Slope stability
Stateczność zboczy

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Slope stability

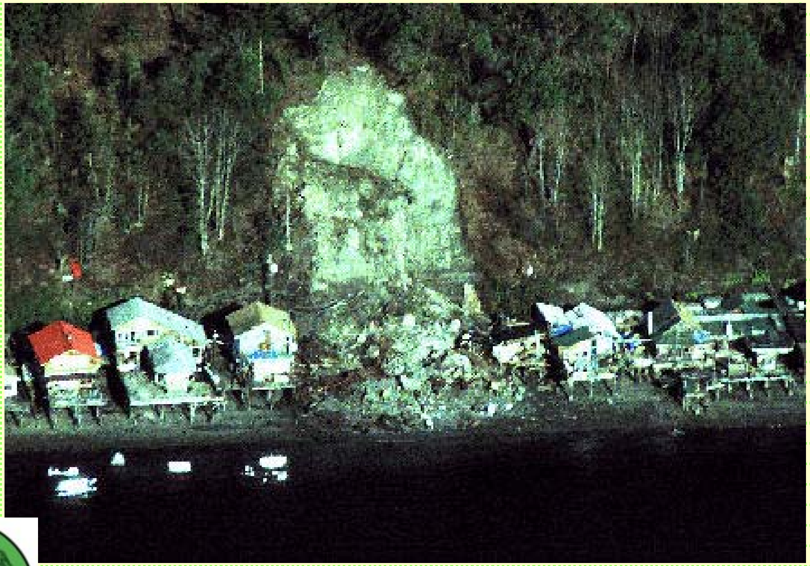
Regions of high landslide risk

- Landslides & other mass movement are ubiquitous
- Promoted by
  - appropriate lithology
  - steep/elevated terrain
  - heavy and intense precipitation
  - earthquakes
- Vulnerability increased by
  - increasing population density
  - use of marginal land
  - rapid land-use change
  - global warming
- Most vulnerable regions
  - Pacific rim (e.g. Japan, Peru, Taiwan, California)

Zermatt (Switzerland) mid -1990s

Slope stability

Landslide hazard impacts



- Injury & loss of life
- Property damage & communication problems
- Social & economic disruption
- Loss of productive land
- Annual economic losses
  - USA >2 billion US$
  - Japan ~4 billion US$
- 1999 Venezuela debris flows ~ 50,000 dead
  - 10 billion US$
  - 10.2% of GDP
- 2000 Swiss & Italian landslides and debris flows ~ 8. 5 billion US$

Slope stability

Major slope-instability related catastrophes of the 20th century

Kansu (China)	1920	Loess flow	200,000 killed
Gros Ventre (Wyoming)	1925	Rockslide	~40 killed
Madison (Montana)	1959	Rockslide	>100 killed
Vaiont (Italy)	1963	Rockslide	2,600 killed
Aberfan (Wales)	1966	Debris-slide	144 killed
Huascaran (Peru)	1970	Complex	25,000 killed
Nevado del Ruiz (Colombia)	1985	Debris flow	23,000 killed
Casitas (Nicaragua)	1998	Debris flow	+2,000 killed
Venezuela	1999	Complex	+20,000 killed
Swiss/Italian Alps	2000	Debris flow	38 killed

Slope stability

Types of mass movement

- Landslide: loose term that encompasses wide range of gravity-dominated mass movement processes that transport material downslope
- 3 main categories of mass movement:
  - Falls
  - Flows
  - Slides
- All three can involve rock, debris, or soil

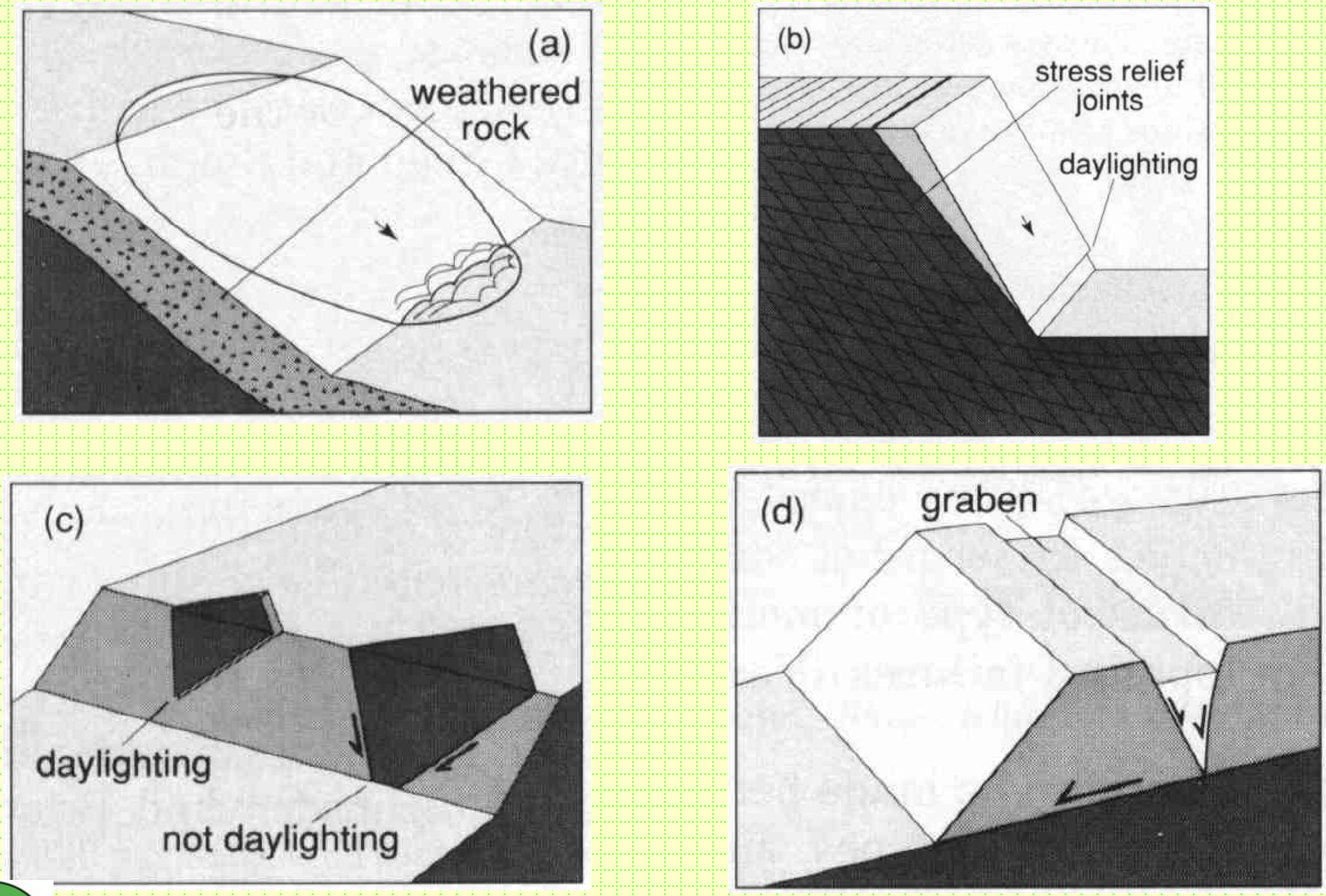
Gros Ventre (Wyoming)

Slope stability

Classification of mass movement

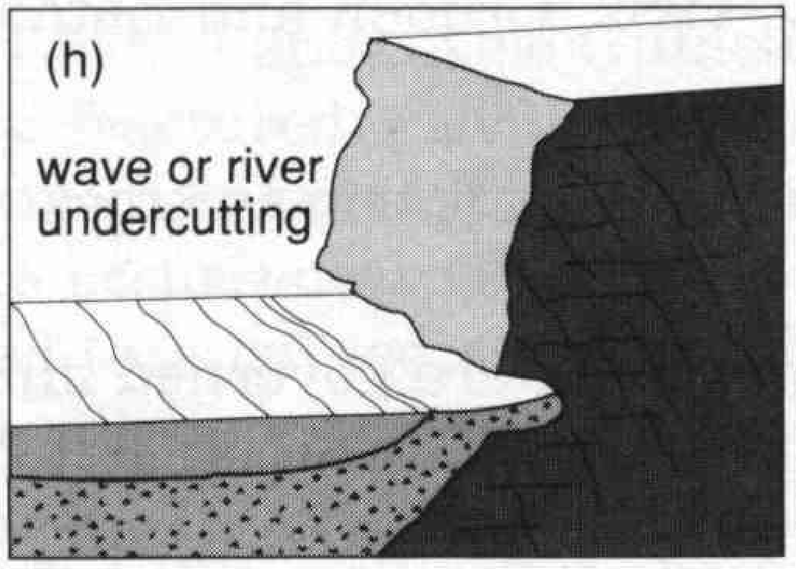
Movement	*Rock*	*Debris*	*Soil*
Fall	Rock fall	Debris fall	Soil fall
Topple	Rock topple	Debris topple	Soil topple
Slide			
Rotational	Rock slide	Debris slide	Soil slide
Slide			
Translational	Block slide	Block slide	Slab slide
Spread	Rock spread	Debris spread	Soil spread
Flow	Rock flow Rock avalanche	Debris flow	Soil flow

