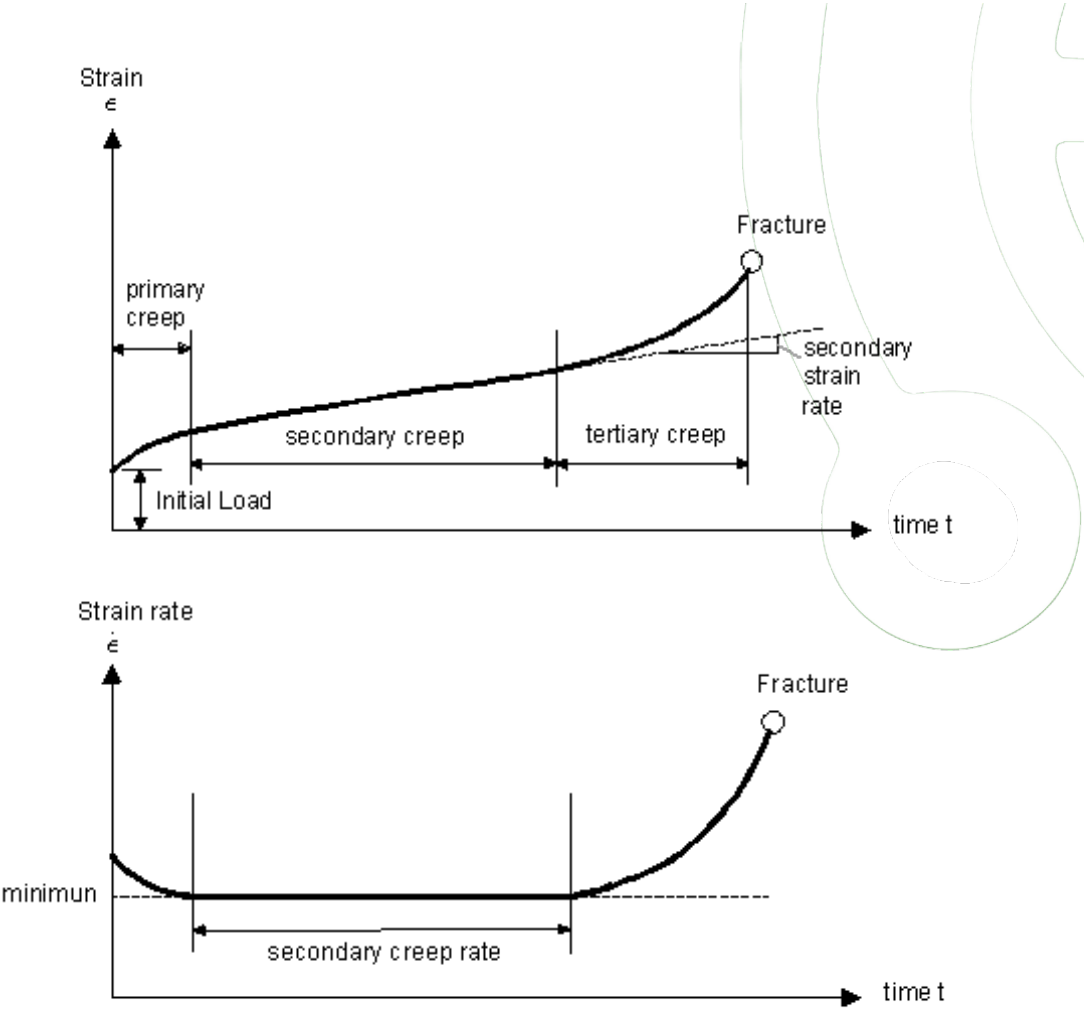
**Varnes (1978)**

# Velocity

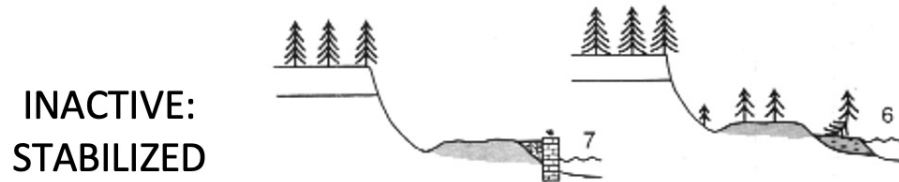
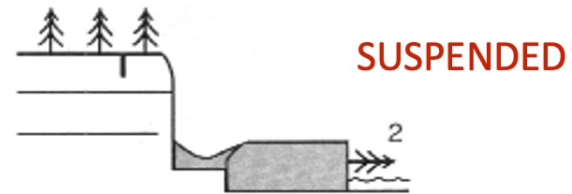
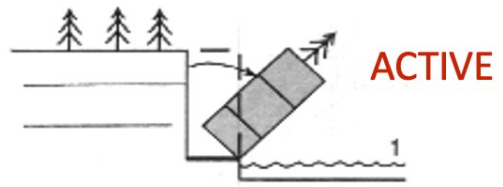
Class	Description	Probable destructive significance	velocity	(m/s)
1	<b>EXTREMELY SLOW</b>	Imperceptible without instruments. Construction possible with precautions	16mm/year	$5 \cdot 10^{-10}$
2	<b>VERY SLOW</b>	Some permanent structures undamaged by the movement	1.6m/year	$5 \cdot 10^{-8}$
3	<b>SLOW</b>	Remedial construction can be undertaken during movement. Insensitive structures can be maintained with frequent maintenance work if the total movement is not large during a particular acceleration phase	13 m/month	$5 \cdot 10^{-6}$
4	<b>MODERATE</b>	Some temporary and insensitive structures can be temporarily maintained	1.8 m/h	$5 \cdot 10^{-4}$
5	<b>RAPID</b>	Escape evacuation possible. Structures, possessions and equipment destroyed	3 m/min	$5 \cdot 10^{-2}$
6	<b>VERY RAPID</b>	Some lives lost, velocity too great to permit all persons to escape	5 m/s	5
7	<b>EXTREMELY RAPID</b>	Catastrophe of major violence. Buildings destroyed by impact of displaced material. Many deaths. Escape unlikely		

