ÉCOLE POLYTECHNIQUE
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Slope Stability

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Slope stability is one of the most widespread geological hazard. Very few countries are not touched by such a risk. Thus, it is one of the main task of engineering geology. This book treats of this matter for geologists and engineers concerned by territorial management.

1. Slope stability as a human issue

Geological risks are not only scientific problems. Their impacts on the life of humans on the earth are numerous and various according to the type of phenomenon. Their socio-economical incidences are very large. Particularly slope stability affects the safety of populations of all the mountainous areas around the world.

1.1. Debate on the human impacts of unstable slopes

In order to develop the self-questioning of students and to valorise their own life experience, a debate in groups is proposed about the main human components of the topic.

Debate on the following questions and make a synthesis of the various opinions :

Are the slope instabilities a fatality that should be integrated in life conditions or can the scientists and engineers reduce significantly the risk ? Examine the various phenomena that can affect slopes in mountainous areas.

How can we define the acceptable risk ?

How is it possible to educate people and local governments to manage slope stability problems ?

Do you think that the global climatic change can sensibly modify the slope equilibrium ? If yes, in which direction for the various phenomena you mentioned ?

1.2. Historical aspects

The history of slope hazards starts mainly form the retreat of the last glaciation, some 14'000 years ago. Many major events let large traces in the landscape and in the geological conditions. For the alpine framework, the famous work of Albert Heim (1932) constitute a comprehensive review of such phenomena.
Among these more or less mute witness, let us mention :

- Events during the last deglaciation : Example of Flims in Graubünden Canton (fig 1.1)

Figure 1.1 : About 14'000 years ago, many landslide occurred in glaciated areas due to the melting of ice acting as a mechanical support of the foot of slopes. For example, in the Graubünden Canton, one of the largest landslide of the world (12 km^3 of material) took place, closing entirely the Rhine Valley (see the geological map of Heierli). The profiles of Heim show the structure of the slide in the direction of the movement (upper profile). On the lower profile parallel to the Rhine, Heim describes the divergence of the Sturzstom into two flows : the main in downward direction, the minor one upwards the Rhine valley. Lake deposits formed at both sides of the mass. The erosion of the Rhine is still very active : gorges let outcrop these landslide series (see photos). Sedimentological details show that the movement was very rapid. In some parts, the mass remains entirely rocky. In some others, the mechanical fragmentation lead to an abundant fine matrix. This lithology defines the famous "Pavonibrei", dedicated to one of the first geologist who studied this field. Many researches were devoted to this famous case and many will do it again in the future.

- Middle Age : Mt-Granier (Chartreuse Massif, French Alps)(fig 1.2)

Figure 1.2 : The rock avalanche of the eastern cliff of Mt-Granier occurred at about midnight November 24th 1248, as it is reported by the monk Mathieu Paris (1200-1259). The phenomenon started from the base of the slope in the 200 m thick marls and limestones of Valanginien. Above this series, the cliff of cretaceous limestones of more than half a km thickness collapsed suddenly. The cause was probably heavy rains which induced important pressures in the karstic network. The debris tongue got the moraines of the villages of Les Marches and Myans (horizontal extension of 7.5 km). The scheme of Nicoud show how the avalanche moulded the morainic hills at the front of the mass and the important role of the marls in the debris. Five parishes disappeared and two were partially destroyed. Between 1000 and 2000 people were killed. This event was interpreted as a divine punishment. After Jacques Berlioz.

- 18th Century : Derborence in Valais Canton (fig 1.3)

Figure 1.3 : The southern cliff of the Diablerets Massif (Helvetic nape) collapsed in the cirque of Derborence in two episodes : first on September 24th 1714, making 18 fatalities. Second on June 23rd 1749 dammed the river and formed the lake of Derborance which is more or less filled by sediments today (photo). Totally about 50 millions m^3 of limestones and marls collapsed from the cliff on a vertical elevation of 1900 m. The profile of Heim show two deviations of the block flow (the first one is visible on the photo) and the rather high general slope (19º), corresponding to a height / length ratio much higher than for a rock avalanche (see §5.5.10). This catastrophe was a source of inspiration for artists : the famous roman of Charles Ferdinand Ramuz, later the movie of Francis Reusser.

- 19th Century : Arth-Goldau in Schwytz Canton (fig 1.4)

Fig 1.4 : Every year, on September 2nd at 5 pm, the great clocks of Goldau's church ring to recall the dramatic 1806 rock avalanche which destroyed in some seconds the valley between Rigi and Rossberg. The Rossberg massive conglomerate summit slid on a very regular strata of marls dipping of about 20 degrees. The mass was about 40 million of m^3. The debris cover an area of 6.6 km^2. The rock avalanche destroyed 111 houses, 4 churches and 220 stables. 700 persons lost their life. Heim measures on his profile an longitudinal angle (atg h/l) of only 11° to 13°, which is typical for rock avalanche. A witeness said: "Le soleil s'était voilé, le jour avait disparu; terre, pierres, maisons et arbres tourbillonnaient dans les airs; le village de Goldau a été rasé au sol avant même que les masses de terre ne l'atteignent, par la simple pression de l'air. Tout cela s'est passé si vite, que je n'ai même pas eu le temps de fuir cette destruction, advenue en un instant.

More recently, important events of slope rupture happened, especially in the Alpine range (see chap 5).

1.3. Basic definitions

Geological risks need to be treated according to the general notions of natural and anthropogenic hazards problem. They have to be recalled here, in order to avoid confusions. The following definitions are given particularly in the logical setting of slope stability.

General definitions

Landslide (F = glissement de terrain)
Landslide is used in two different meanings in this lecture :
- Landslide s.l. : all slope mass movements, including for example also falls and debris flow, according to the definition of the Landslide Commission of IUGS
- Landslide s.s. : slopes of earth or debris affected by slide movements (see §5.3)
The meaning used in a sentence will be determined by the context.

Phenomenon (F = phénomène)

Typical geodynamical movement of material affecting a slope. For example, rock avalanche, landslide, mudflow etc. Generally such phenomena are characterized by an intensity that often corresponds to a volume of unstable material.

Hazard (F = danger or aléas in France)
The hazard of a case of a phenomenon is the probability p that a considered amplitude of the phenomenon will be reached and passed. It is a dimensionless factor ($p < 1$).

Vulnerability (F = vulnérabilité)
The vulnerability V describe the part of an exposed object which is damaged by an hazard. Vulnerability varies between 0 (no damage) and 1 (total lost).

Damage (F = dommage)
Human fatalities and financial cost of damaged objects. Damage D is the product of the total cost C of the object and its vulnerability to an considered hazard
$D = C \cdot V$

Risk (F = risque)
The risk R is the product of the hazard and the value of the object and its vulnerability.
$R = p \cdot D$

2. Main mechanical aspects of slope instability

In this chapter, we will examine the main forces that tends to move the geological material along a slope and the forces that tends to keep this material in place. Before starting these mechanical equilibrium, it is necessary to describe the main cinematic conditions of debris transport on slopes.