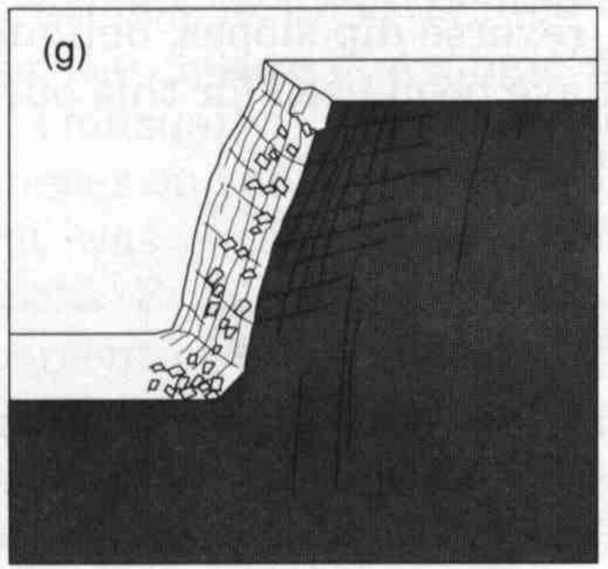
Slope stability

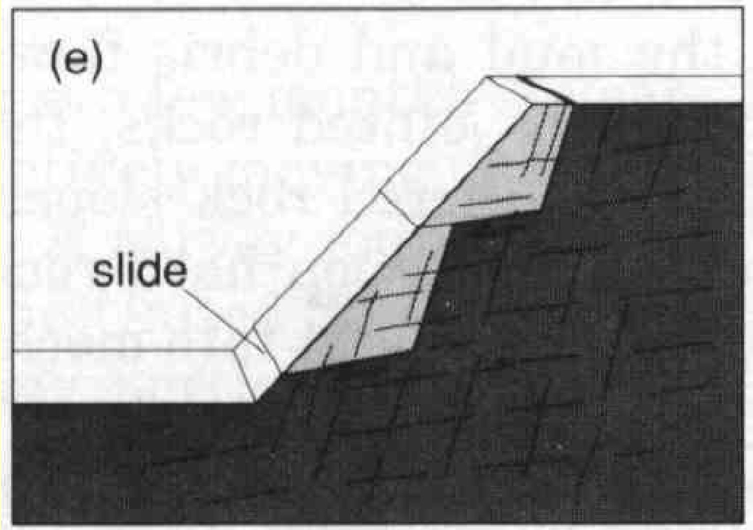


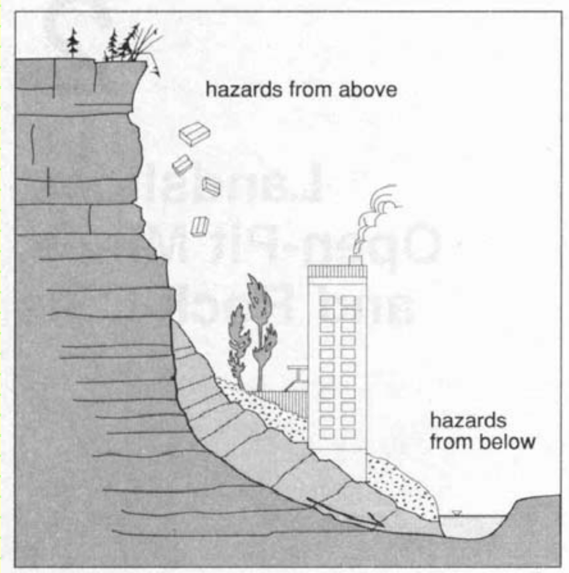
Slope stability

Slope stability

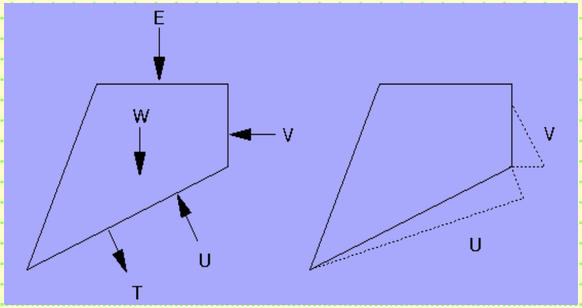


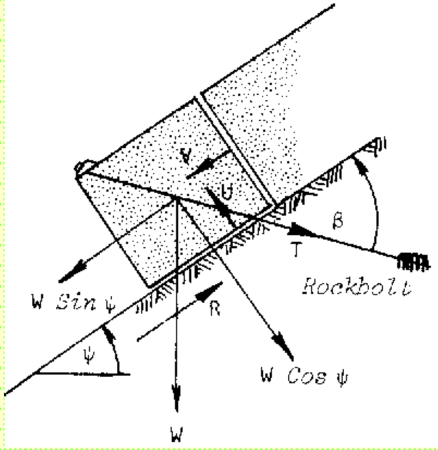


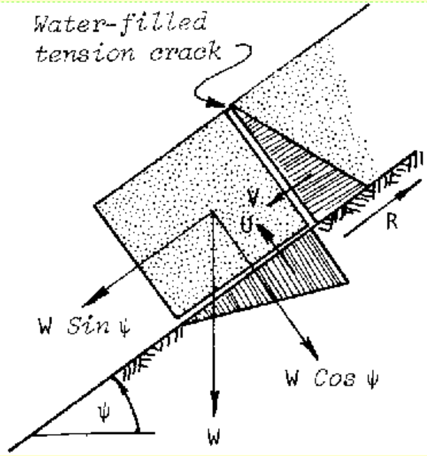


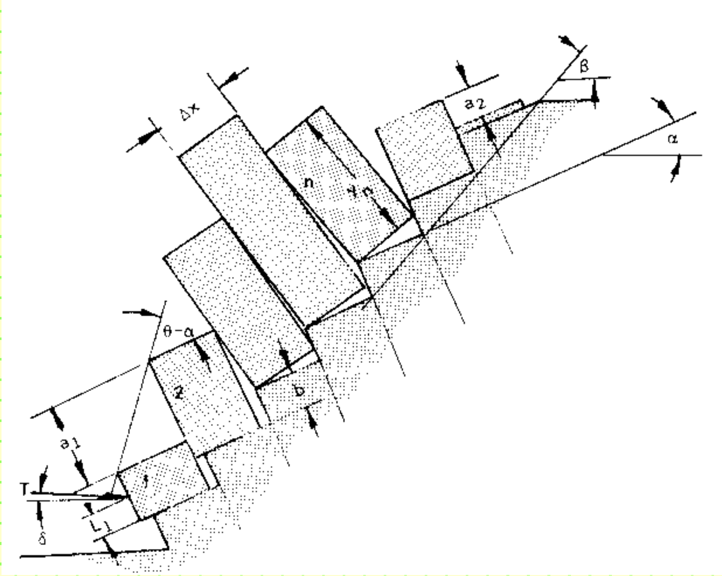


Slope stability









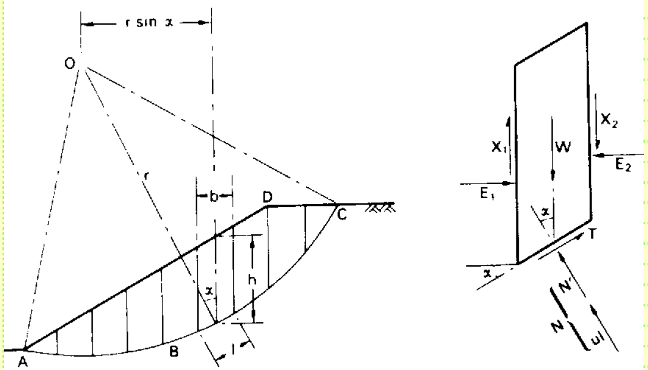
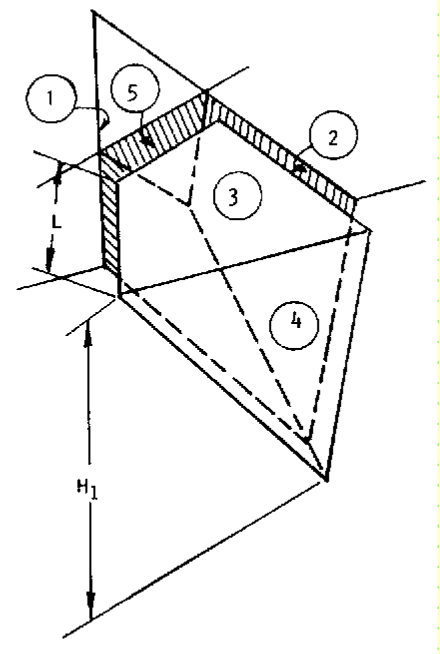


Fig. 9.5 The method of slices.



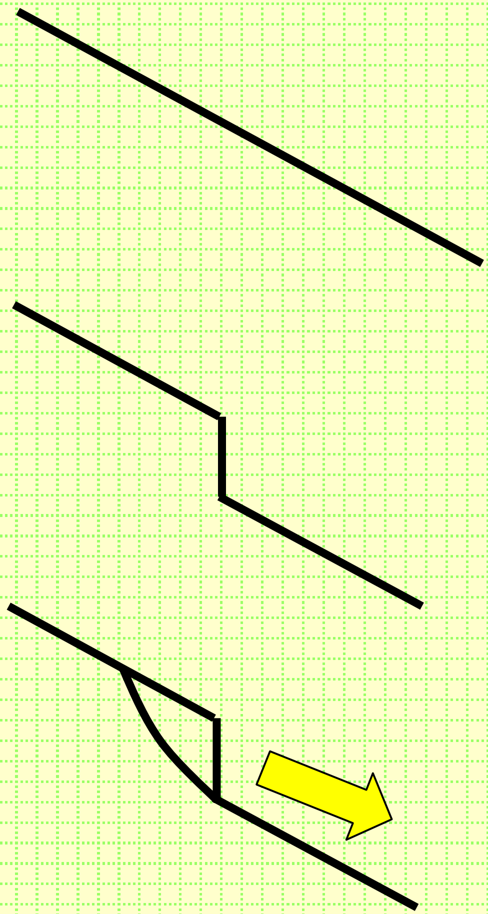
Slope stability

Why mass movement occurs

Stable slope

Slope steepened beyond threshold angle of stability

Stability restored by failure



- Mass movement occurs wherever a slope is steepened beyond its threshold angle of stability
- The steepest angle at which a slope can maintain itself
- At higher angles a slope will restore stability by failing
- A slope can be destabilized by external (exogenic) and internal (endogenic) factors

Slope stability

Exogenic destabilising factors

- slope steepening or heightening
  - erosion
  - tectonism (faulting, uplift)
  - human activities (grading)
- removing lateral or underlying support
  - river erosion
  - cutting construction
- slope loading
  - construction
  - previous mass movement