**IUGS/WGL (1995)**

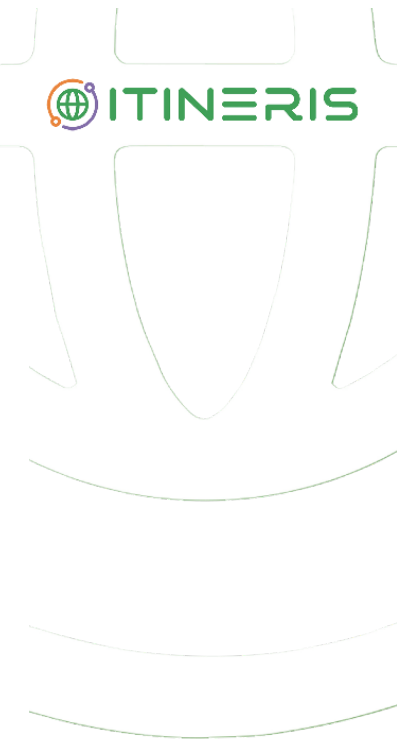
# Creep law



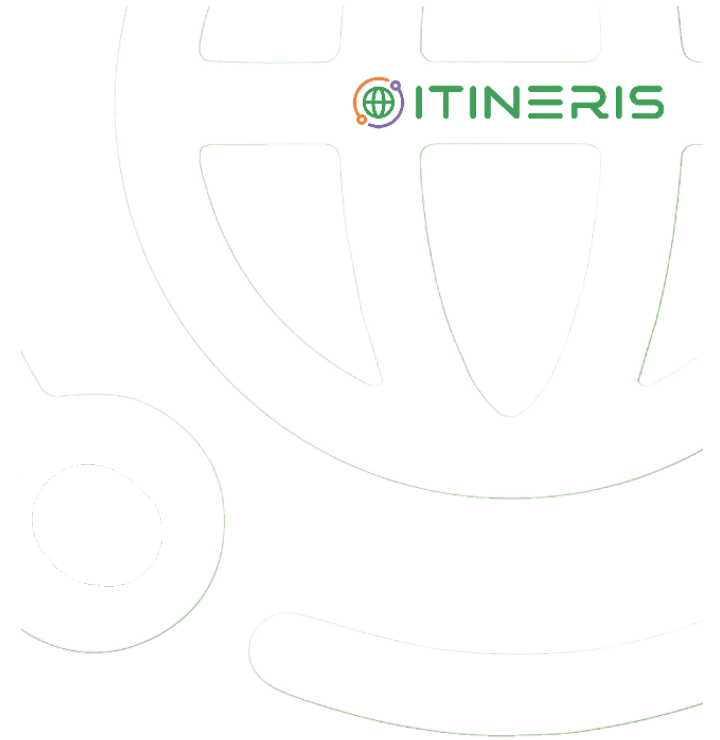
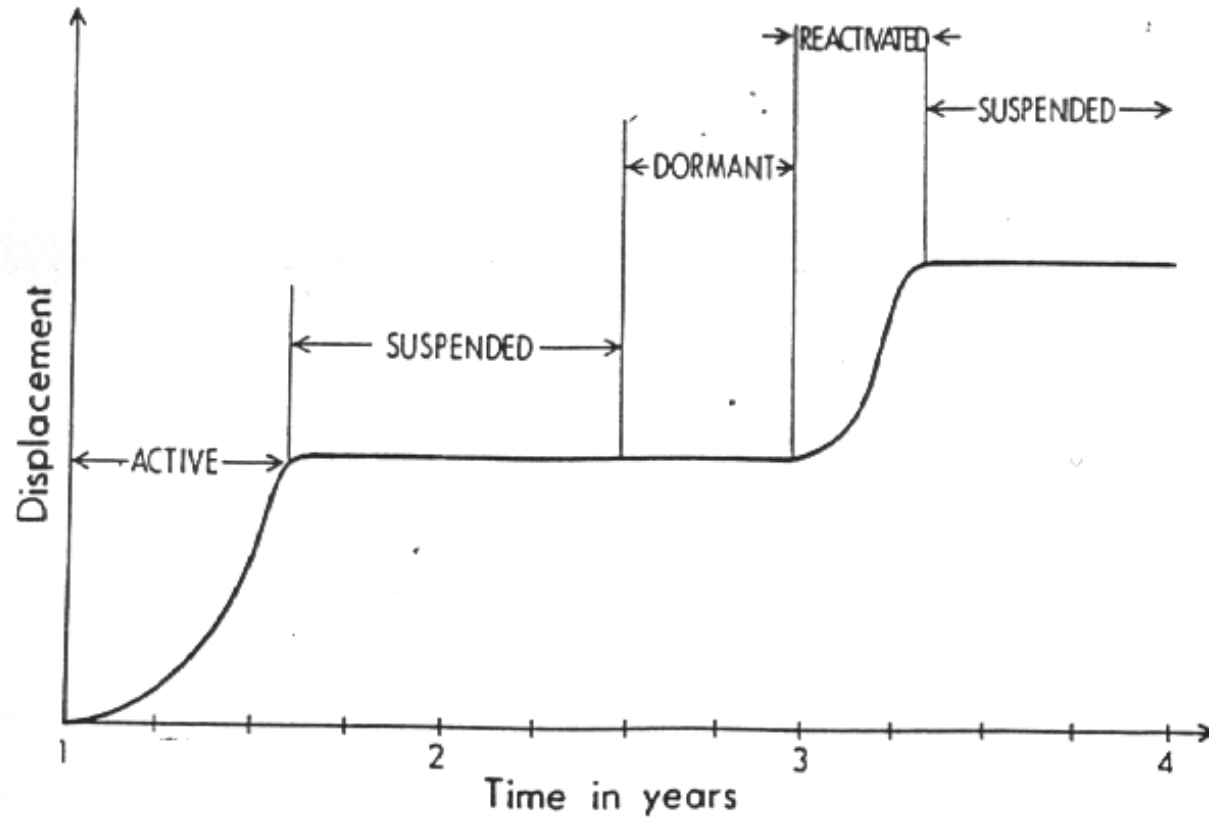
# State of activity