2.1. Elementary movements of particles

On the pure geometrical point of view, material is moving down a slope according to different elementary trajectories. These unitary movements will be integrated later as basic component in more natural phenomena (see §5).

2.1.1. Fall (F = chute)

Fall movement concerns a block which is suddenly released from a vertical cliff point. It falls down more or less vertically (fig 2.1).

Figure 2.1 : Primary trajectory of particles in fall movement.

2.1.2. Toppling (F = basculement)

A block is rotating around its base towards the slope (fig 2.2). Its becomes more and more instable when its gravity centre is reaching the border of the base surface. When it passes this limit, the block will roll down the slope (see §2.2.1).

Figure 2.2 : Trajectory of particles in toppling movement

2.1.3. Slide (F = glissement)

A mass is sliding when it is doing a translational movement at the surface of the slope. All the particles of the mass are moving at the same direction and the same velocity. Shearing is concentrated at the foot of the mass (fig 2.3).

Figure 2.3 : Trajectory of particles in slide movement

2.1.4. Flow (F = écoulement)

A fluid or plasic mass is flowing along a slope when the velocities are different inside the mass. Shearing occur not only at the contact of the slope but also inside the mass (fig 2.4). The most common case is a laminar flow with parallel velocity vectors. In reality, many rapid flows are turbulent.

Figure 2.4 : Trajectories of particles in flow movement (laminar flow and turbulent flow).

2.2. Mechanical equilibrium and factor of safety

Although the aim of this book is not soil or rock mechanics, it is necessary to identify the main forces that acts on slope debris. First of all, consider a solid phase in air, without water. Then, we will show the role of water in this mechanical system (see §2.4).

These forces classed in two categories :

2.2.1. Driving forces

They act to move the particles down the slope. The main force of this kind is gravity.

$$F = G\, mM/r^2$$

with G = gravitational constant
M = mass of the earth
m = mass of the particles
r = distance to the centre of the earth

2.2.2. Resisting forces

They fight against the driving forces. They are mainly internal forces of the matter or material strength. As many slope movements involve shear stresses, the most importance factor is the shear strength.

In an elastic solid, the law of Mohr – Coulomb calculates this resisting force by using two important factors :

- angle of friction Φ: this angle can be materialized as the maximum possible slope angle for a heap of non cohesive dry particles (e.g. sand)

- cohesion c : it represents the binding forces due to natural bounds between particles and can be approximate with the tension strength of the cohesive material.

The Mohr – Coulomb equation calculates the failure conditions, that means the limit strength that can be mobilized by a material (fig 2.5).

$$\tau_f = c + \sigma \mathrm{tg}\Phi$$

Figure 2.5 : Mohr diagram with determination of the angle of friction and cohesion by using triaxial test. If the stress state remains below the Mohr-Coulomb straight line, then the failure will not occur.

2.2.3. Factor of safety

The relationship between driving and resisting forces allows to evaluate the stability of a slope. We use the notion of factor of safety defined as

$$F = \mathrm{resisting\_forces}/\mathrm{driving\_forces}$$

So, we can identify three cases :
F>1 Slope is stable
F=1 Slope is at the limit of stability
F<1 Slope is moving

2.3. Example of application to a road trench

Suppose a trench excavated in a rock for road construction. The oblique slope presents a planar discontinuity parallel to the topography, which can potentially lead to the failure of a thin sheet of rock. This situation is the simplest case of the friction on an incline plan (fig 2.6). The equilibrium is calculated without water influence.

Figure 2.6 : Example of calculation of the limit equilibrium of a slope containing a planar discontinuity. The driving force is the projection of the sheet weight on the discontinuity. The resisting force is the composition of friction angle and cohesion along the surface.

Exercise :

In the example of fig 2.6, it is possible to game with couples of cohesion and friction angles which lead to failure. We fix the following geometrical parameters :

β = angle of the discontinuity = 30°

L = length of the sheet of rock = 10 m

e = thickness of the rock sheet = 1 m

Calculate the limit friction angle corresponding to the following cohesion values and comment the result :

c [kN/m$_2$]	0	5	10	20
Φ [°]	……………….	……………….	……………….	……………….

2.4. Mechanical effects of groundwater

Groundwater in soils and in rocks have many effects on slope stability. At this stage of the lecture, only the simplest effect is described : the hydrostatic pressure in a rock fissure (fig 2.7).

Figure 2.7 : The filling up of an open fissure in a rock massif leads to important stress on rock blocs, according to the experience of the Pascal's barrel : with a very few amount of water, it is possible to increase considerably the pressure till a failure of the solid barrier.

3. Characterization of unstable slopes towards a classification

There are several possible ways to characterize unstable slopes. As the stability of slopes is depending of many factors, the question is to choose the most predominant ones, which can be used as a base of a classification. Two main ways are used in fact in the literature and in practice : geodynamic and material approaches.

3.1. Geodynamic approach

The geodynamic approach integrates two main factors : spatial and temporal distribution of velocity.

3.1.1. Cinematic trajectories (or spatial distribution of velocities)

As described in chapter 2.1, typical particle movements are defined according to the spatial distribution of velocity vectors or displacement vectors. This typology of elementary movements constitutes the base of classification of natural more or less complex phenomena. Examples are given in table 3.1.

Primary movement	**Example of corresponding phenomena**
Fall	Rock fall, rock avalanches
Slide	Landslide, rockslide
Flow	Earthflow, mudflow

Table 3.1 : Relationship between primary movements and some corresponding phenomena.

3.1.2. Temporal distribution of velocity and degree of activity

For each movements, we are able to define a mean velocity of the instable mass. This value is integrated during an observation period (for example one year for slow movement and one minute for a rock fall). Such mean velocities are very different for the various slope movement. It is convenient to characterize the various cases encountered in the field and is a base for risk assessment. Cruden and Varnes (1996) propose a scale of seven classes of velocity valid for all slope movement types (landslide s.l.). Velocity varies from extremely low to extremely rapid movements (see §4.4).

Such scales which are unique for all kind of movements, are not well adapted to the description of the activity of landslides s.s., especially in their influence on civil works. For example, to qualify a landslide as slow when the velocity can reach up to 13 m per month is not very realistic in practice. We suggest to use other scales which are more convenient in slope engineering, for example the one of table 3.2.

from	to	velocity	typical movement
0	1cm/y	very slow	Landslide s.s
1cm/y	5cm/y	slow	Landslide s.s
5cm/y	20cm/y	mod. slow	Landslide s.s
20cm/y	1m/y	moderate	Landslide s.s
1m/y	1m/month	mod. rapid	Landslide s.s
1m/month	1m/d	rapid	Landslide s.s
1m/d	1m/h	very rapid	Landslide s.s
1m/h	1m/s	extr. rapid	Landslide s.s, flows
1m/s			rock avalanche

Table 3.2 : Proposal of a scale of velocity which would be more valid for practical slope geological engineering in landslides.

Another important factor is the velocity variation during time. On the base of this criteria, it is possible to separate sudden phenomena from more or less regular displacements. Their management is then quite different in practice. Particularly, the relationship between peak velocity and mean velocity should be calculated for the characterisation of this dynamic regime (fig 3.1).