Slope stability

Endogenic destabilising factors

- Weathering
  - weakens slope material and reduced its resistance to gravity-induced movement
- Vegetation loss
  - reduced binding effect of plant roots; may account for 90% of stability of some slopes
- Soil saturation
  - due to vegetation loss or increased run-off due to urbanisation
  - results in elevated pore water pressure that exerts a positive internal force

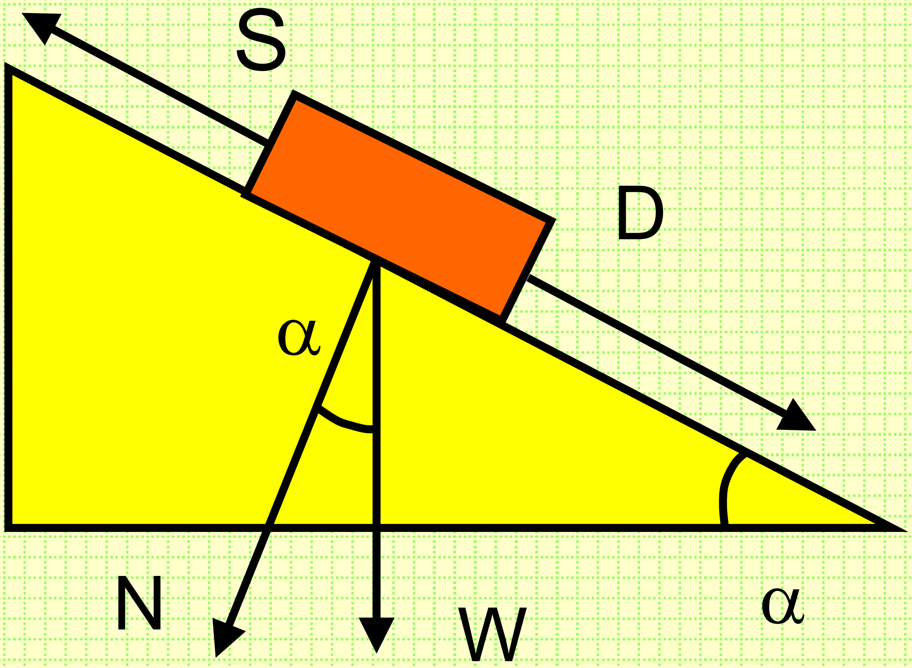
Slope stability

The mechanics of instability development

- All slopes under constant stress due to gravity
- Exogenic and endogenic factors together
  - change the balance of forces acting on a slope allowing stress (driving force) to overcome material strength of the slope (resisting force)
- Once this happens a slope will fail and start to move
- MATERIAL STRENGTH (Shear Strength) = maximum resistance to *shear stress*. Depends on 2 factors:
  - Internal cohesion (depends on weight above)
  - Internal friction (determines angle of rest)
- Exogenic factors lead to an increase in shear stress
- Endogenic factors lead to a reduction in shear strength (shear resistance)

Slope stability

Relationship between driving & resisting force



Weight of a block (W) resolved at an angle (α) parallel to the slope, creates a shear stress or driving force (D)

Sliding is resisted by the shear strength (S) - a function of the cohesion of the material and the static friction between block & slide plane, which increases as the normal force (N) increases

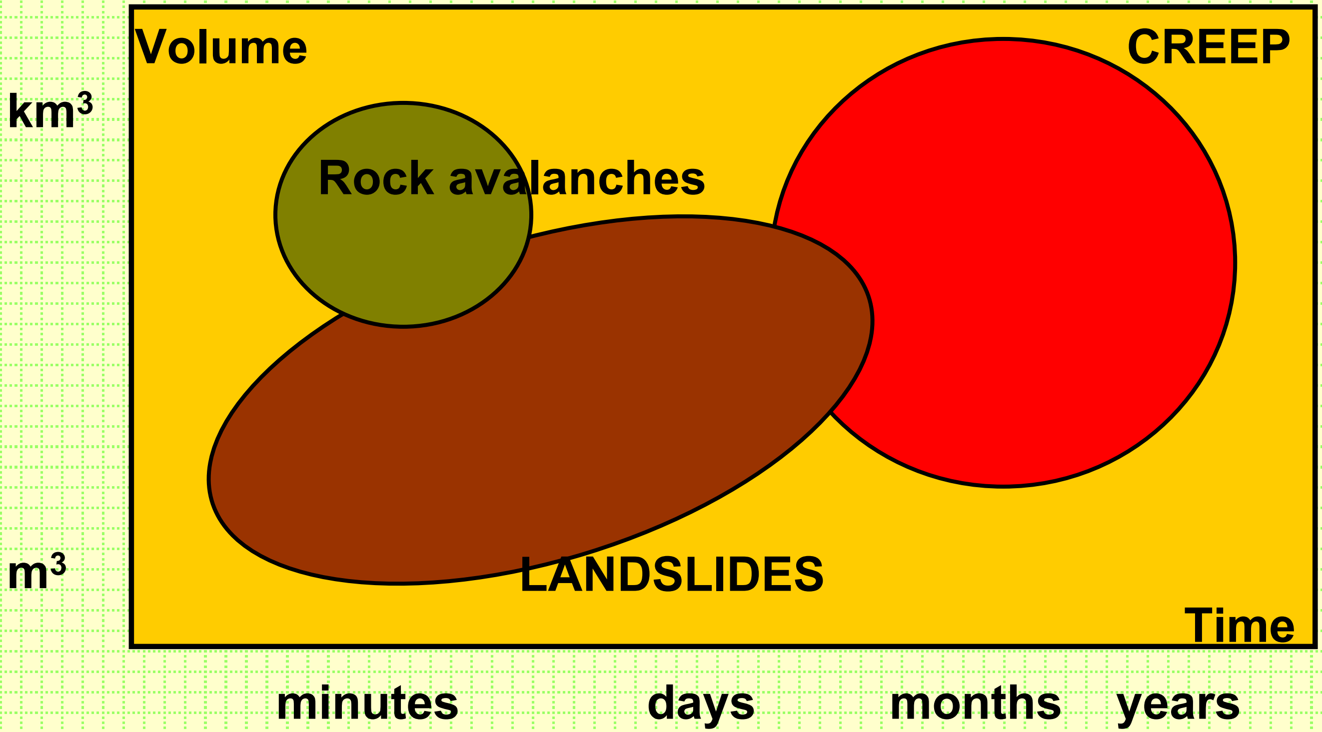
The block will remain in place as long as the driving force does not exceed this combined shear strength

Triggering slope movement

- Once a slope has been destabilized, failure can be triggered
- This may be near-instantaneous (rock avalanche or debris flow) or slow acting (creeping slump)
- Quake-related ground shaking
  - (usually M 3-4 or greater)
- Intense precipitation
  - raise pore fluid pressure
  - fluidize slope material
- lateral pressure
  - ice in fractures
  - dyke intrusion