**INACTIVE:  
ABANDONED**

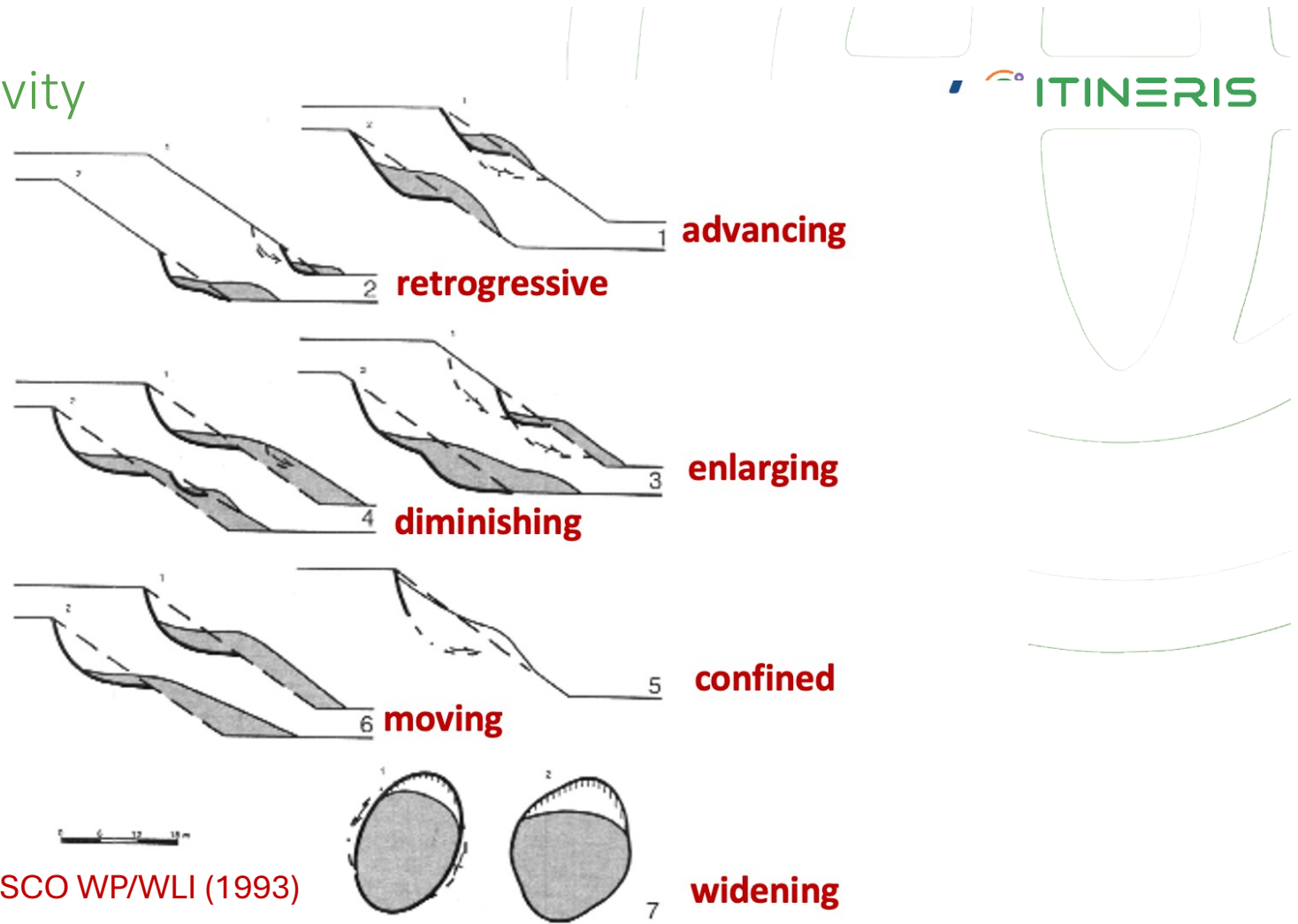


## State of activity

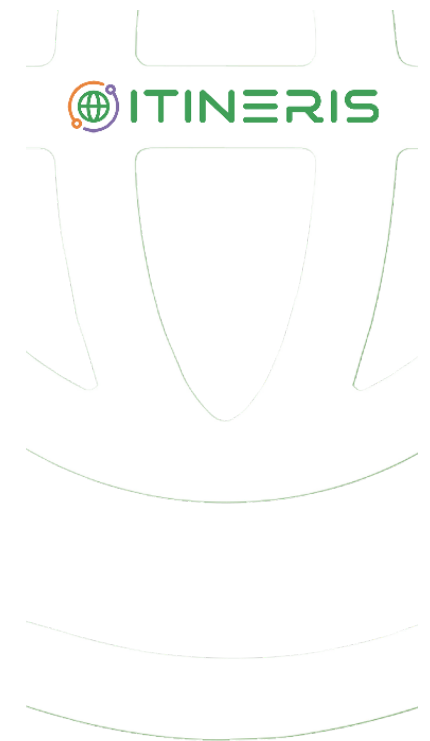
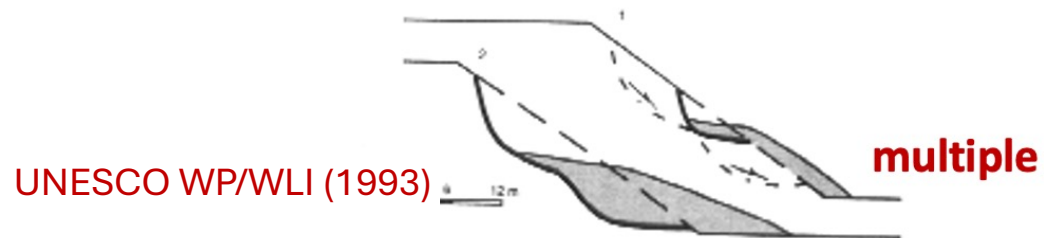
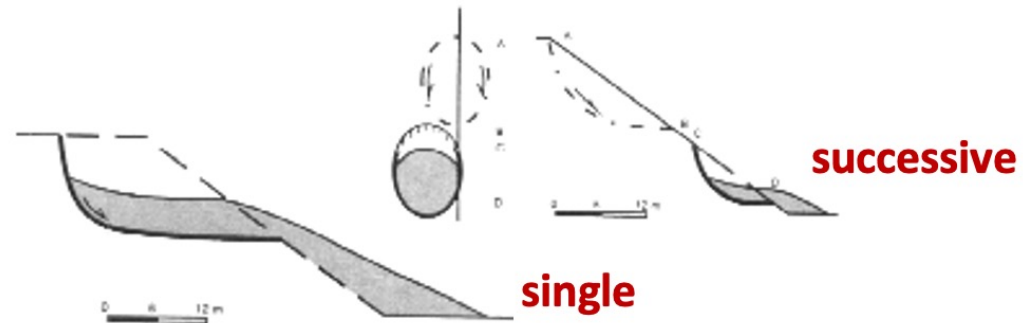
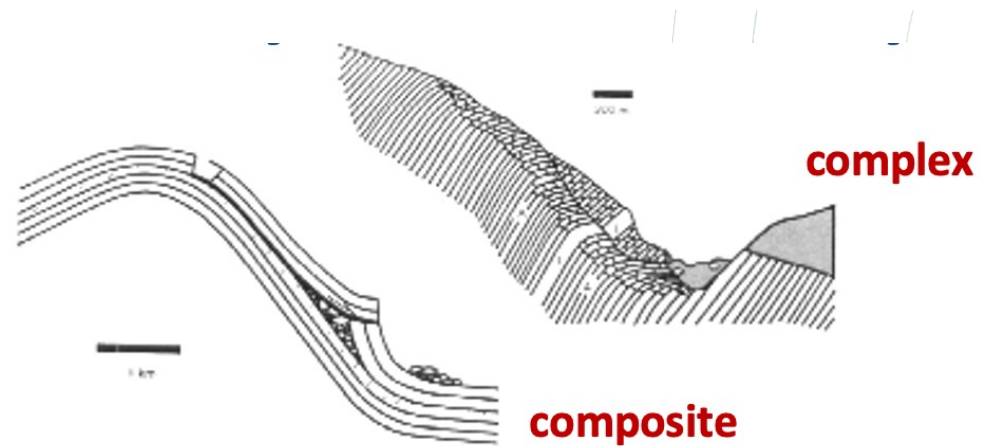


UNESCO WP/WLI (1993)

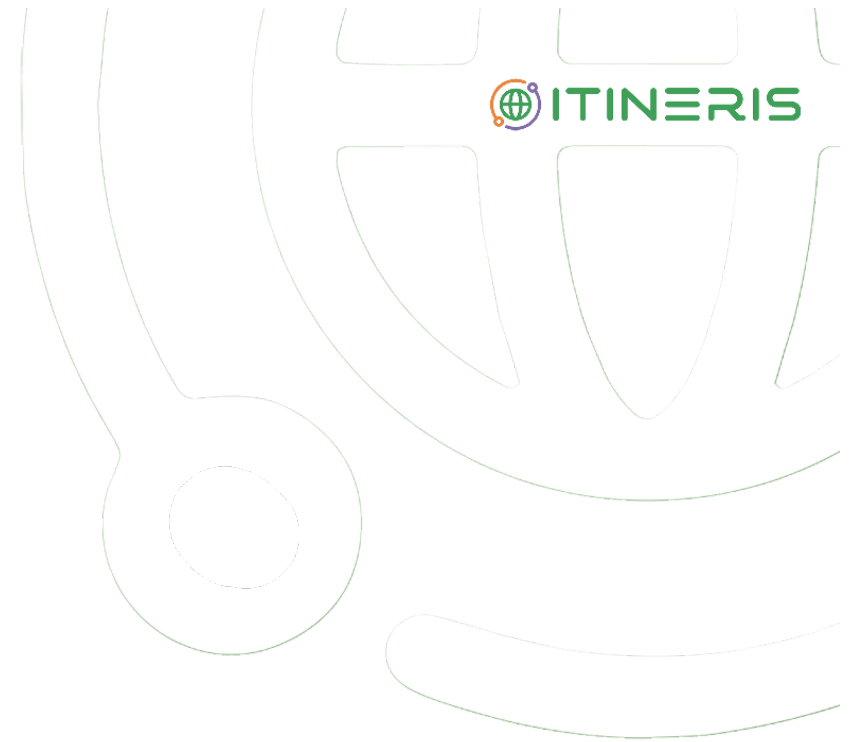
# Distribution of activity



# Style of activity



# Landslides: Classification



## Varnes (1978)

Type of movement	Type of material		
	Rock	Debris	Earth
<b>Fall</b>	Rock fall	Debris fall	Earth fall
<b>Topple</b>	Rock topple	Debris topple	Earth topple
<b>Rotational slide</b>	Rock slump	Debris slump	Earth slump
<b>Translational slide</b>	Rock slide	Debris slide	Earth slide
<b>Lateral spread</b>	Rock spread	Debris spread	Earth spread
<b>Flow</b>	Rock flow	Debris flow	Earth flow
<b>Complex</b>	Combination of two or more principal types of movements		

## Cruden & Varnes (1996)

- A landslide is classified considering a combination of descriptive terms related to the activity and the characteristics of 2 movement types:
  - activity state / activity distribution / activity style
  - type / material / water content and velocity of the **first movement**
  - type / material / water content and velocity of eventual **second movement**
- It is considered as the **first movement**:
  - for the **complex activity style** the movement that takes place first
  - for the **composite activity style** the movement at topographically higher altitude
- Example of complete classification of a landslide (Frank Slide, Canada)  
**complex, extremely rapid, dry, rock-fall debris-flow**  
 Note: The term "complex" indicates that first the rock fall occurred and then the debris flow.

## Cruden & Varnes (1996)

Type of movement	Material	Water content	Velocity
Fall	Rock	Dry	Extremely slow
Topple	Debris	Moist	Very slow
Rotational slide	Earth	Wet	Slow
Translational slide		Very wet	Moderate
Spread			Rapid
Flow			Very rapid
			Extremely rapid

## Frank slide (Canada)



 ITINERIS

**complex, extremely  
rapid, dry, rock-fall  
debris-flow**

# Sassa geotechnical classification

Type of shear

- I. Slide
  - A. peak strength slide
  - B. residual strength slide
- II. Liquefaction
- III. Creep

Grain size of material

- I. Rock ( $d > 20$  mm)
- II. Sandy soil ( $0.074 < d < 20$  mm)
- III. Clayey soil ( $d < 0.074$  mm)

Type of motion

- I. Fall
- II. Slide
- III. Flow

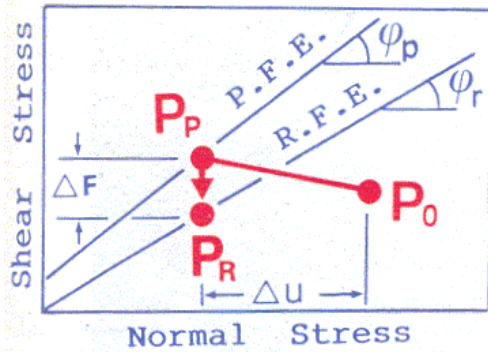


Kyoji Sassa (1989)