Figure 3.1 : Velocity regime of unstable slopes for the different phenomena.

3.2. Geomorphological approach

The geomorphology is often the first approach of landslides in remote sensing recognition and in field mapping. Thus the geometry of landslides have been studied in details for the various types of phenomena.

The morphology must be as most as possible characterized by numerical parameters in order to make possible various calculations (e.g. volume) and to compare one case with another one. On a typical schematic landslide, the main morphological terms are defined (fig 3.2) as well as the common parameters (fig 3.3).

Figure 3.2 : Main geomorphological terms of idealized complex earth slide-earth flow (Varnes 1978). L = total length; D = Depth of surface of rupture ; HC = length of surface of rupture ; VC = depth of displaced mass.

Figure 3.3 : Main geomorphological parameters of a landslide (modified from Cruden and Varnes). 1 = Width of displaced mass; 2 = Width of surface of rupture; 3 = Length of displaced mass; 4 = Length of surface of rupture; 5 = Depth of displaced mass; 6 = Depth of surface of rupture D; 7 = Total length L; 8 = Original ground surface.

The morphology brings indirectly many data on the phenomena. For example, it is possible to detect in the morphology if the landslide is rotational or translational, if one or several masses are sliding. One of the most interesting geometrical feature is the relationship height / length because it is a key factor for large rock fall evolving into dry debris flow. It allows the distinction between common rock fall and sturzstrom, which show very small values of h/l (see §5.5.10).

3.3. Material approach

The characterisation of an unstable slope is naturally concerned by the material which is moving. More or less detailed categories of geological material are used (fig 3.4).

Figure 3.4 : General categories of geological material moving in unstable slopes

Varnes (1978) proposes to separate the material in three categories :

Definitions

Bedrock
Hard or firm rock that was intact and in its natural place before movement

Debris
Transported or residual soil with a predominant coarse material (< 80% < 2mm)

Earth
Transported or residual soil with a predominant fine material (> 80% < 2mm)

From these general descriptive characterisation, it is interesting to deduce a mechanical behaviour. For that, it is necessary to precise the composition and the behaviour in different saturation conditions. The following factors are of very high importance :
- Solid – water - air content (fig 3.5)
- Grain size distribution and especially the amount of fine matrix (eg silt/clay)(fig 3.6)
- Shape of coarse elements (e.g. rounded or planar elements)(fig 3.7)
- Structural arrangement of the deposit (e.g. inclined stratification)(fig 3.8)
- Plasticity and liquidity limits (fig 3.9)
- Mineralogy of clay material (e.g. highly plastic smectite)(fig 3.10)
- Compaction (e.g. over-consolidation)

Figure 3.5 : Laboratory measurement of the three components of a porous media : solid, liquid and air. Calculation of induced parameters commonly used in geotechnical characterization.

Figure 3.6 : Grain size distribution of clastic rocks and the amount of fine matrix (USCS). By sifting and sedimentation, one measures the respective weights of the particle size classes. The curve describes the percentage in weight of the particles which are lower than a given size. The limits of the classes are those of Unified Soil Classification System used in geotechnics; in pedology, the upper limit of the gravels is fixed at 20 mm and the limit sand-silt (called silt) at 0.05 mm. Examples of sediments: A = alluvial sandy gravel; B = argillaceous silt; C = morainic sandy and silty gravel.

Figure 3.7 : Shape of coarse elements.
The triangular diagram illustrates the names given to various shapes of sedimentary particles. Grains are plotted on the diagram using various calculations of the long (L), intermediate (I) and short (S) diameters of the grain. Based on a method developed by Sneed and Folk, 1958.

Figure 3.8 : Structural arrangement of the deposit. Particularly in coarse soils the other textures are rarely conserved in cores.

Figure 3.9 : Plasticity and liquidity limits. a) Opening of the notch at the beginning of the experiment. b) Opening after a sufficient number of falls to close again the notch on 13 mm. c) 3mm thickness: diameter for which the clay ribbon is fractured thanks to the deshydration caused by the heat of the hand.

Figure 3.10 : Mineralogy of clay material (after Pettijohn et al. 1972). In fact, the concept of clay used in geotechnics covers various minerals which have sometimes very different behaviours (for example kaolin and smectite have a very large difference of plasticity index).

These characters can be determined very precisely in laboratory. But most of them can be reasonably assessed in the field during geological mapping of unstable slopes. The "geotype" concept developed in GEOLEP is a tentative of systematic field parameterisation of soils, specifically for slope stability assessment (Table 3.3).

Table 3.3 : Characterisation matrix of "geotypes" for field mapping of unstable slopes in quaternary deposits. HGU = homogeneous geological unit. Project of hazard mapping of Vaud Canton.

4. Systematic classification of phenomena

Many attempts to find an universal classification are published. Several "churches" (North-America, UK, France, Germany etc) propose different systems, some more or less taxonomic, some not. They are rather different in the fundamental principles and in the names of phenomena.

In recent classifications, the one of Varnes (1978) is very interesting because it integrates the geodynamical and material approaches. Geodynamic behaviour and material composition are theoretically two different things and they should be combined to determine many possible cases. That was done by Varnes (table 4.1).

Table 4.1 : Classification of Varnes by intersecting geodynamic behaviour and nature of material.

This principle is reasonable for many phenomena. For example, both rock and earth can slide : rock slide and earth slide. In fact, material and geodynamic is not independent. That is why some phenomena remain theoretical, such as earth fall and earth toppling.

The classification of Varnes is largely used, not only in North America. The types of landslides selected for the Multilingual Landslide Glossary, published in 1993 by the International Geotechnical Societies of UNESCO. Developing this glossary, Cruden and Varnes proposed in 1996 a system of global description of landslides which will be selected in this lecture as a principal classification system.

More recently, Hungr at al (2001) published a detailed classification of flow type phenomena, which is very useful to define more precisely the mass movement between the solid and the fluid phases.

In the practice of engineering geology, we need a general classification which can be used in various geological contexts in interaction with risk assessment, construction and environmental problems. It must be :
- not too detailed
- robust in different geological settings
- phenomena should be identified and mapped on the field without deep recognition.

For this lecture, we propose a classification based essentially on the system developed in 1996 by Cruden and Varnes but completing it by the recent works of Hungr et al. for flow type phenomena. Although it was developed in the North-American context, it is well adapted to the Alpine geology. However, some descriptors will be simplified in order to keep them applicable on the field.

Thus, the classification contains the five main types of slope instability phenomena : fall, toppling, slide, spread and flow. When it is necessary, sub-types will be described in order to fit as most as possible to the field treated in practice. We add also a sixth type which is a gravitational mass movement but not typically a slope instability : the collapse of natural or artificial cavities.

As proposed by Cruden and Varnes, the classification is given by a sequence of descriptors. Example : slow wet earth slide. It is a flexible system because only the main descriptor (geodynamic type) is obligatory. A double description have to be done when the geodynamic conditions change from the beginning of the movement to the end. The two descriptions are connected by a -. For example, a rock fall evolving into a debris flow must be described by a double characterization : Rock fall – debris flow.