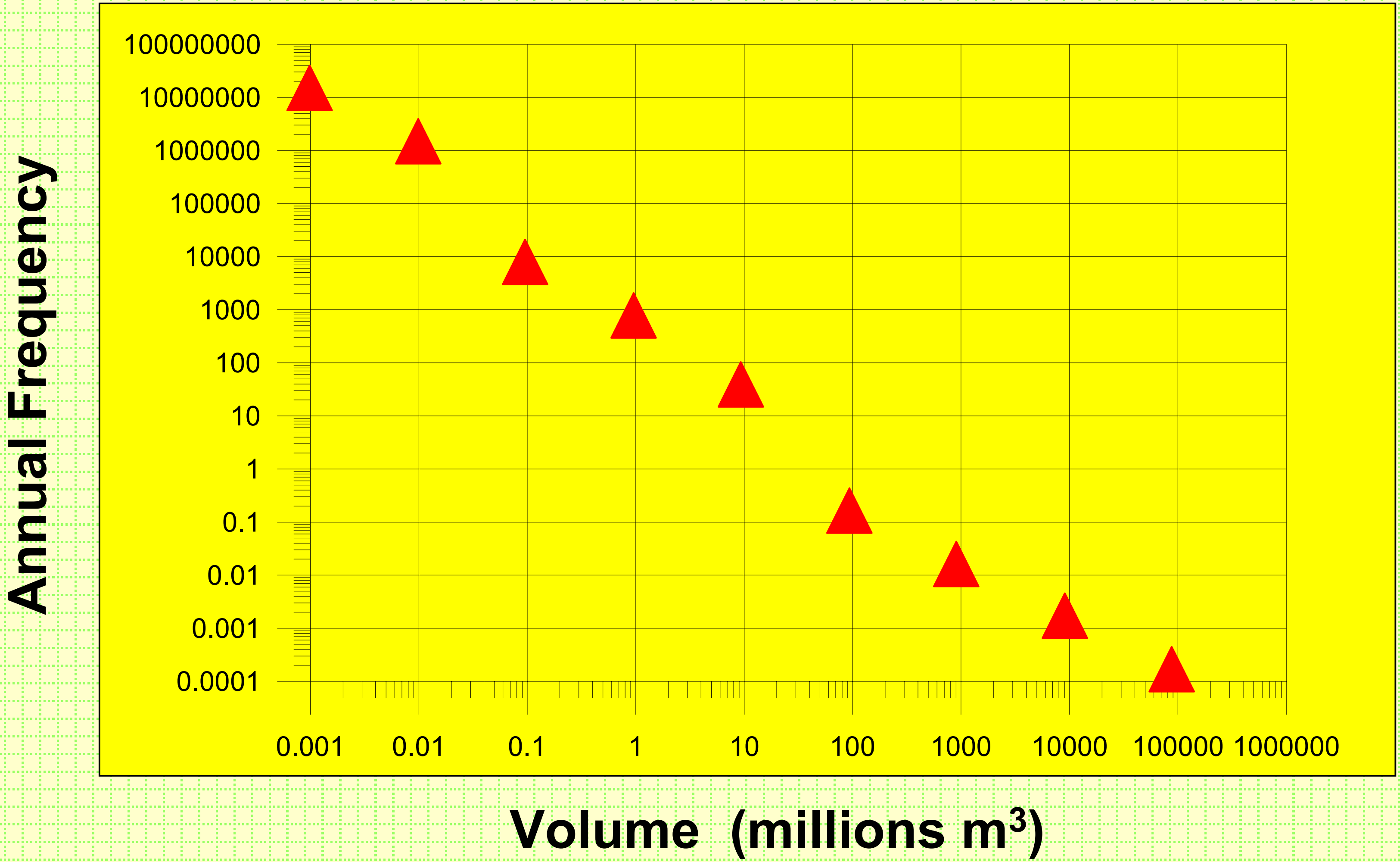
Slope stability

Mass movement hazards: scales and velocities



Slope stability

Mass movement hazards: frequencies and volumes



Slope stability

Focus on landslides

La Conchita (California)
Northridge quake 1994

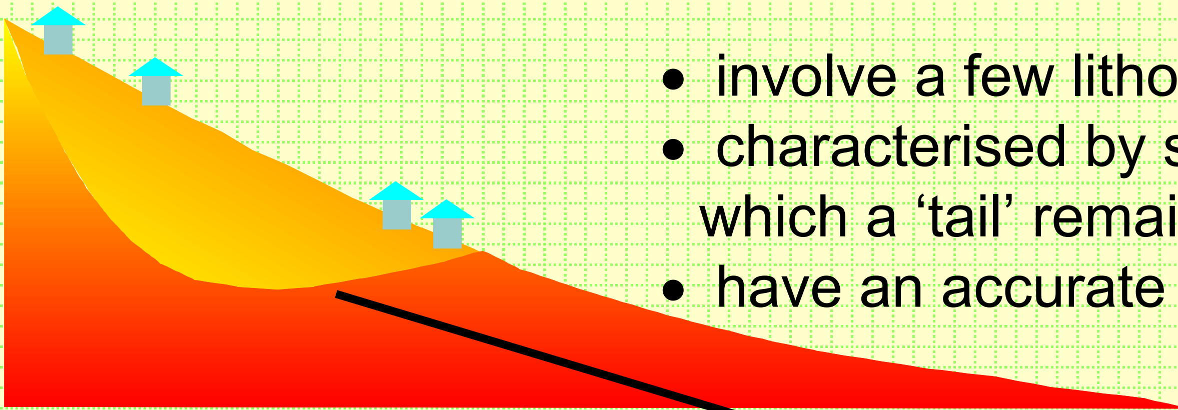
- Slide refers to movement of coherent body over a basal discontinuity or shear surface (weak level of rock or soil)
- Principal types
  - Rotational
  - Translational
- Volumes often 100,000 m^3 or less but can reach 1000 km^3
- Often reactivated and may work back up slope
- Typically travel metres in hours/days but can be slower and much faster

Slope stability

Rotational landslides

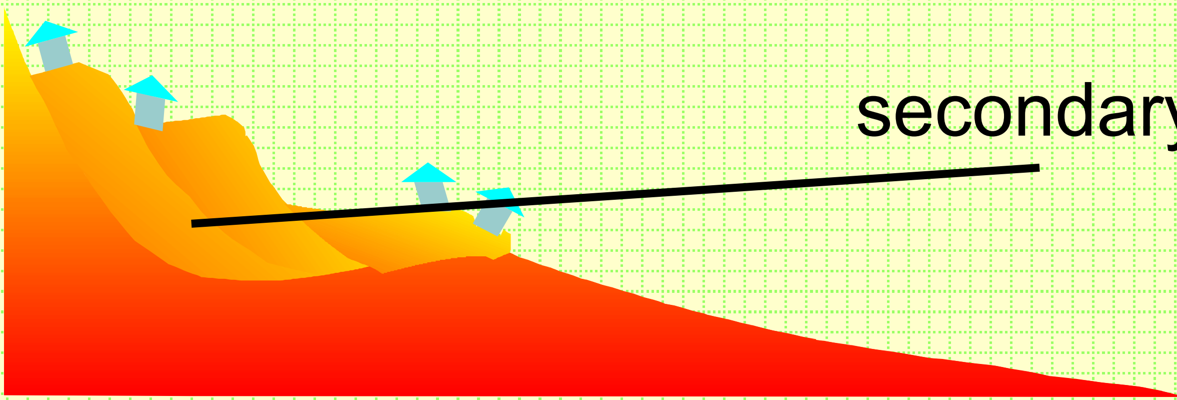
Typically:

- involve a few lithological units
- characterised by slump morphology in which a 'tail' remaining in a scar
- have an accurate failure surface(s)



principal shear plane

secondary shear planes

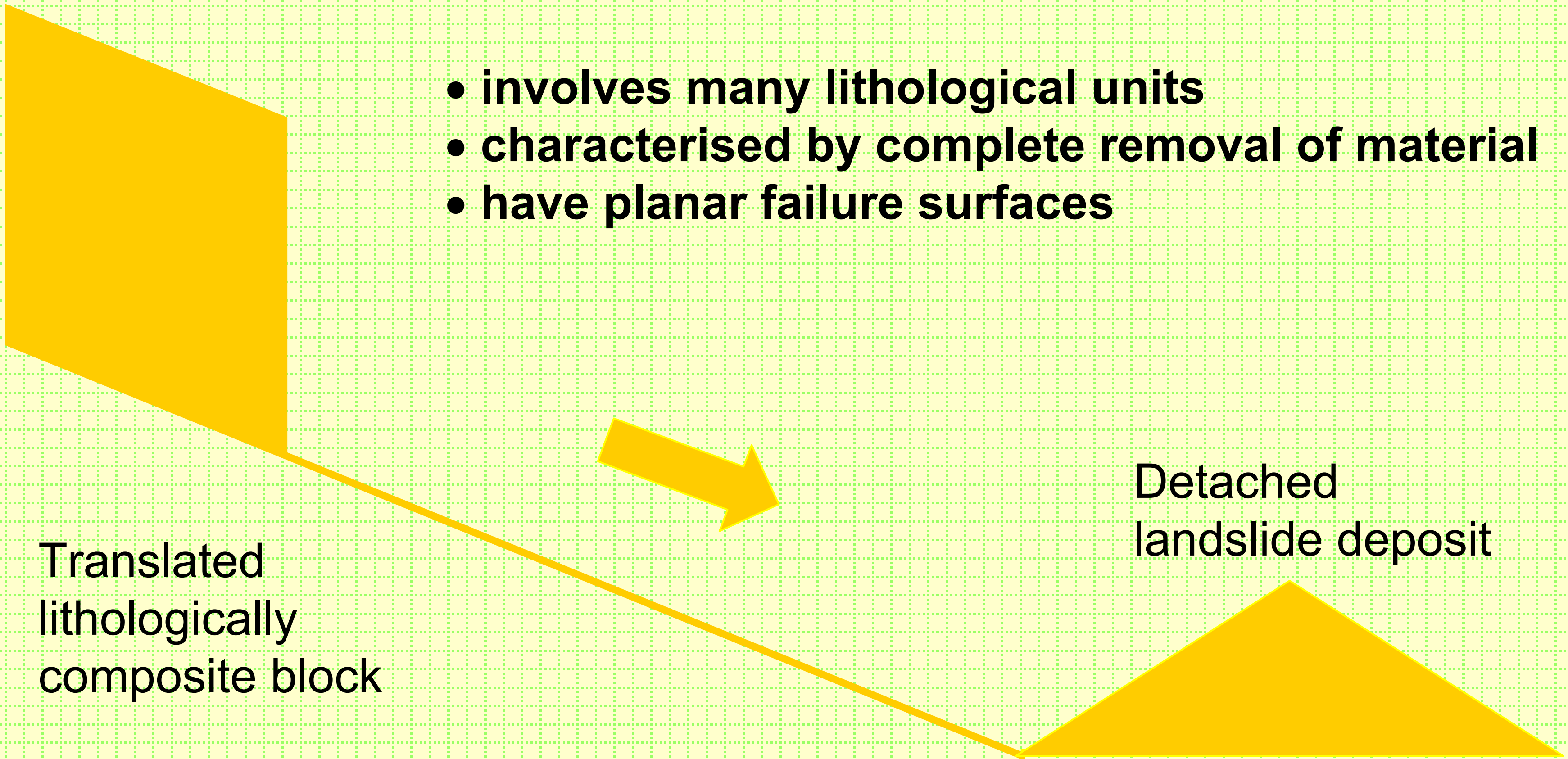


Slope stability

Translational landslides

Typically:

- **involves many lithological units**
- **characterised by complete removal of material**
- **have planar failure surfaces**



Slope stability

Giant rock avalanches

Kofels slide (Austria)

- Extreme landslide events
- Volumes of 100,000 m^3
- Velocities are very high ~ 100 m/s due to very low coefficients of friction
- Travel kilometers in a few minutes
- 1-2 per decade
- Transport mechanism problematical
  - originally thought travelled on cushion of compressed air