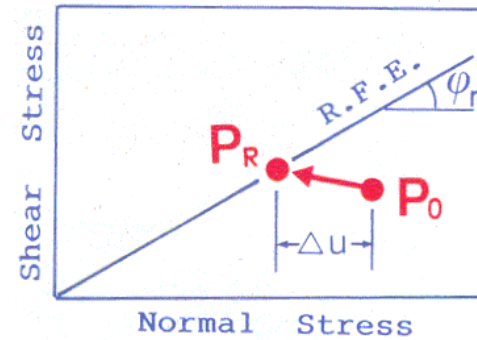


# Sassa geotechnical classification

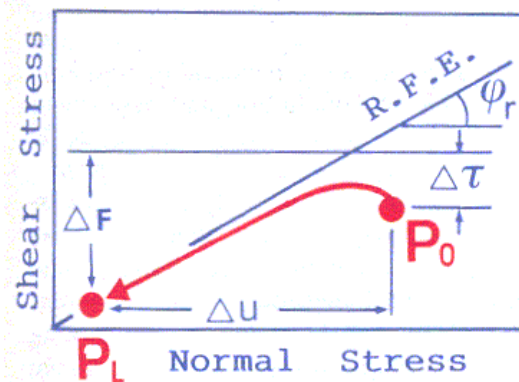
IA. Peak strength slide



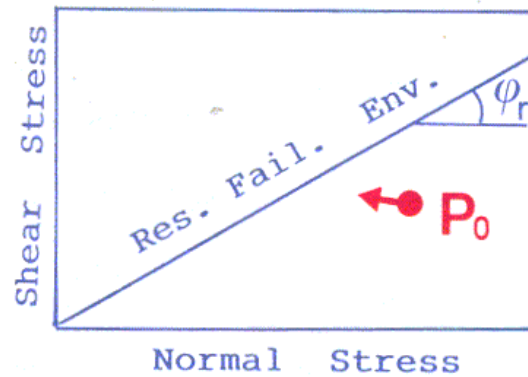
IB. Residual strength slide



II. liquefaction



III. creep



# Hungr et al. (2014)

Oldrich Hungr · Serge Leroueil · Luciano Picarelli

## The Varnes classification of landslide types, an update

Landslides (2014) 11:167–194  
 DOI 10.1007/s10346-013-0436-y  
 Received: 22 April 2013  
 Accepted: 23 September 2013  
 Published online: 30 November 2013  
 © Springer-Verlag Berlin Heidelberg 2013

Oldrich Hungr  
 (Canada)

2015 Varnes Medal



# Hungr et al. (2014)

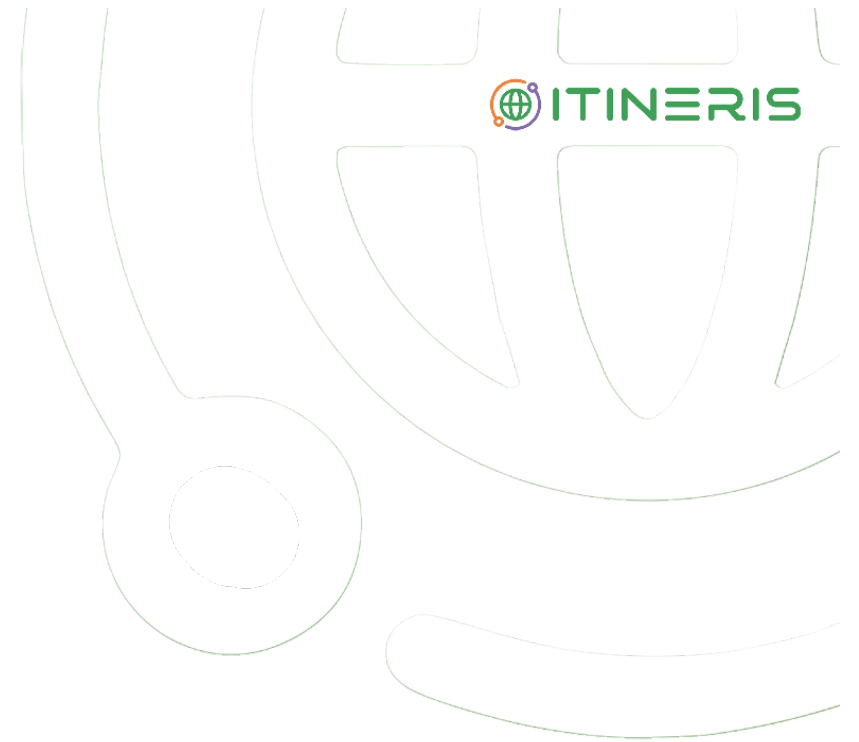
**Table 5** Summary of the proposed new version of the Varnes classification system. The words in italics are placeholders (use only one)

Type of movement	Rock	Soil
Fall	1. <i>Rock/ice</i> fall <sup>a</sup>	2. <i>Boulder/debris/silt</i> fall <sup>a</sup>
Topple	3. Rock block topple <sup>a</sup>	5. <i>Gravel/sand/silt</i> topple <sup>a</sup>
	4. Rock flexural topple	
Slide	6. Rock rotational slide	11. <i>Clay/silt</i> rotational slide
	7. Rock planar slide <sup>a</sup>	12. <i>Clay/silt</i> planar slide
	8. Rock wedge slide <sup>a</sup>	13. <i>Gravel/sand/debris</i> slide <sup>a</sup>
	9. Rock compound slide	14. <i>Clay/silt</i> compound slide
	10. Rock irregular slide <sup>a</sup>	
Spread	15. Rock slope spread	16. <i>Sand/silt</i> liquefaction spread <sup>a</sup>
		17. Sensitive clay spread <sup>a</sup>
Flow	18. <i>Rock/ice</i> avalanche <sup>a</sup>	19. <i>Sand/silt/debris</i> dry flow
		20. <i>Sand/silt/debris</i> flowslide <sup>a</sup>
		21. Sensitive clay flowslide <sup>a</sup>
		22. Debris flow <sup>a</sup>
		23. Mud flow <sup>a</sup>
		24. Debris flood
		25. Debris avalanche <sup>a</sup>
		26. Earthflow
27. Peat flow		
Slope deformation	28. Mountain slope deformation	30. Soil slope deformation
	29. Rock slope deformation	31. Soil creep
		32. Solifluction

For formal definitions of the landslide types, see text of the paper.

<sup>a</sup> Movement types that usually reach extremely rapid velocities as defined by Cruden and Varnes (1996). The other landslide types are most often (but not always) extremely slow to very rapid

# Landslides: Causes



## Preparatory and triggering causes

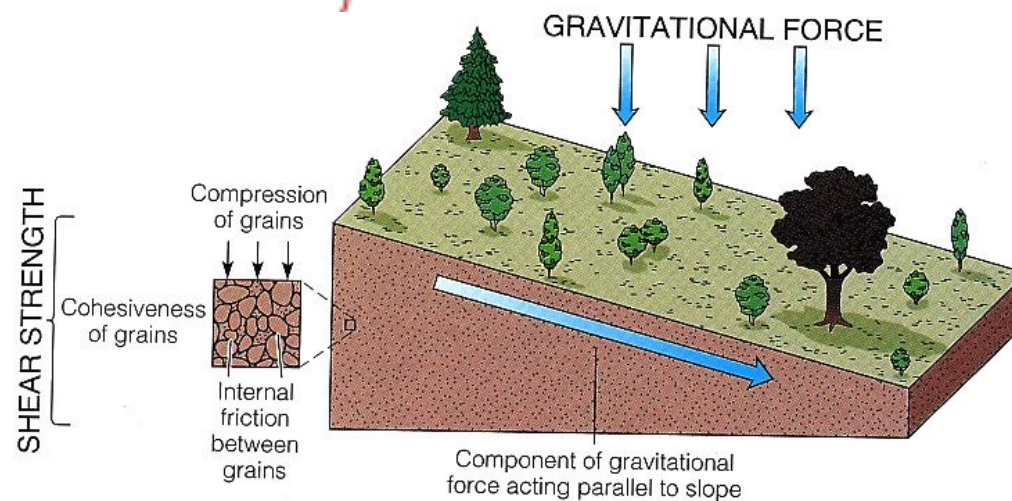
- **preparatory causes:** intrinsic instability factors, related to the lithological, structural, morphological and climatic characteristics of the area. They are relatively fixed elements, constant over time.
- **triggering causes:** transient events acting on an already weakened slope which trigger the landslide movement (eg. heavy rainfall, man-made actions earthquakes, etc.)