4.1. Principal descriptor : geodynamic type

The International Classification of the Glossary is chosen :
- Fall
- Topple
- Slide
- Spread
- Flow

We just add the collapse of cavities.

4.2. Second descriptor : material

The Varnes' classification is taken as it is, except for the flow type movements for which the concepts of Hungr will be used (table 4.2)

Type of movement	Material		
	Rock	Soil	Soil
		Predominantly coarse	Predominantly fine
Fall	Rock fall	Debris fall	Earth fall
Topple	Rock topple	Debris topple	Earth topple
Slide	Rock slide	Debris slide	Earth slide
Spread	Rock spread	Debris spread	Earth spread
Flow	Rock avalanche	Sand, silt, gravel flow Sand etc. flow slide Debris flow Debris avalanche Debris flood	Clay flow slide Peat flow Earth flow Mud flow
Collapse	Gypsum or carbonates	-	-

Table 4.2 : Fusion of the geodynamic type with the material descriptor. According to Cruden and Varnes (1996) and Hungr et al (2001) modified.

4.3. Third descriptor : water content

For a general description, we can retain the limits proposed by Cruden and Varnes (table 4.3).

Adjective	Condition
Dry	No moisture visible
Moist	Presence of water but not free. The material behaves like a plastic solid
Wet	Presence of free water. The material can behave in part as a liquid
Very wet	Material flows under low gradient due to the high water content

Table 4.3 : qualitative description of the water content according to Cruden and Varnes (1996).

However, to fix the limit between flow and slide movements, these limits are often insufficient. They should be replaced by the more precise limits given by Hungr (table 4.4). This table tries to give a correspondence between the limits of Hungr and the classic definition.

Hungr	Behaviour according to Cruden and Varnes	Water content
Near plastic limit	Plastic solid behaviour	Moist
At or above liquidity limit	Materials flows	Wet or very wet
Saturated	Free water	Very wet

Table 4.4 : Tentative of correspondence between the limits of water content according to Hungr (2001) and the Cruden and Varnes' (1996).

4.4. Fourth descriptor : velocity

The Cruden and Varnes' scale can be retained as it is (fig 4.1). Notice that the limit between very rapid and extremely rapid corresponds to the escape speed of people. This value is very important to assess the hazard concerning the lost of human life.

Figure 4.1 : The seven classes of velocity for the landslides. According to Cruden and Varnes 1996.

It is to remark that this scale of velocity, which concerns all the types of landslide s.l, is thus very few sensible for the common landslides that the engineer has to treat (see §3.1.2). Furthermore, we recommend to characterize the landslides by the mean and the maximum velocities. Hungr et al. (2001) give a graphic of the maximum velocities for various phenomena (fig 4.2).

Figure 4.2 : Maximum velocities of movements for the flow type phenomena (after Hunger et al., 2001).

4.5. Fifth descriptor : activity

Cruden and Varnes (1996) decompose the activity descriptor into three sub-descriptors :
- state of activity
- distribution of activity
- style of activity.

This very complete system should be simplified in practice, as proposed below.

4.5.1. State of activity

The recent velocity measurements on a landslide, ancient observations and a geomorphological investigation allow to fix a degree of activity. The International Glossary fixes four degrees (fig 4.3).

- Active : currently moving and present velocity different of zero
- Reactivated : moves now after a period of suspension
- Suspended : currently moving but not presently
- Inactive : do not move since a minimum of one year.

The inactive movements can be decomposed four sub-cases :
- Dormant : the causes are still present but does not move now
- Abandoned : the causes are no more existing
- Stabilized : the causes have been suppressed by remedial measures
- Relict : very old activity completely smoothed geomorphologically.

Fig. 4.3 : Degrees of activity of a landslide according to the International Glossary (Cruden and Varnes). (1) active - erosion at toe of slope causes block to topple ; (2) suspended - local cracking in crown of topple ; (3) reactivated - another block topple ; (4) dormant - displaced mass begins to regain its tree cover and scarps are modified by weathering ; (5) stabilized - fluvial deposition stabilizes toe of slope, which begins to regain its tree cover ; (6) relict - uniform tree cover over slope.

In practice, all these types are difficult to identify. Otherwise, it is interesting to say a bit more about active landslides on the base of geomorphological features. A more applicable description would be :
- very active : well distinguishable parts of landslides which move more actively than the mean activity of the slope
- few active : slow movements
- doubtful movements : some features let suppose that the mass in unstable but cannot be proved
- potentially susceptible to be reactivated : not active but susceptible to move again easily by minor changes of the conditions
- old stabilized landslides : reactivation is not probable.

4.5.2. Distribution of activity

Cruden and Varnes here also present a very detailed way to describe the geometrical evolution of the landslide due to its activity :
- Advancing : surface of rupture extends downwards
- Retrogressive : surface of rupture extends upwards
- Widening : surface of rupture is extending to one or both lateral margins
- Confined : landslide with a scarp but no visible rupture in the foot zone

- Diminishing : displacing material decreasing with time
- Moving : displacement without change in the surface of rupture.

This sub-descriptor of the spatio-temporal evolution of the landslide can be used if they add something to the general description of the case but they must not be applied systematically because they make the system very heavy.

4.5.3. Style of activity

A third sub-descriptor is used for the activity of landslides according to Cruden and Varnes. It mainly illustrates the relationship between several parts of a landslide. Five adjectives are introduced :
- Complex : landslides with at least two types of movements in sequence (eg complex rock topple – rock slide)
- Composite : different parts of the landslide show different types of movements
- Multiple : several sub-masses moving with the same type of movement
- Successive : several mass moving with the same type of movement but not sharing their material or surface of rupture
- Single : a single mass is moving, often as un unbroken block.

The use of the three first adjectives can be recommended for not simple cases which are current in the field. The two last terms can be abandoned.

5. From a classification to the field

In this chapter, each type and subtype will be treated in details. Characterization will be structured on the following manner :
- Name of type and subtype
- Translation (French and German)
- Definition
- Typical geological material
- Mechanism
- Geodynamic behaviour
- Intensity quantification
- Protecting measures

Where subtypes must be defined, only common characterization is given in the general type description. Non common characters are dispatched to each subtype.

The typical movements are illustrated by real examples in the field, treated by the author of this lecture or issued from the literature. They show the natural variability of such phenomena.

5.1. Fall

Translation
F = chute D = Fallen or Fall

Definition
The basic trajectory of falling particles is defined in §2.1.1. In the natural phenomenon, material is suddenly detached from a cliff along a vertical rupture surface. During its falling movement, the mass can rebound, roll and slide on the lower part of the cliff or on the debris accumulation (fig 5.1.1).

Figure 5.1.1 : Schematic profile of rock fall from a cliff.