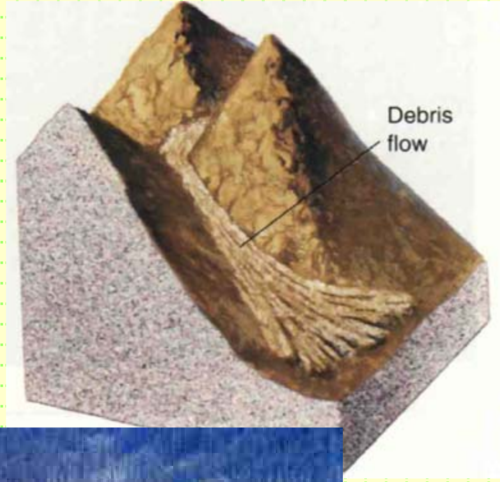
Slope stability

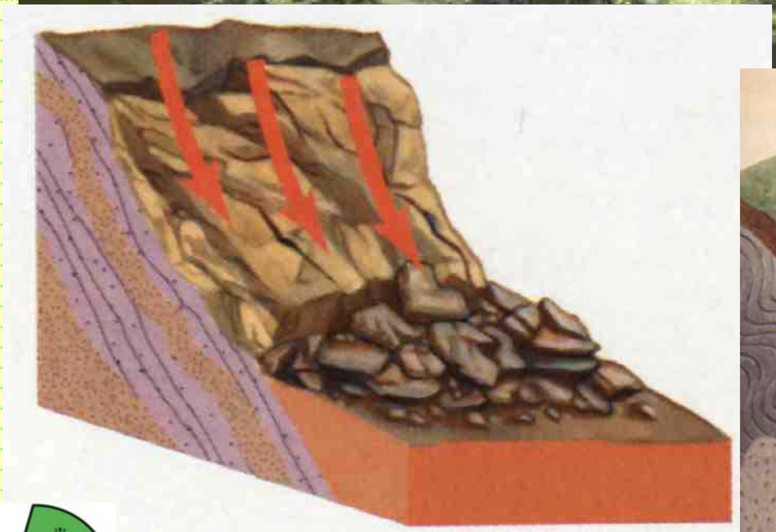
Giant rock avalanches

- Only about 100 described in literature
- Few first-hand observations
- Occur in all types of rock
  - Young Mountains
  - Volcanoes
- Can be natural or triggered by human activities
  - Vaiont (Italy) 1963
- Total destruction: no mitigation feasible except evacuation

Vaiont (Italy) 1963

Slope stability





Slope stability

Rock avalanches: historic & prehistoric

Name	*L (km)*	*V (km^2)*	*Killed*	*Country*
Elm, 1881	2.3	0.01	115	Switzerland
Huascarán, 1970	16.5	0.07	18,000	Peru
Vaiont, 1963	1.5	0.25	2,000	Italy
Mayunmarca, 1974	8.2	1.00	451	Peru
		Prehistoric		
Flims	16	12		Switzerland
Saidmarreh	19	20		Iran
Shasta	50	26		USA
Popocatapetl	33	28		Mexico

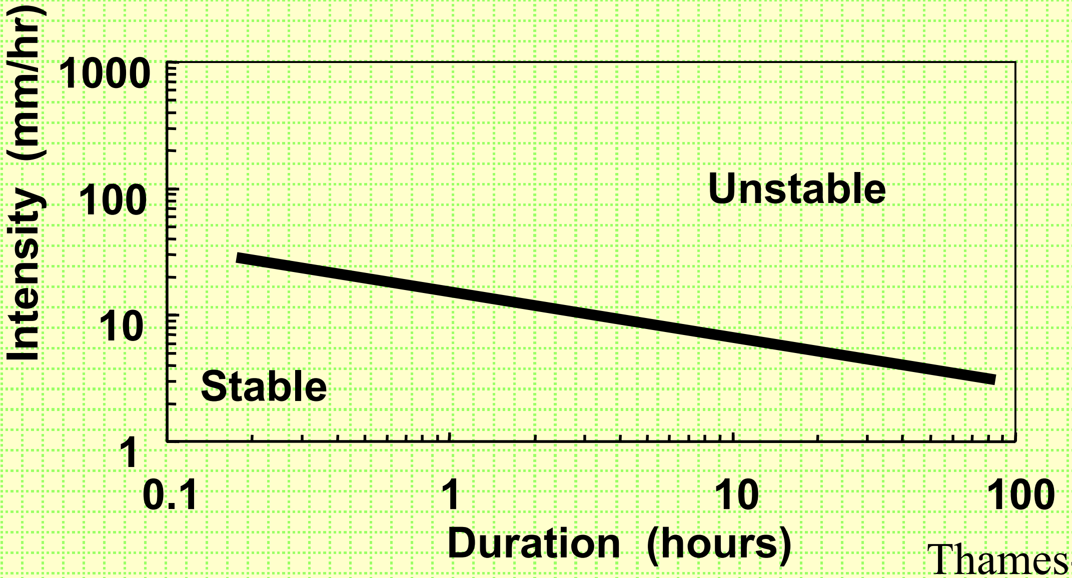
Slope stability

Rainfall-generated mass movement

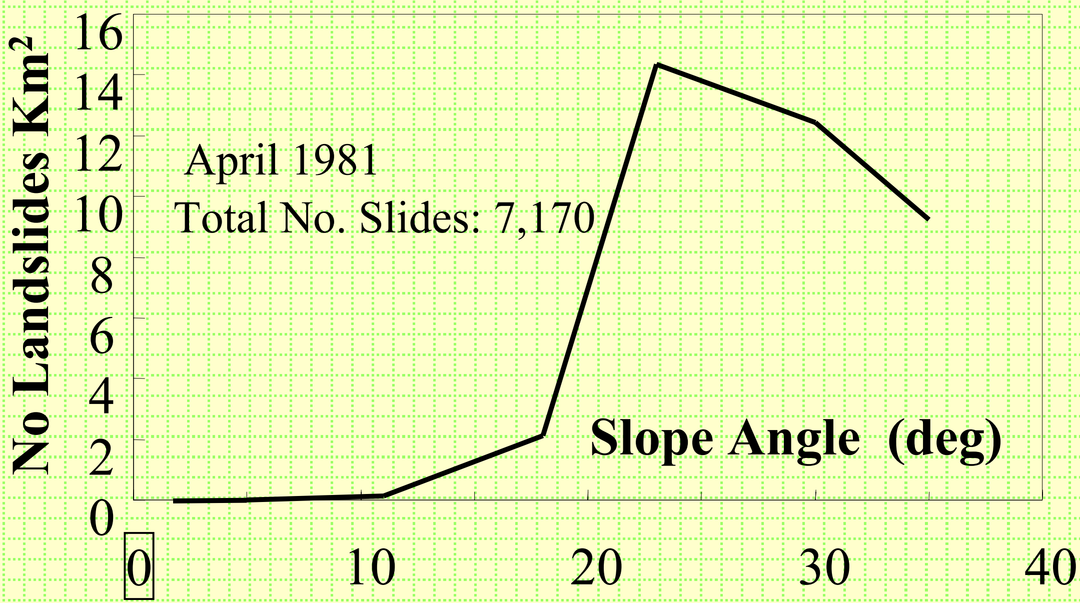
- Function of rainfall intensity and duration
- Slope angle also important; steeper the angle the more likely that rainfall will trigger failure
- Movement triggered in two ways:
  - elevated pore pressures
  - fluidization and mobilization of slope material
- Former - slides
- Latter - debris flows

Casitas volcano Nicaragua 1998

Slope stability



Thames-Te Aroha, New Zealand,



Slope stability

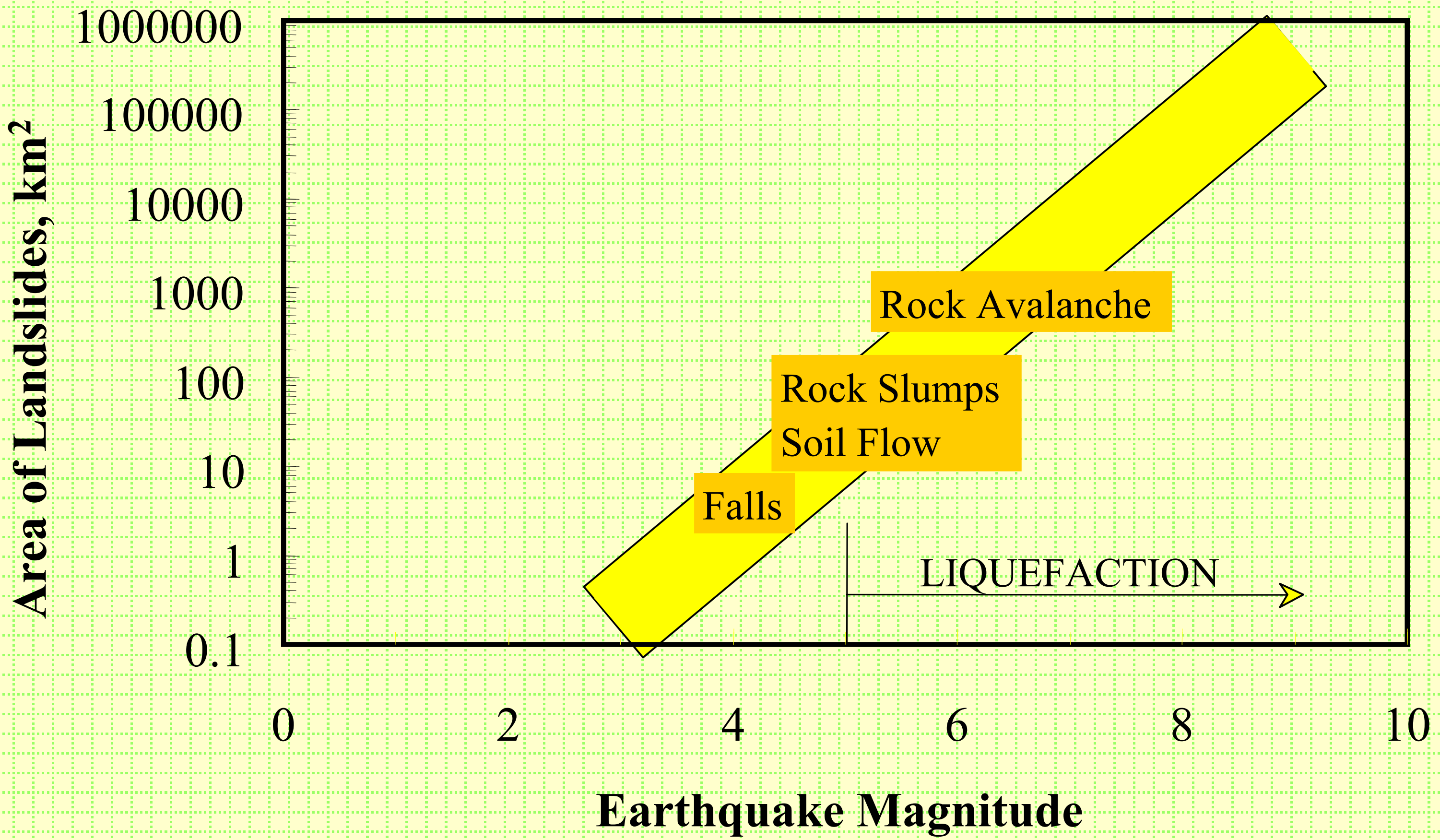
Seismically generated mass movement

- Increasingly severe problem as steep marginal land around growing cities is colonized
- Ground shaking and liquefaction both constitute effective triggers
- Quake-related mass movements range from small volume rock falls to major collapses with volumes > 100,000 m^3
- Impact subsumed within quake figures; e.g. responsible for > 50% quake deaths in Japan