## Preparatory and triggering causes

Failure along a surface occurs when the forces that favor the movement (destabilizing forces) overcome the forces that oppose the movement (resistant forces), that is when:

$$F = \frac{\sum(\text{Forze resistenti})}{\sum(\text{Forze destabilizzanti})}$$

**factor of safety**



# Checklist of landslide causes

<p>1. GROUND CONDITIONS</p> <ul style="list-style-type: none"> <li>(1) Plastic weak material</li> <li>(2) Sensitive material</li> <li>(3) Collapsible material</li> <li>(4) Weathered material</li> <li>(5) Sheared material</li> <li>(6) Jointed or fissured material</li> <li>(7) Adversely oriented mass discontinuities (including bedding, schistosity, cleavage)</li> <li>(8) Adversely oriented structural discontinuities (including faults, unconformities, flexural shears, sedimentary contacts)</li> <li>(9) Contrast in permeability and its effects on ground water contrast in stiffness (stiff, dense material over plastic material)</li> </ul>
<p>2. GEOMORPHOLOGICAL PROCESSES</p> <ul style="list-style-type: none"> <li>(1) Tectonic uplift</li> <li>(2) Volcanic uplift</li> <li>(3) Glacial rebound</li> <li>(4) Fluvial erosion of the slope toe</li> <li>(5) Wave erosion of the slope toe</li> <li>(6) Glacial erosion of the slope toe</li> <li>(7) Erosion of the lateral margins</li> <li>(8) Subterranean erosion (solution, piping)</li> <li>(9) Deposition loading of the slope or its crest</li> <li>(10) Vegetation removal (by erosion, forest fire, drought)</li> </ul>

Popescu (1994) - A suggest method for reporting landslide causes

## Checklist of landslide causes

### 3. PHYSICAL PROCESSES

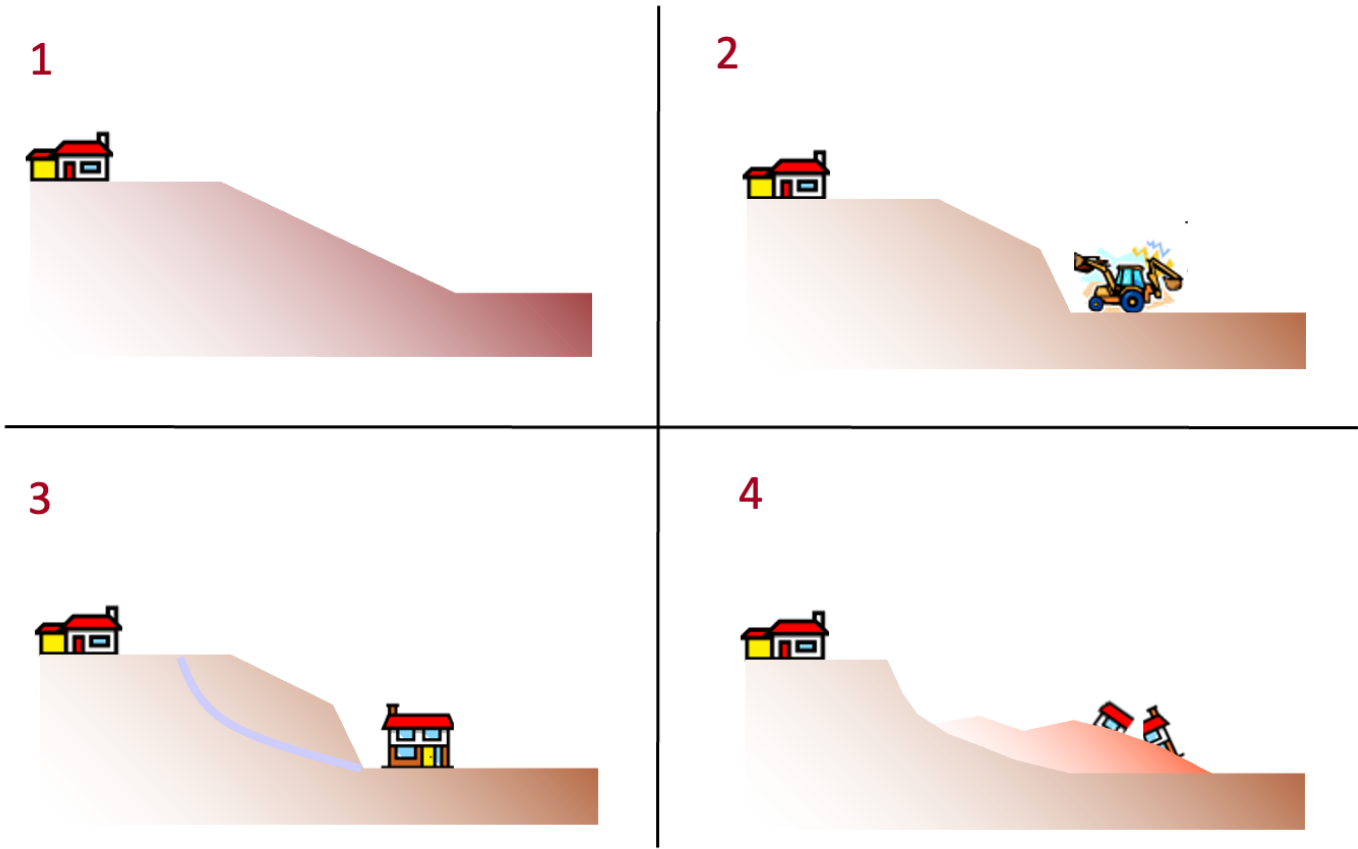
- (1) Intense, short period rainfall
- (2) Rapid melt of deep snow
- (3) Prolonged high precipitation
- (4) Rapid drawdown following floods, high tides or breaching of natural dams
- (5) Earthquake
- (6) Volcanic eruption
- (7) Breaching of crater lakes
- (8) Thawing of permafrost
- (9) Freeze and thaw weathering
- (10) Shrink and swell weathering of expansive soils

### 4. MAN-MADE PROCESSES

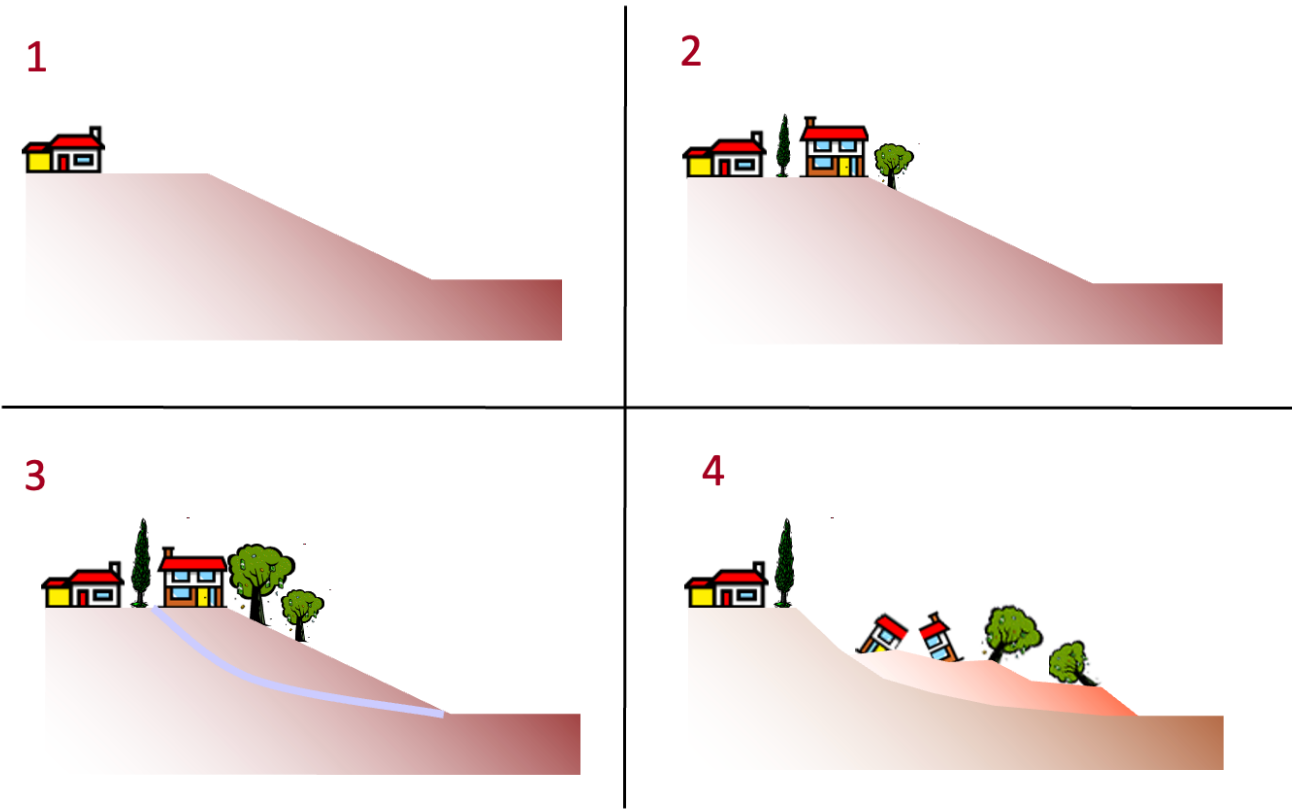
- (1) Excavation of the slope or its toe
- (2) Loading of the slope or its crest
- (3) Drawdown (of reservoirs)
- (4) Irrigation
- (5) Defective maintenance of drainage systems
- (6) Water leakage from services (water supplies, sewers, stormwater drains)
- (7) Vegetation removal (deforestation)
- (8) Mining and quarrying (open pits or underground galleries)
- (9) Creation of dumps of very loose waste
- (10) Artificial vibration (including traffic, pile driving, heavy machinery)