Typical geological material
- Principally coherent rocks (eg plutonic rocks, lavas, gneisses, limestones, sandstones, conglomerates)
- Rarely earth and debris material

Mechanism
See subtypes

Geodynamic behaviour
See subtypes

Intensity quantification

Kinetic energy E_c of particles :

$E_C = 1/2 \cdot mv^2$

m = mass of the particle

V = translation velocity of the particle at the impact

Units of EC : J or $N \cdot m$ or $kg \cdot m^2 / s^2$

In Switzerland, the limits 30 and 300 kJ separate low, middle and high intensity. The table 5.1 helps to feel concretely what means these particular values.

Mass	Volume	Equiv. sphere diam.	Velocity	Kinetic energy		Remark
m	V	d	v	E_c	E_c	
kg	m^3	m	m/s	kJ	MJ	
1	0.0	0.1	10	0.05	0	
10	0.0	0.2	10	0.5	0	
100	0.0	0.4	10	5	0	
175	0.1	0.5	10	9	0	limit stone-block
600	0.2	0.8	10	30	0	Limit low-middle intensity
1000	0.4	0.9	10	50	0	
1000	0.4	0.9	20	200	0	
1000	0.4	0.9	25	313	0	
6000	2.3	1.7	10	300	0	Limit middle-high intensity
1500	0.6	1.0	20	300	0	Limit middle-high intensity
6000	2.3	1.7	20	1200	1	
9600	3.6	1.9	10	480	0	
9600	3.6	1.9	20	1920	2	
9600	3.6	1.9	25	3000	3	limit of Geobrugg nets
2.7E+05	100.0	5.9	10	1.3E+04	13	small rock-mass fall
2.7E+05	100.0	5.9	40	2.1E+05	212	small rock-mass fall
2.7E+08	1.0E+05	58.6	10	1.3E+07	1.3E+04	large rock-mass fall
2.7E+08	1.0E+05	58.6	40	2.1E+08	2.1E+05	large rock-mass fall
2.7E+09	1.0E+06	126.2	40	2.1E+09	2.1E+06	small rock avalanche
2.7E+12	1.0E+09	1259.5	40	2.1E+12	2.1E+09	largest rock avalanches

Table 5.1 : Some particular cases of rock fall kinetic energies. The effect of power 2 affecting the velocity is easily demonstrated.

Protection measures

See subtypes

Fall movements concerns masses of very different size, from gravel dimension to huge parts of mountains. These sub-types must be distinguished because they differ in many things : mechanism, spatial extension, frequency, hazard, alert management etc.

5.1.1. Subtype : Rock-particle falls

Translation

F = chutes de pierres ou blocs D = Steinschlag - Blockschlag

Definition

Diffuse fall of individual rock particles of relatively small dimensions (less than 100 m3). It is the common erosion process of cliffs. In Switzerland, a size limit of 0.5m is fixed between stones and blocks (fig 5.1.2 and 5.1.3). Only block size particles constitute really a hazard.

Figure 5.1.2 : Example of stone-fall due to normal erosion of cliffs, on the right part of the picture. Ladakh mountains, north of Baralache La (Transhimalayan Road). Severe freezing in winter make the block flow gently down the slope (left side). Dark colour = green rocks. In front of these debris, a recent deep erosion cuts the alluvium. Photo Parriaux.

Figure 5.1.3 : Example of a single block-fall from a conglomerate formation in Grindelwald Burglauenen (February 2nd 1994). The houses would be completely destroyed if the block had chosen a slightly different trajectory. Photo Geotest AG.

Material

Finely jointed rock material

Mechanism

Frost action in joints (ice swelling)
Hydrostatic pressure in joints
Earthquakes

Geodynamic behaviour

More or less continuous erosion phenomenon, especially active during winter (frost – thaw action) and heavy rainfalls.
Velocity : very rapid to extremely rapid.

Protecting measures

- bolting of unstable blocks in the cliff (fig 5.1.4)

Figure 5.1.4 : Bolting of oligocene conglomerates in the northern flank of Geneva Lake.

- more or less sophisticated wire nets (fig 5.1.5)

Figure 5.1.5 : Geobrugg AG net for retaining blocks. The experience is made on a net with Rocco rings showing chronologically the stop of a stone falling at a speed of 26 m/s.

- earth dams (see fig 5.1.7)

Case studies

Case study 5.1.1.A : "Chasseron" Canton of Vaud
In the Jura range, the top of anticlinals are often eroded. The thick series of Middle Jurassic limestones are in a dip-opposite position (photo A). As they are deposited on marls of Argovien, the foot of the cliffs is deeply weathered. A fracture family, more or less perpendicular to the stratification, exposes these cliffs to rock fall (photo A). Recently, a rock block of half a cubic meters threatened to fall on a restaurant built at the foot of the cliff (photo B). The block could be extracted from the top of the cliff with a mobile crane.

5.1.2. Subtype : Rock-mass falls

Translation
F = éboulement D = Felssturtz

Definition
Fall of a great part of a cliff in one mass or several successive masses (total volume from 100 m^3 to millions of m^3 for one event). The rock mass is fragmented (fig 5.1.6). The downward extension remains small (h/l ratio > 0.5).

Figure 5.1.6 : In 2002, the village of St-Niklaus in central Alps was threatened by rock mass fall. A gneiss massif comprised between two main fissured zones forms a series of triangular steps, steeply eroded by glaciers (photo A). Schistosity is slightly in opposite direction of the slope. The lower step began to move progressively downwards. An observation network installed by the geologist Rovina showed that the massive was sliding and slightly toward the valley. Huge blocs of gneiss moved in the frontal part of the mass with wide tension fractures (photo B) before falling. A working place was installed at the surface of the unstable plateau to perform a recognition borehole (photo C) and to mine very dangerous parts of the mass. Mining operation succeeded with a first rock fall followed by a second one some days later. At the same time, a dam was under construction to secure the village and the railroad to Zermatt (photo A).

Material
Thick bedded or poorly jointed rock material

Mechanism
Hydrostatic pressure in joints
Frost action in joints (ice swelling)
Earthquakes

Geodynamic behaviour
Discontinuous erosion phenomenon, especially active during heavy rainfalls.
Velocity : very rapid to extremely rapid

Protecting measures

- Anchoring of the cliff (fig 5.1.7)

Figure 5.1.7 : When the stable underground is to far for bolting, anchors are used to prestress the unstable cover against a deeper layer. Anchors are made of a cable placed in a borehole. The extremity is sealed in the stable layer. Prestressing is conferred to a concrete plate. Plates can remain individual or be incorporated in a retaining wall. Example of stabilisation of the upper part of the Chenailette landslide that cut the road leading to Plans-sur-Bex in Prealps.

- Construction of pillars (fig 5.1.8)

Figure 5.1.8 : Ancient quarries represent sometimes a risk of instability. Example of pillars supporting the foot of a dip-slope limestone series in an abandoned quarry (Canton of Luzern).