Northridge (California) 1994

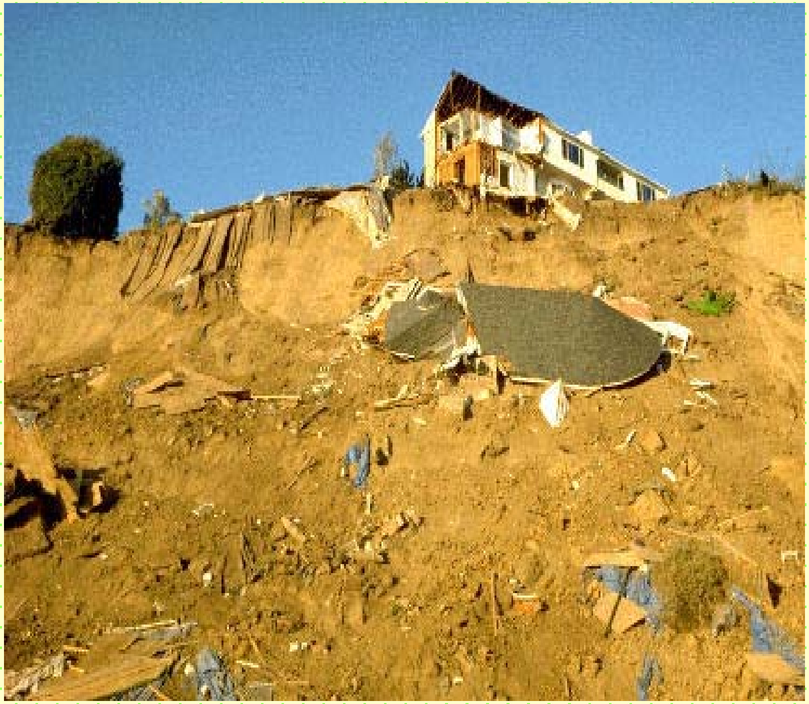
Slope stability

Earthquake magnitude v mass movement size



Slope stability

Mass movement triggering mechanisms during quakes



Northridge (California) 1994

- **Ground shaking promotes stress pulse loading**
  - **large oscillatory stresses in slopes and embankments**
- **Stresses have short durations but are repeated many times**
  - **stress sense may be consistent**
  - **may alternate repeatedly**
- **Superimposed on initial stresses in slope**

Slope stability

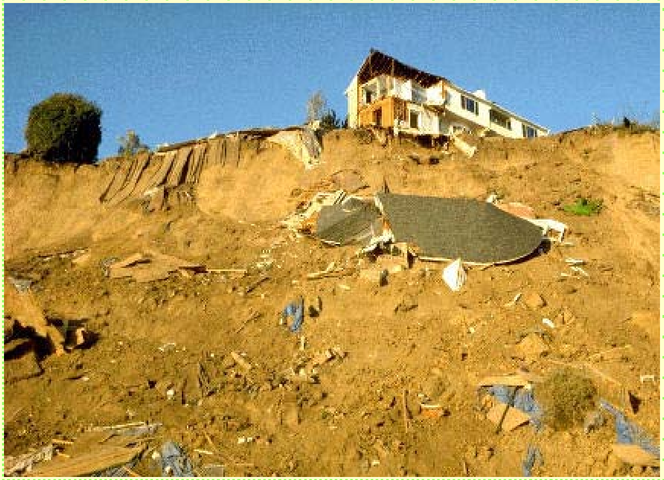
Quake triggering of slope failure

- **Failure can occur due to**
  - decreased strength of the slope
  - increased shear stress acting on the slope
  - liquefaction of sand or silt deposits
- **Probability of failure**
  - increases with number of pulses
- **Fewer, higher amplitude, pulses over longer time may also be effective**

El Salvador 2001

Slope stability



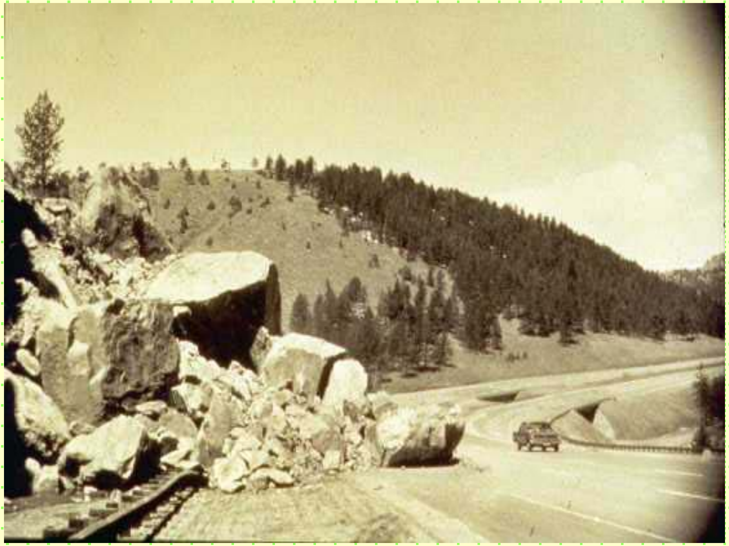



Quake triggering of slope failure II

- **Velocity of ground motion also important**
  - **probability of failure rises with increased velocity**
- **Mass movement may be delayed**
- **Primed slopes may fail hours, days or weeks later due to**
  - **aftershocks**
  - **rainfall infiltrating cracks and fissures and raising pore water pressures**

Taiwan 1999

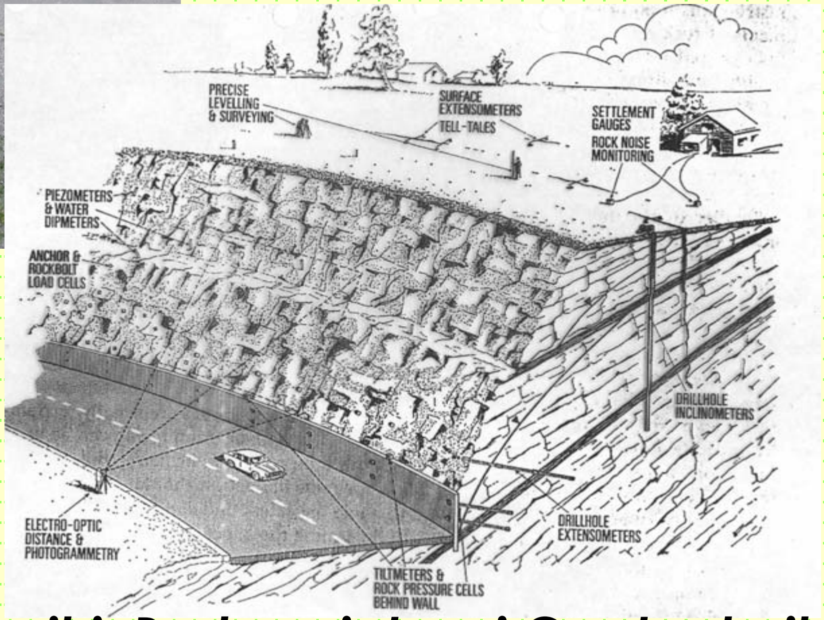
Slope stability



Slope stability

Slope stability

Slope stability



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Seismogenic mass movement impacts

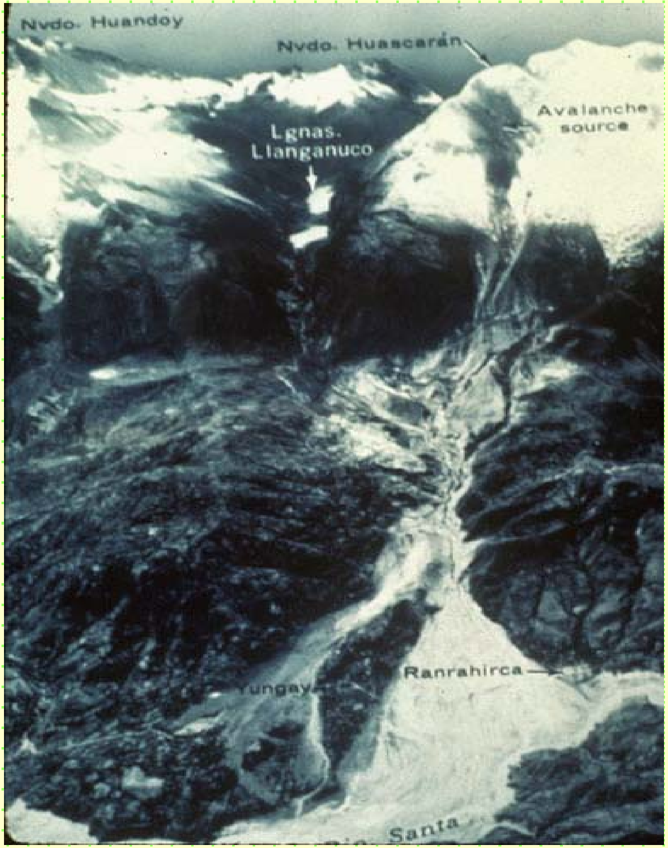
- Lateral spreads
  - occur on shallow slopes
  - can be locally very damaging
  - Alaska 1964; damaged 200 bridges
  - San Francisco 1906; ruptured water mains and hindered fire fighting
- Flow failures
  - slopes > 3 degrees
  - rapid & destructive
  - killed 200,000 in 1920 Kansu (China) quake
  - submarine failures may generate tsunami