Popescu (1994) - A suggest  
method for reporting  
landslide causes

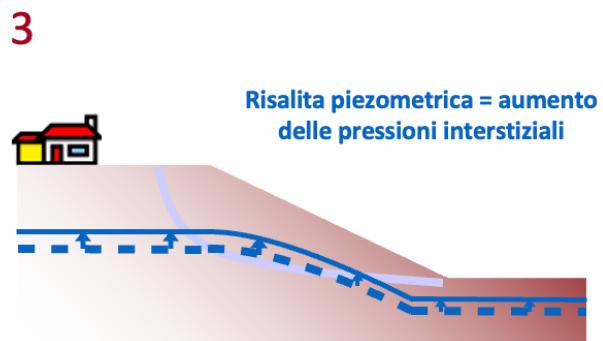
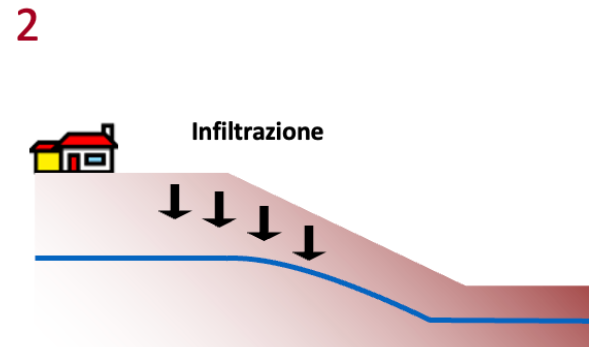
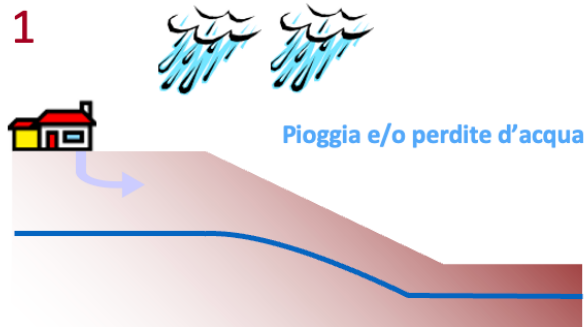
# Excavation of slope toe



# Loading of the slope crest



# Rainfall infiltration

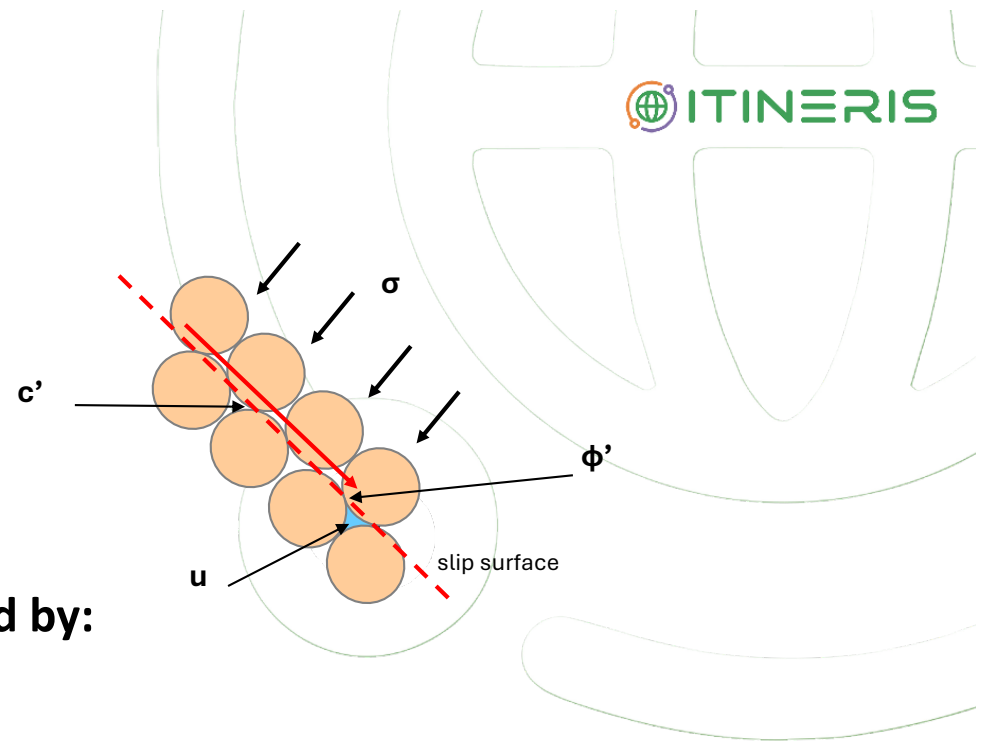


## Shear strength reduction

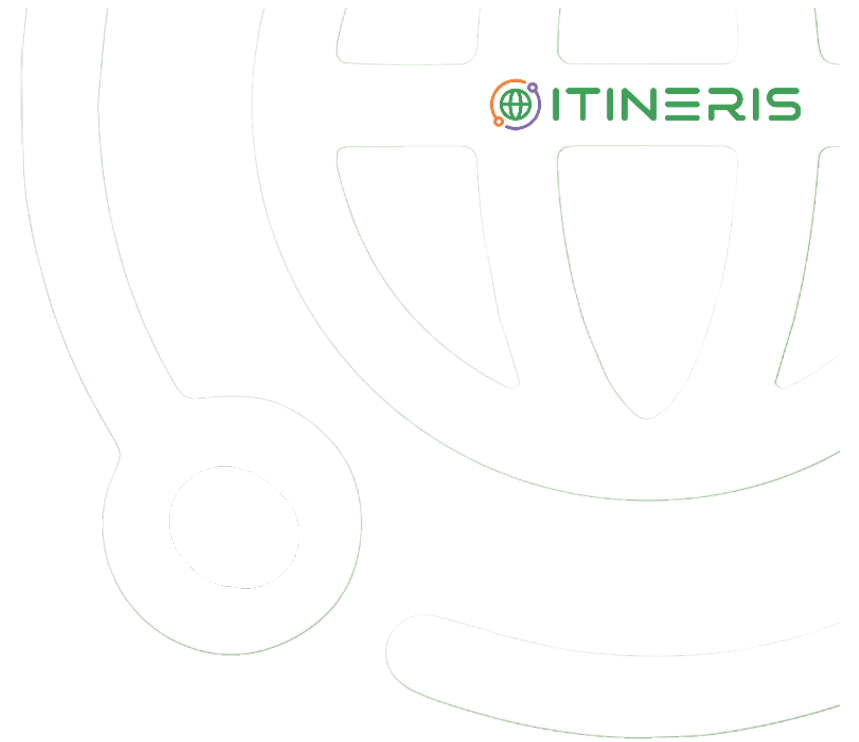
$$\tau = c' + (\sigma - u)\tan\phi'$$

**A reduction of shear strength can be caused by:**

- reduction of the normal stress ( $\sigma$ ) on the potential slip surface
- increase in pore water pressure ( $u$ )
- reduction of friction angle ( $\phi'$ )
- reduction of cohesion ( $c'$ )