- Earth dams

Case studies

Case study 5.1.2.A : "Sandalp" Canton of Glaris
The rock-mass fall took place in a series of rather tabular limestones of Parautochtone, north of Tödi Massif. The movement made in two main events : on January 24 (0.5 million m^3) and on March 3, 1996 (1.8 million m^3). Volume accumulated = 3 million m^3. Drop height = 900 m. A high column of limestones slid on an undulated stratification surface which was dipping of about 20° in an oblique direction towards the valley (photo A). The debris cover the axe of the valley and the foot of the opposite slope. This natural dam created a little lake upwards and inhibited a hydroelectric reservoir existing at this place (photo B). The extension of the debris is drawn on the map on the ancient topography.

Case study 5.1.2.B : "Randa" Canton of Valais
In 1991 an important rock-mass fall occurred on the left side of the Zermatt valley, NW of the village Randa (photo A). It happened in two phases : the first rock-mass fall on April 18^{th} (10 mio m^3) and the second on May 9^{th} (20 mio m^3). A thick layer of dust issued from mechanical fragmentation of the weathered parts of the gneiss settled down on the Zermatt valley (photos B and C). The rock-mass of April 18^{th} caused a seism of magnitude 3 on the Richter scale. It covered the Vispa river, a part of the village which was unoccupied at that moment and the Visp-Zermatt railroad along several hundred meters. On May 9^{th}, a more important layer of blocks covered the entire hamlet and a larger part of the railroad. The Vispa river was blocked and formed a lake which flooded a part of the village. This event took place on a ancient rock-fall site (photo D). The correcting measures were numerous : pumping of the waters flooding the village, then excavation of a channel across the debris, displacement of the road and the railroad, and finally excavation of a gallery bypassing the debris cone in the left side of the valley, in order to evacuate flood water in good conditions. The scar shows presently wide tension cracks in the gneiss and remains unstable. The total amount of the damage rose to 80 mio of Swiss francs. Photos from CREALP.

5.1.3. Subtype : Rock avalanche

Translation
F = écroulement D = Bergsturtz or Sturzstrom

Definition
Sudden fall of a huge part of mountain (>5 mio m^3). The fall movement leads to an extremely rapid debris flow.
It will be treated with the flow-type movements (see §5.5.10).

5.2. Topple

Translation
F = basculement, fauchage D = Kippen or Hackenwurf

Definition
Forward rotation, out of the slope, of a soil or a rock mass about a point or axis below the centre of gravity of the displaced mass (original definition of the International Glossary). Although topple phenomenon show many variations, especially more or less deep movement, no sub-type will be described here.

Figure 5.2.1 : Schematic profile of the superficial topple phenomenon in a slope. The flexion surface is potentially a slide surface but with a high rugosity.

Let us mention very deep toppling affecting massifs by decompression phenomena. It makes the rocks more fragmented and more permeable on a thickness that reaches about 500 m in Alpine central massifs (fig 5.2.2.).

Figure 5.2.2 : Deep toppling in Alpine massifs. In the south part of the Gothard road tunnel, phenomenon of deep toppling was observed at the time of boring of the tunnel. The zone of toppling is approximately 150 m thick and affects mainly the micaschists and gneiss of the Tremola series whose plans of schistosity approach the vertical. This phenomenon was accompanied by the apparition of springs inside the tunnel (points 1 and 2). Before these works, a fissural aquifer had been established in the solid mass. Considering other underground works in such Cristalline massifs, Maréchal could conclude to higher permeability of rocks down to 600 m below ground surface due to deep toppling (see graphic).

Typical geological material
- Principally anisotropic rocks (sedimentary or metamorphic) in steep dipping position.
- Rarely earth and debris material etc…

Mechanism
Decompression of rock massifs in slopes
Frost action in joints (ice swelling)
Hydrostatic pressure in joints
Edge effect of debris fallen in open joints

Geodynamic behaviour
Slow movement, more or less continuous. Topple can lead to rock fall or landslides.
Velocity : generally very low.

Intensity quantification
Intensity quantification is not so precisely defined as for rock fall. For example, this phenomenon is not specified in the official list of phenomena for hazard assessment procedure in Switzerland. Topple should be associated with landslides s.l. In such a way, intensity is characterized by velocity (see § 5.3).
Depth of rotation points is also a fundamental parameter.

Protection measures
Superficial topple can be stabilized by bolting or pillars. For deeper movements, drilled anchors are needed. Drainage boreholes are very efficient because they cut peak hydraulic pressures during critical wet periods. If an evolution toward a rock fall is suspected, measures for such movements should be implemented downwards.

Case studies

Case study 5.2.A : "Clairvaux Creek", Jasper, Alberta, Canada
Toppling have been studied in details for the Transcanadian Highway no16. Along the Clairvaux creek, the road cuts underdip slopes in a series of sandstones and slates of Precambrian. Such a thin bedded series is much exposed to topple. The non-toppled rocks are near vertical. The strike is subparallel to the road. The cut have a slope between 60 to 80°. The picture show the intense toppling which caused several intervention of the Road authority (rock scaling, ditch cleanup etc.). In this area, Cruden et al (1993) presented the two typical cases of toppling in such an underdip situation. Drawing a : complex rock topple rock slide. Drawing b : chevron topple

5.3. Slide

Translation
F = glissement D = Rutschung or Gleiten

Definition
As described in chap 2.1.3. the cinematic movement of a slide particles corresponds to a translational movement at the surface of the slope. All the particles of the mass are moving at the same direction and the same velocity (Fig 5.3.1). Shearing is concentrated at the foot and at the sides of the mass. In fact, "translational" must be considered at the small scale inside the mass. So, slide is distinguished with flow in which particles show a more erratic trajectories inside the moving body. At the scale of the whole mass, the slide movement can be translational or rotational or a mixing of both movements.

In practice, slide and flow movement are not always easy to distinguish because there is a geological continuity between these two phenomena. We propose to use as a main criteria the scale of the non-parallelism of particle trajectories : in sliding movements, the particles trajectories are mainly parallel at the decametre and hectometre scales (unlike the flow movement). This criterion is better than the thickness of the shear zone which can be rather high in some slide movements.

Figure 5.3.1 : Schematic profile of the slide phenomenon in a slope.

Typical geological material
- All type of rocks containing potentially shearing joints
- cohesive soils ("earth" according to Varnes definition) below the liquidity limit, rarely debris

See also subtypes.

Mechanism
Solid flow over a shearing zone. Triggering factors : erosion, hydrogeological conditions, seismology.

Geodynamic behaviour
Very variable from case to case. In competent rocks, sudden rockslides. In more plastic masses, more or less continuous movements.
Velocity : from very low to extremely rapid in the case of rockslides.

Intensity quantification
As many slide movements show a rather regular displacements, statistical event approach have no sense. The main intensity quantifications are :

- velocity
- thickness

In the Swiss regulation for hazard mapping, mean annual velocity characterises the low (< 2 cm/y) and the middle intensity. High intensity is defined on the base of peak velocities during special events (> 0.1 m/d for superficial movements or > 1m/event or if strong differential displacements take place).

Protection measures
Very variable according to the volume, the thickness, the velocity and the material (see subtypes).

Subtypes must be defined in this very wide and variable class of movements.