Lateral spread
San Francisco 1906

Slope stability

Destructive seismogenic slides: Huascaran (Peru) 1970

- 1949 Tadzhikistan
  - slide moving at 360 km/h destroyed town of Khait & killed 12,000
- 1970 Magnitude 8 quake struck offshore Peru
  - Overhanging peak of Nevados Huascaran detached
  - Debris fell 3.7km and traveled 11km ~ 4 minutes
  - 18,000 killed
  - Several towns buried under 30m debris



Slope stability

Controls on seismogenic mass movements: Guatemala City 1976

- Magnitude 7.5
- 10,000 mass movements > 15,000 m^3
- 11 slides > 100,000 m^3
- Distribution not linked to pattern of pre-quake mass movement
- At smallest scale - slope steepness and topography main controls
- At larger scale - seismic intensity more important
- 90% of movement in weak pumice deposits
- Below 50 degrees debris slides most common
- Above - rock slides & falls

Slope stability

Debris flows

Campania (Italy) 1998

- Material flows downslope as mixture of rock fragments and wet mud/clay
- Soils, clay-rich rocks, volcanoes
- Volumes
  - most ~10,000 m^3 or less; some 10 km^3
- Fast: 0.1- 20 km/hr
- Highly destructive
- Ruiz (Columbia,1985); Venezuela (1999)
- Swiss & Italian Alps (2000)

More about debris flows

- **Most tend to be relatively superficial**
- **Can be quake or precipitation triggered or related to volcanic activity**
- **May evolve from landslide**
  - **Mount St. Helens**
  - **Tessina (Italy)**
- **Viscosities variable: most contain 20 - 80% debris**
  - **if high, plug flow common**
  - **if low, may be very turbulent**
- **Capable of transporting large boulders & objects**

Dilute debris flows
Pinatubo

Persistent debris flows: Tessina (northern Italy)

- Primary failure activated in 1960 and involved 1 million m^3
- By 1964 the flow was 2km long
- In 1990 the flow was reactivated threatening neighboring towns Funés, Lamosano, Tarcogna
- Threat continues today
- Requires continued intervention and monitoring

Slope stability

Alpine debris flows 2000

- Up to 74cm rain fell over 4 days
- A 1 in several 1000 years event
- Water ran off saturated soil to form debris flows
- Also triggered slides and rock falls by raising pore water pressures
- 38 killed and over 40,000 evacuated
- Gondo debris flow (southern Switzerland) most lethal
- impact exacerbated by construction in high risk areas

Forecasting mass movements

- Statistics
  - Distribution of known slides
  - Return times of earthquakes
  - Return times of storms
- Monitoring
  - Local sites
  - Satellite/aerial remote sensing
- Modelling

Slope stability

Mitigating Landslides

- Monitoring and Forecasting: EDM; interferometry
- Physical intervention
  - slope drainage (critical)
  - slope regrading
  - restraining structures (piles, buttresses etc)
  - vegetation
- Avoidance
  - land use restrictions
  - hazard mapping and land use zonation
  - Geological & engineering surveys before development
  - Insurance
- Warning and evacuation measures
- Raising Public Awareness

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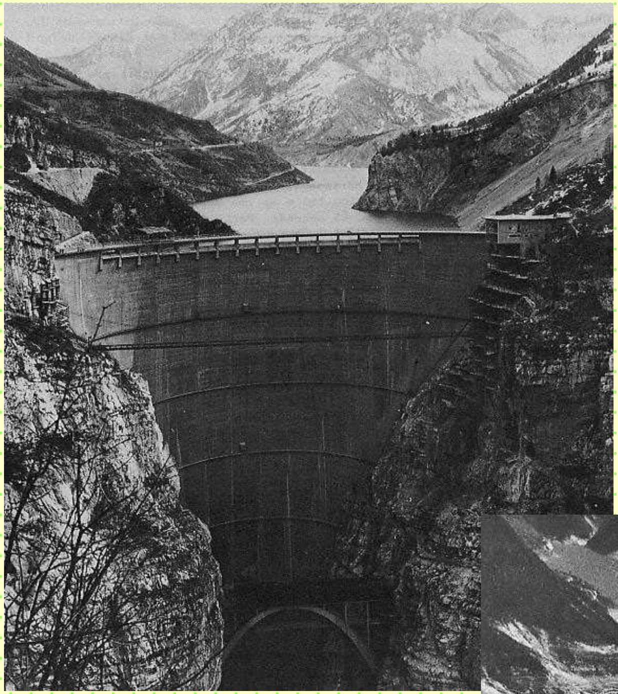
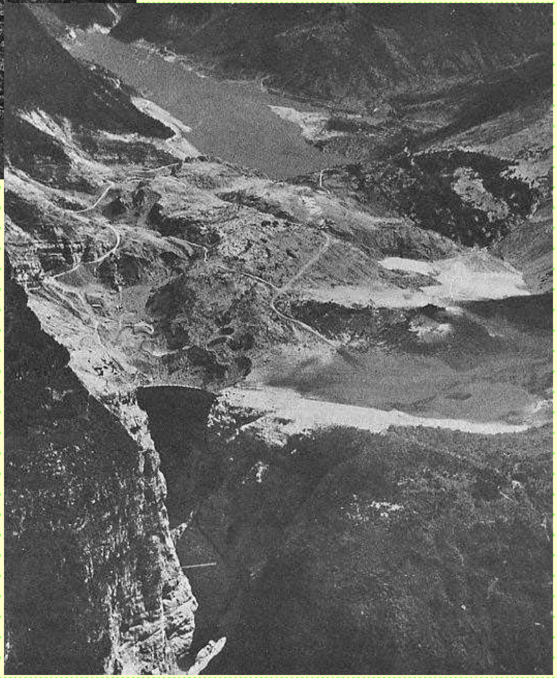
Landslide monitoring & mitigation: Tessina

Slope stability

Vaiont dam disaster 1963

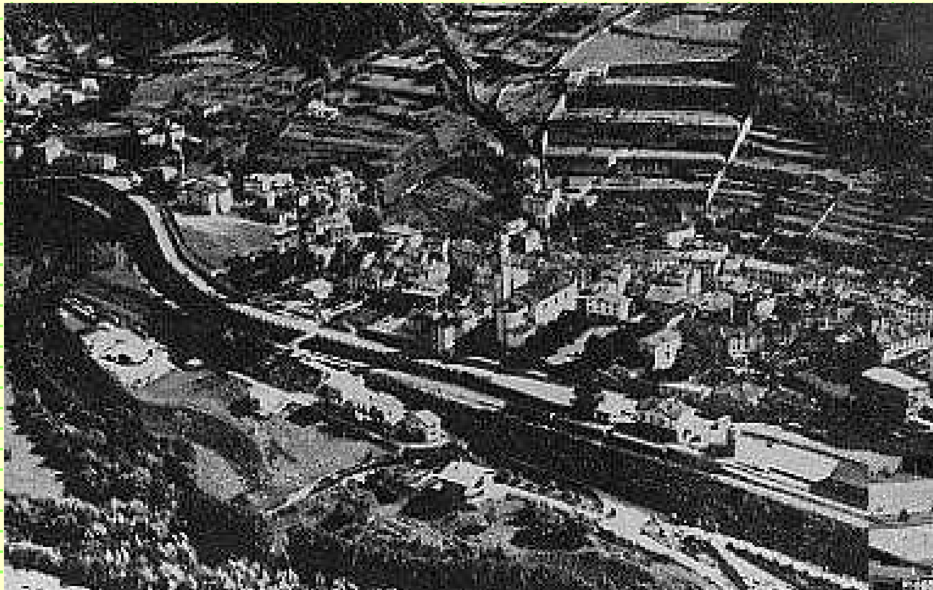




- Dam constructed 1957-60
- 276 m high. World's 2nd highest dam
- Slope started to creep as lake filled
- Accelerated to 80cm/day
- 9.10.63 275 millions tons of rock slid into lake
- 25 millions m^3 of water displaced over dam
- Three towns destroyed
- 2000+ killed