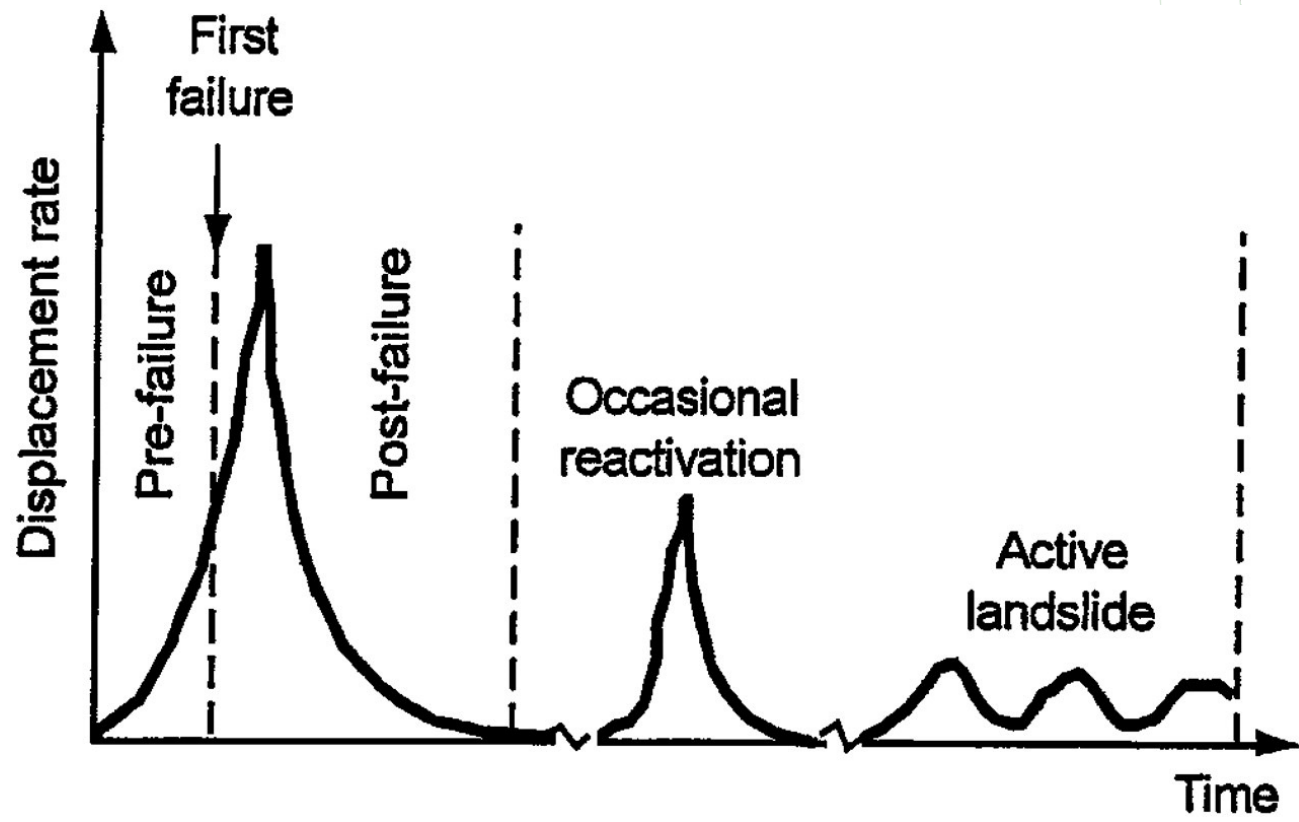
# Landslides: Effects



## Failure mechanism

Mechanism	Material	Strength	Failure	Frequency	Intensity /velocity
First-time slide	material that previously was not affected by shear failure	Peak	Fragile	Low (not frequent)	High
Reactivated slide	pre-existing shear surfaces that may be given by previous landslides, tectonics (faults, shear bands, folds), induced by stress relief, glacial or periglacial processes	Residual	Ductile	High (very frequent)	Low
Liquefaction	water-saturated, unconsolidated sediments are transformed into a substance that acts like a liquid, due to rise of pore water pressure and reduction of effective stress to zero	Zero	Flow-like	Very low (rare)	Very high
Creep	long-term slow viscous permanent deformation under the influence of constant stress	Deformation at stress level below peak strenght	Deformation without failure	Continuous	Very low

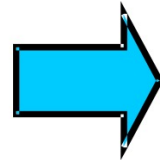
# Failure mechanism



Fell (2007)

# Impact and consequences

**Rapid long run out landslides**  
 Caused by earthquakes and heavy rainfalls

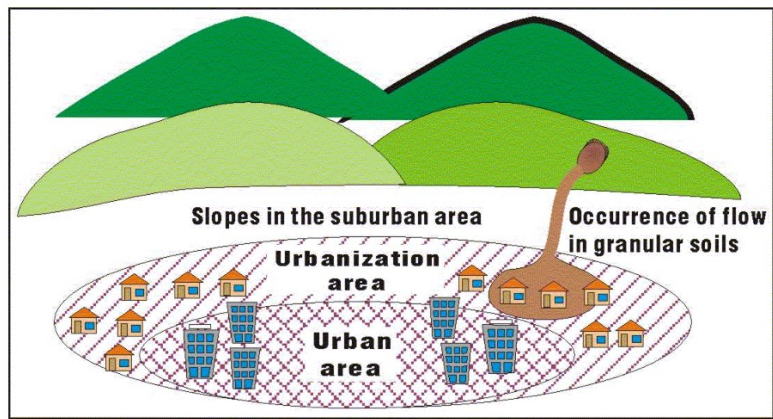


- Characteristics**
- Rapid Motion
  - Great Impact Force
  - Wide Disaster Area



**Great number of death**

	Rapid - velocity -	Slow
Long run-out distance	Rapid long run-out landslides (liquefied slides, etc)	slow long - traveling landslides (Earth flows, etc)
short-moving landslides	Rapid short-moving landslides (first-time slides)	Slow short-moving landslides (reactivated landslides)



Kyoji Sassa (2001)