5.3.1. Subtype : Shallow rotational earth slides

Translation
F = glissement rotationnel peu profond en terrains meubles
D = oberflächliche Rotationsrutschung in Lockergestein

Definition
Shallow slides in unconsolidated formations (earth material) often present a more or less circular rupture form, especially if they have a short longitudinal extension and their structure is rather isotropic. They can lead to translational slides if they move on longer distances and also become flows if the water content is increasing downwards.

Material
Embankments (fig 5.3.2) and landfills (also mining landfills)
Lacustrine deposits
Glacial and periglacial deposits
Unconsolidated pyroclastic material

Figure 5.3.2 : Rotational rupture is the most common form of landslides affecting embankments, especially when they are built to rapidly on low permeability and compressible sediments. Photo LCPC.

Geodynamic behaviour
Velocity : Generally rather low velocity due to plasticity of material but can accelerate if fluidization occurs.

Protecting measures
Retaining walls with or without anchors
Runoff collection and drainage (often drainage also in the bedrock below earth cover)

Case studies

Case study 5.3.1.A : "Peney", Canton of Geneva.
The landslide of Peney affects the right side of Rhône River downwards Geneva. Thick quaternary deposits are unstable in this region, especially in the external side of meanders. Some of these landslides threaten buildings of the suburb of Geneva. The landslide of Peney is very near of the Verbois dam. The Rhône River have an artificial level about 15 m higher than the natural one. Sliding occur in the higher part of quaternary deposits : till and inframorainic silts which are aquifer. The base is a very solid layer of ancient alluvium. The movement is more or less continuous, varying slightly with rainfalls. Periodically, the reservoir is lowered in order to evacuate sediments. During such intervention, the movements become very high (more than one metre of displacement in one week at some places). Strong seepage stresses inside the silts due to high hydraulic gradient are responsible of the instability.

5.3.2. Deep rotational slides

Translation
F = Affaissement
D = Sackung

Definition
In rugged relief regions, some slopes present deep and large parts which are displacing as one mass in a slight rotational movement (fig 5.3.3). The internal structure is rather well conserved (fig 5.3.4). Depth can reach several hundreds of metres. The upper part of the mass

has a form of plateau. The lower part is showing very discrete convex inflection. The surface of rupture is steep. The sides are often underlined by slightly concave avalanche corridors. Such a slide can pass to a more superficial and more active translational movement when the material becomes more weathered and its structure broken down.

Figure 5.3.3 : Schematic movement of deep rotational slides.

Figure 5.3.4 : The Cornalle – Luges landslide starts from the top of the steep slope bordering the north of Geneva Lake. In this upper area, the rock mass moves like a step of stairs. The general structure of molassic strata remains but becomes a bit fuzzy (upper part of the picture). From the foot of this step, the molassic rocks looses its structure and become a homogeneous clayey mixture containing blocs of sandstone. The morphology corresponds to a classical earth slide or earth flow (lower part of the picture). The slide crosses the motorway, the railroad Lausanne – Bern and continues as a narrow channel to the Geneva Lake. Many drainage works make this landslide rather inactive presently.

Material

Generally rock material (variable lithology) with main structure not parallel to the slope (often dip opposite to the slope). The sliding surface can be complex and drawn by a net of connected joints.
Rarely Quaternary deposits.

Geodynamic behaviour

Velocity : Generally very low velocity (many slides dates from the last glacier retreat). Rarely, such a slide can suddenly pass to catastrophic rock mass movement (rock avalanche).

Protecting measures

Such large masses are very difficult to stabilize. It is more reasonable to learn to live with them. This means to avoid if possible making underground works inside them and to observe any eventual acceleration.

Case studies

Case study 5.3.2.A : "Hope landslide", British Columbia, Canada.
The huge deep rotational slide of Hope in British Columbia is mainly due to the weathering of the felsic and mafic rocks in the discontinuities. These zones of weakness are filled with a fine matrix of chlorite and fibrous amphibole. The mass of 48 mio of m^3 yielded brutally in 1965, covering the road under 50 m of debris and making 4 victims. It was believed a long time that this event was due to a seism because of a perfect coincidence with shocks measured on a seismograph of the area. In fact, studies of the spectrum of vibration showed that they were the consequence of the brutal rock slide and not the cause (after Clague, 1985).
Reference of figures :

a) *Geology of the Hope Slide (Von Sacken and others, 1992).*
b) *Pre- and post-slide longitudinal profiles of the Hope Slide. Note that only a small amount of rock was removed from the lower slope, below the lower fault (LF). Most of the rock came from the upper slope, above the upper fault (UF) (Von Sacken and others, 1992).*

c) *Section of Penticton records for January 9, 1965, the day of the Hope Slide (Weichert and others, 1994). The two events on the seismograms are interpreted to be the two phases of the landslide. Penticton in 120 km far from the Hope Slide.*

5.3.3. Translational rock slide

Translation
F = glissement translationnel (part. glissement couche sur couche)
D = Translationsrutschung

Definition
The sliding surface is near a plan. It often corresponds to the bedding of sedimentary rocks (also called "planar slide") or the main schistosity of metamorphic rocks. If the persistant joint family is slightly folded, the rupture surface can present a more or less undulated form.

Material
Sedimentary rocks containing argillaceous intercalations (fig 5.3.5)

Figure 5.3.5 : Landslide at Ecaravez in Belmont near Lausanne. On February 14th 1990, after intensive rainfalls, a rather rapid translational landslide occurred in the village of Belmont, eastern of Lausanne. A dipslope series in molassic marls and sandstones was truncated by the construction of a trench for a conduit. This work cut entirely the upper sandstone layer. The suppression of this support involved the landslide of the entire slope upwards the trench. The sliding mass destroyed a house and mud invaded other houses up to the first step.

Metamorphic rocks with continuous mica-rich layers.

Geodynamic behaviour
Velocity : Generally slow movement. Can present catastrophic acceleration due to works cutting the foot of the dipping layers (see Belmont)

Protecting measures
Bolting the unstable sheet of rock inside the stable one beneath if the thickness is low. If not, anchoring is necessary.
Drainage of sliding joints with boreholes.

Case studies

Case study 5.3.3.A : "Saillon quarry rockslide", Canton of Valais.
The quarry of Saillon was mining Dogger limestones of the inverse flank of the famous Nappe de Morcles in Central Alps (photo A). As in many old quarries, the extraction technique was made by the mining of rock material at the foot of the slope. In this case, the limestones layers are dipping parallel to the slope with angles varying between 40 and 60°. In April 1991, after the foot of a layer was exploded, the entire sheet of limestone slid very rapidly on an surface between two stata, which was very smooth and lustrated by old tectonic shearing movements (photo B). The rock slide happened just one hour after the workers lived the place early in the evening. The rock mass crushed the machines pouring out their fuel near the Sarve spring just below the quarry

(photo C). Fortunately the fuel tank containing several thousand of litres resisted to the shock. One hour sooner, the event would have kill several persons.