Slope stability

The Piave valley: before and after the landslide



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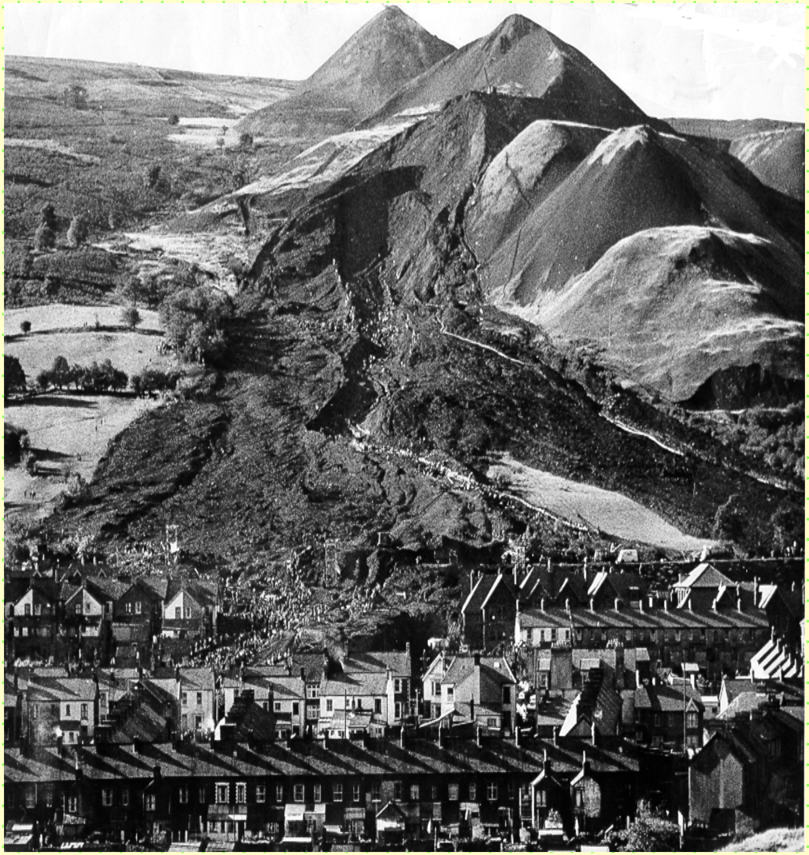
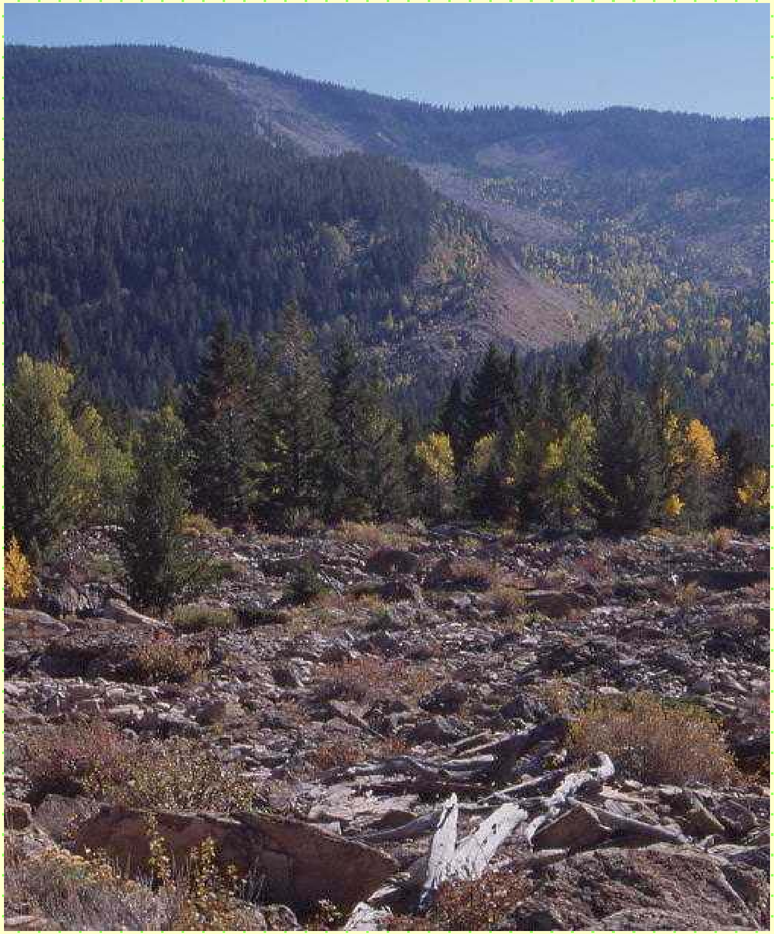
Aberfan debris flow (South Wales) 1966



- Occurred at overloaded & unmonitored coal tip
- Early morning on 21.10.66 upper part of tip subsided by up to 6m
- 9.15am ~150,000 m^3 of debris broke away
- Flow of super-saturated rock waste moved downslope as high velocity viscous surges
- Cottages & school buried up to 10m deep
- 144 killed (116 children)

Gros Ventre (Wyoming, USA) 1925

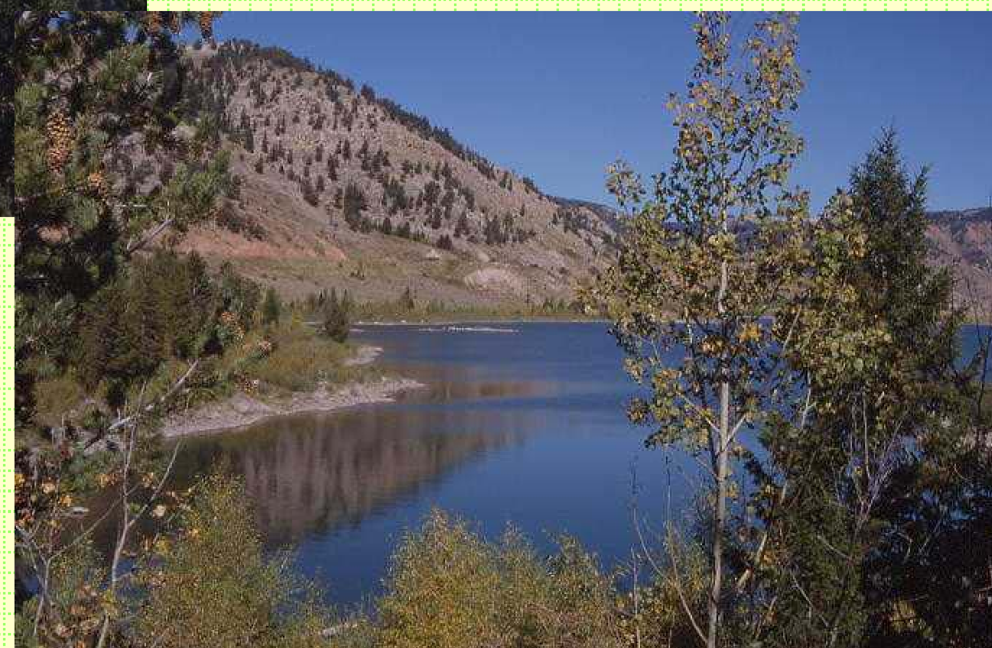


- On 23.6.1925 50 million m^3 of rock slid on saturated clays after heavy rain/snow melt
- Debris dammed river valley to height of 75m
- 65m deep lake formed in 3 weeks
- Seepage through dam prevented overtopping
- Snow melt in Winter of 1927 caused overtopping on 18.5.27 and catastrophic debris flow

Slope stability

Gros Ventre (Wyoming, USA) 1925

Landslide scar photographed in 1999



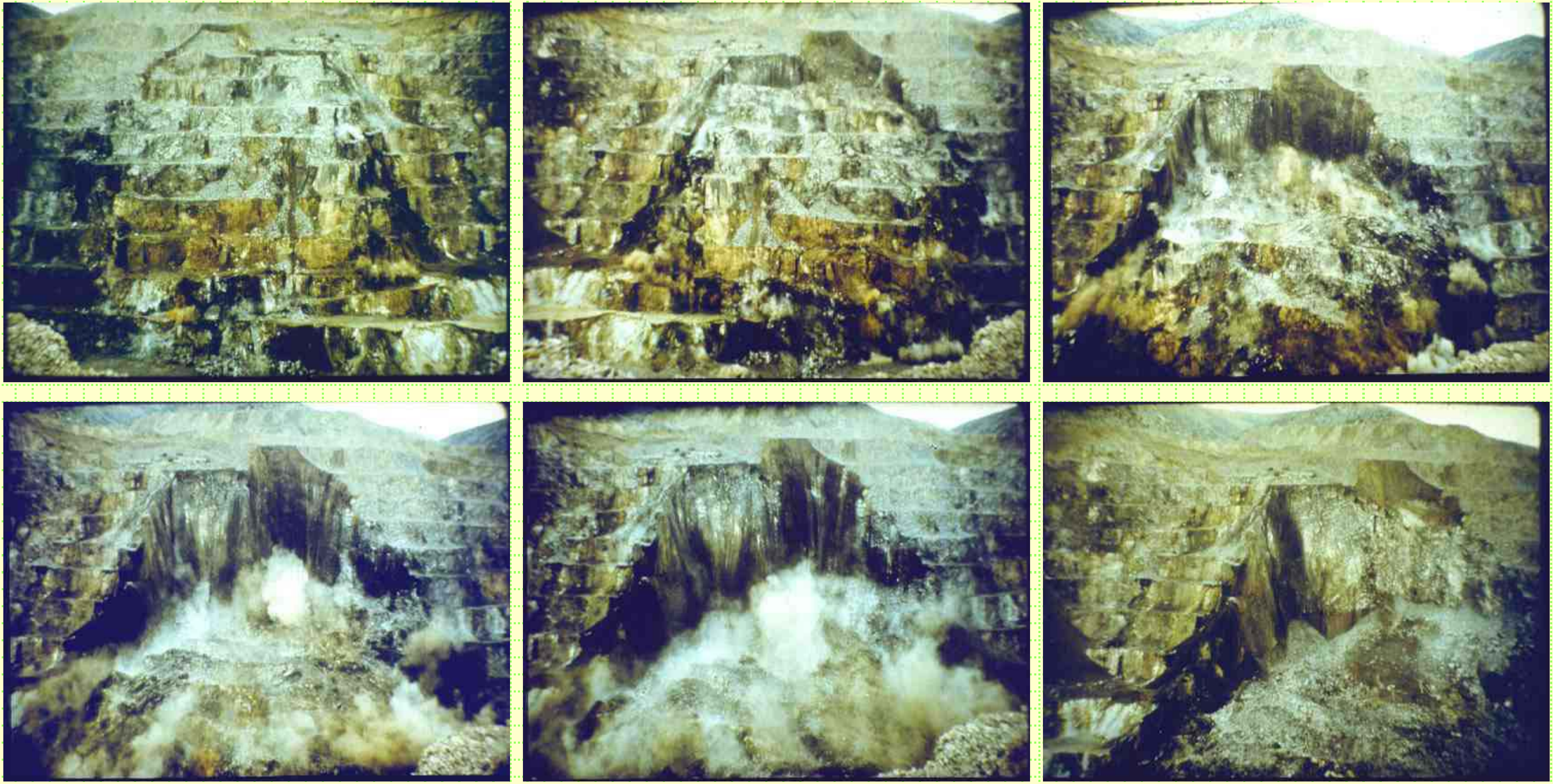
Overtopping of lake resulted in debris flow killing ~ 10 people

Slope stability

Gros Ventre (Wyoming, USA) 1925 - surface

Slope stability

Slope stability



Slope stability

Slope stability