# Impact and consequences

## Rapid Long-Runout

- Liquefaction
- Debris flows
- Debris avalanches
- Rock avalanches



## Rapid Short-runout

- First-time slides
- Falls
- Topple
- Rockslides



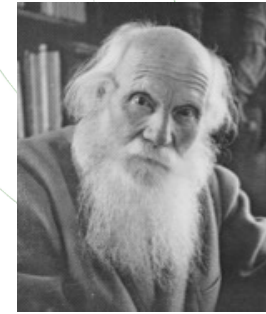
## Slow Long-runout

- Earth flows
- Mudflows
- Mudslides

## Slow Short-runout

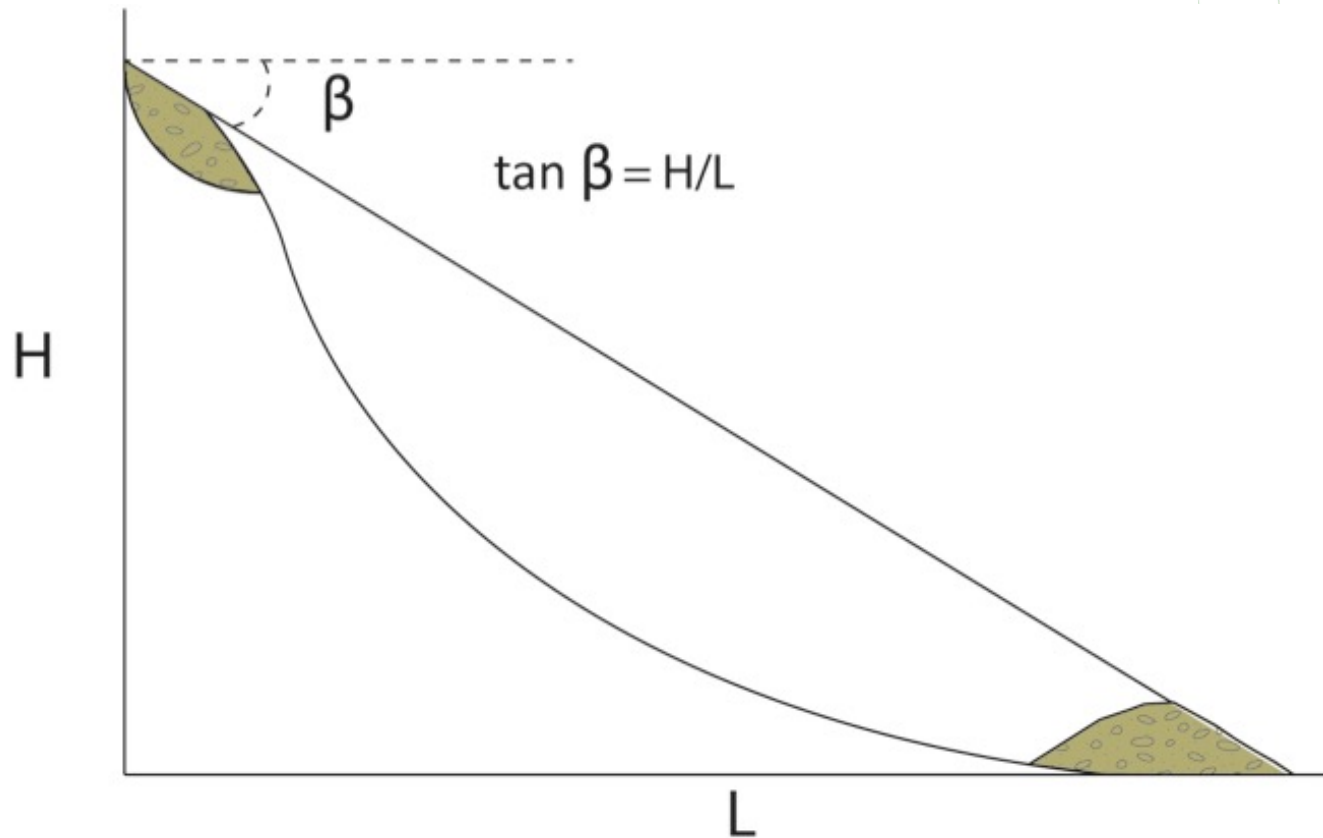
- Reactivated slides





Albert Heim (1932)

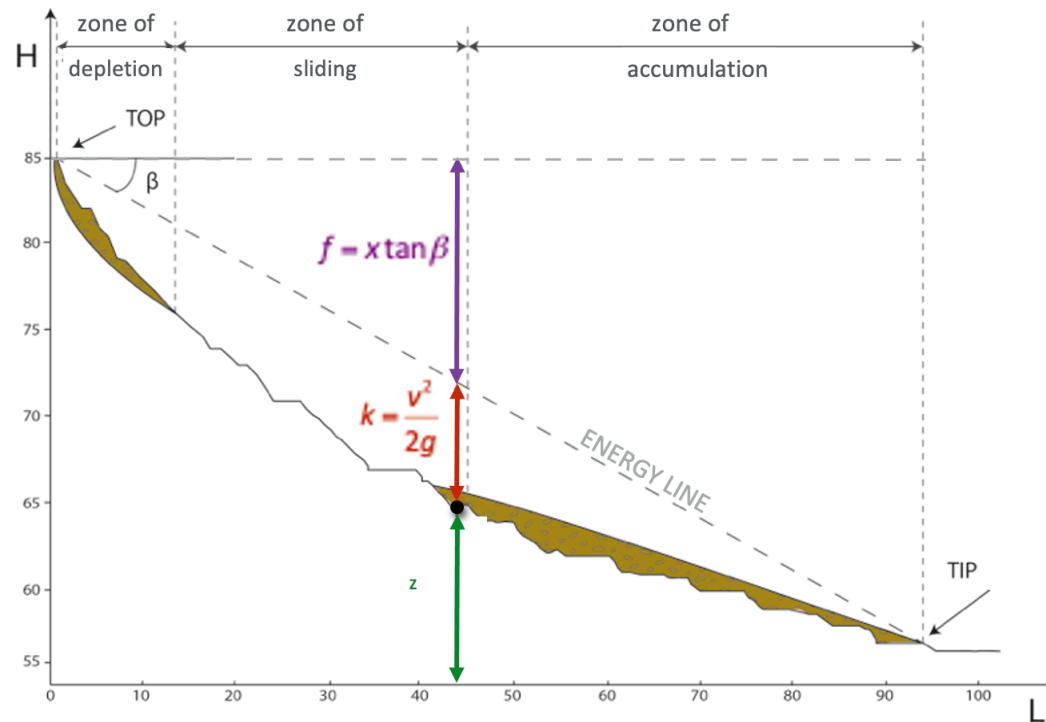
## Travel angle



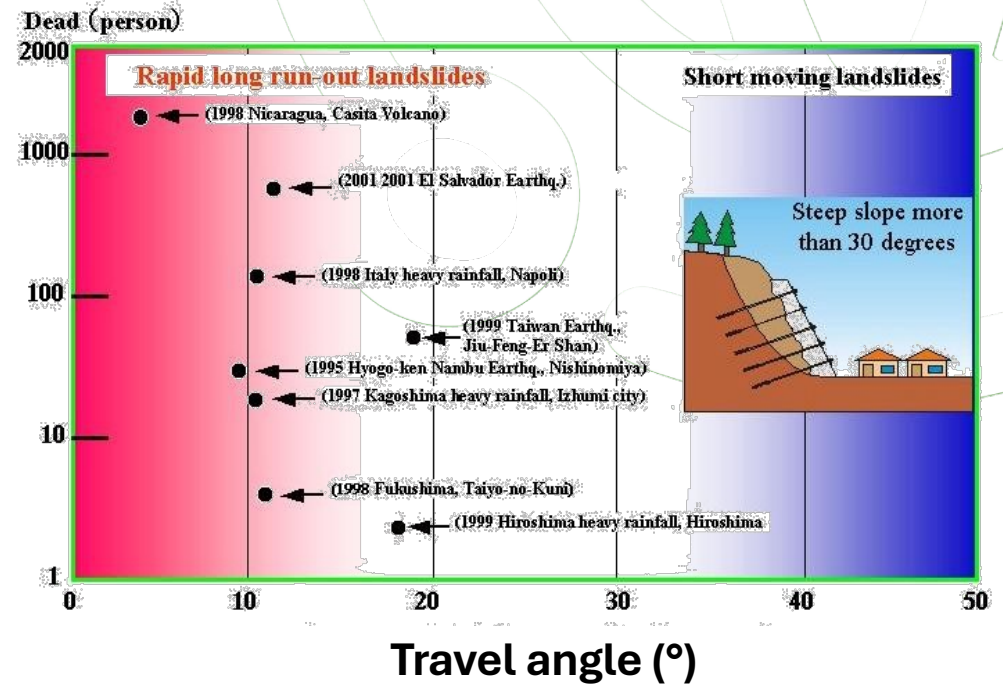
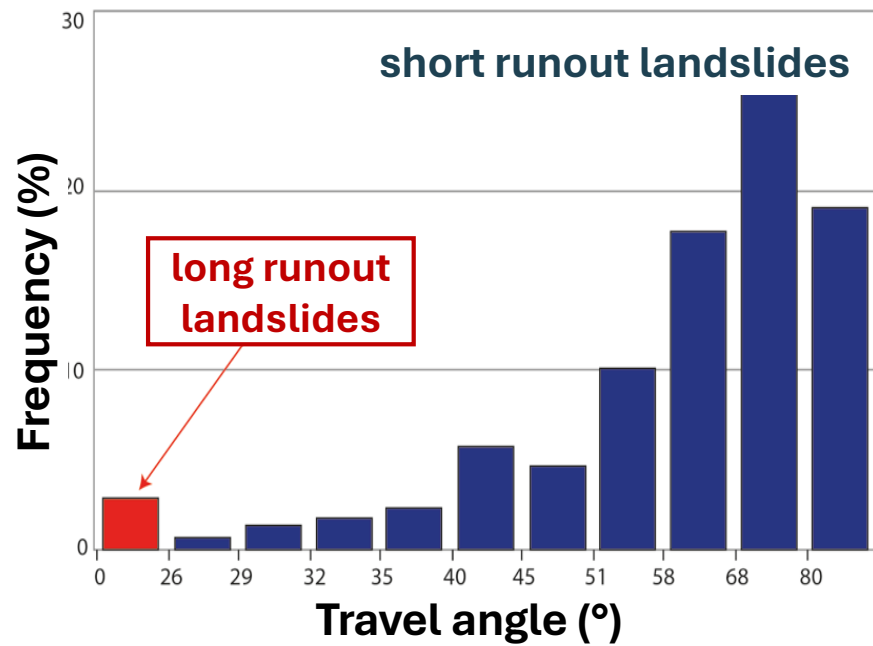
# Energy line model

Potential energy + Kinetic energy + Friction energy dissipation = constant

$$z + \frac{v^2}{2g} + x \tan \beta = \text{constant}$$



# Travel angle and risk for human life





# THANKS!

**IR0000032 – ITINERIS, Italian Integrated Environmental Research Infrastructures System**  
(D.D. n. 130/2022 - CUP B53C22002150006) Funded by EU - Next Generation EU PNRR-  
Mission 4 “Education and Research” - Component 2: “From research to business” - Investment  
3.1: “Fund for the realisation of an integrated system of research and innovation infrastructures”



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