Case studies

Case study 5.3.3.B : "Vajont rockslide", Northern Italy.
In the sixties, the dam of Vajont was built on a tributary of the Piave River in the Italian Alps. The site of the dam was ideal for an arch dam : very narrow gorge in massive limestones. The catchment of the reservoir was less ideal because its left flank was known as rather unstable (scheme A). During the first filling up of the reservoir, the movements accelerated. After many discussions, it was decided to empty the lake. During this phase, on October 9th 1963, an important part of left side of the mountain broke down the slope. The movement was a rock slide on a stratigraphic contact in the higher part and a tectonic accident in the lower one.
The scheme C show the geology before rockslide and scheme D after. The unstable mass, estimated at 270 million m^3, slipped brutally to approximately 60 km/h and caused a gigantic wave whose height was more than 200 meters on the opposite flank of the lake. Then the wave turned left towards the dam and flew down the tributary valley at a very high speed. This colossal power didn't damage the dam, but destoyed the city of Longarone which was build on the alluvium cone of the tributary. This catastrophe caused approximately 1800 victims and flooding of 6 villages in the valley of Piave. The rock mass is occupying the entire volume of the lake behind the dam. The photo B shows the sliding surface and the mass from upwards with the small lake behind the rockslide. Since this event, a systematic mapping of landslides in the reservoir catchment was organized all around the world.

Case study 5.3.3.C : "St-German", Canton of Valais.
The village of St-German is constructed on a very nice terrace over the Rhône alluvial plain in Haut-Valais. This rather flat area corresponds to a thick accumulation of debris from a huge rockslide in a dipslope series of calcschists containing very smooth sericite interbedded contacts (photo A). In the beginning of November 2001, the excavation of the Alptransit-Lötschberg railtunnel drained heavily the liasic karst aquifer and the debris mass. The landslide debris, formerly aquifer, were exposed to compaction due to the suppression of the pore pressure (profile). This process caused a slight settlement in the part of the village built on coarse material (see map of settlement amplitude). Some buildings constructed on palustrine spring deposits showed a much larger settlement due to the deformability of such soils. In this zone and at its neibourhood, strong deterioration of houses occurred due to differential settlement. An important spring upwards the village, which was the water supply of the community, disappeared completely. A borehole in the most settled zone allowed to date the rockslide with ^{14}C in the beginning of the peat series, which was installed just after the event : 5000 years BP.

5.4. Spread

Translation

F = étalement D = Driften

Definition

The spread is the horizontal fragmentation and displacement of a rock series or a cohesive soil on a compressive layer. The spreading movement is accompanied by subsidence of masses of the upper material into the softer material. This last one is often liquefied and flow up to the surface between spread masses. In some cases, the horizontal extension can reach several kilometres. No sub-type will be described here.

Schéma

Figure 5.4.1 : Schematic profile of the spread phenomenon in a slope.

Typical geological material

- Principally cohesive soils (for example tills, fine lacustrine or structured peat) overlying liquefiable material such as silts, fine sands, lacustrine chalk or gyttjia.
- More rarely, in rock series, every sedimentary rock over soft rocks, for example soft claystones or siltstones.

Mechanism

Gravitational sliding on fluidised sheet with very low slope angle. Fluidization is often due to earthquakes.
High pore pressure below the cohesive series due to hydrogeological reason.
Weathering.

Geodynamic behaviour and velocities

In quaternary deposits, fluidization can occur and the movement can be rapid to very rapid.
In rock series, the deformation is more plastic and the velocity remains generally extremely low.

Intensity quantification

Spreading movements have no specific quantification systems. By analogy, the descriptors used for slides can be used : velocity and thickness (see §5.3).

Protection measures

Rafts of the upper cohesive formation can be retained by mechanical purpose such anchoring if the movement is slow. As the deformed layer has a fine grain composition, drainage stabilization is not really successful, except in fissured bedrock.

Case studies

Case study 5.3.4.A : "Capitol Spread", USA.
Slope failures and lateral spread occurs in Capitol Lake, Olympia (Washington, USA). The maximum vertical drop is 1 m. This event is related with the Nisqually earthquake that happened on February 28th, 2001. Landslides, debris flows and lateral spread were the consequence of it at various places of the province of Washington. Capitol was affected by liquefaction, lateral spreading and landslide. Several lateral-spread landslides occurred around the margins of Capitol Lake. The dike on the south margin of the lake failed in several places; some of the cracks that formed contained ejected silt, which indicates that liquefaction occurred. Water and sewer lines crossing the area were broken in places. Deschutes Parkway on the west margin of the lake was closed in several places owing to slumping along the edge of the lake. Delimitation of the mass affected by lateral spread is approximated. USGS, 2001

NB : The case of the peat flow of La Vraconne could be also designed as a spread (see §5.5.7)

5.5. Flow

Translation
F = coulée D = Fliessen or Mur

Definition
The basic trajectory of flowing particles is defined in §2.1. In the natural phenomenon, material is moving in a fluid phase with a rather irregular pattern, including non parallel vectors (fig 5.5.1).

Figure 5.5.1 : Schematic profile of the flow phenomenon in a slope.

According to the nature of the fluid, two main type of phenomena can be distinguished :
- water – solid mixture (wet movements)
- air – solid mixtures (dry movements).

For this type of landslide, the recent classification of Hungr (2001) is used defining several subtypes. They are structured into three subtypes groups (table 5.1).

Group	**Name**	**Material**	**Water content**	**Special conditions**	**Velocity**
Flow of rock	Rock avalanche	fragmented rock	Mainly dry	Volume>10'000m3	Extr. Rapid
Flow of coarse soils	N. liq. sand (s g d) flow	Sand, silt, gravel, debris	Mainly dry	No excess pore pressure	Various
	Sand (s d wr) flow slide	Sand, silt, debris, porous rock	Saturated	Liquefaction	Very - Extr. Rapid
	Debris flow	Debris	Saturated	Inside torrential extension	Extr. Rapid
	Debris avalanche	Debris	Part. or fully sat.	Outside torrent. Channels	Extr. Rapid
	Debris flood	Debris	Free water	Flood	Extr. Rapid
Flow of fine soils	Earth flow	Clay or earth	Near plastic limit	Plug movement	Moderate or lower
	Peat flow	Peat	Saturated	Excess pore pressure	Slow to very rapid
	Mud flow	Mud	At or above liq. Limit		Extr. Rapid
	Clay flow slide	Quick clays	At or above liq. Limit	Liquefaction	Extr. Rapid

Table 5.2 : Synthesis of the ten subtypes retained for the present lecture. They are grouped according to the main material classes.

For the distinction between some subtypes, a more precise characterisation is necessary, especially to determine the dynamic behaviour of the flow movement. They are based on the consistency limits :

Plasticity Index (PI)
PI<5% Non cohesive material Sorted (gravel, sand, silt), unsorted (debris)
PI>5% Cohesive material Sorted (clay), unsorted (earth, mud)

Liquidity Index (LI)

LI<0.5	Plastic	Sorted (clay), unsorted (earth)
LI>0.5	Liquid	Sorted (quick clays), unsorted (mud)

Recall :

$$LI = \frac{(w_n - w_p)}{(w_l - w_p)}$$

avec
w_l = liquidity limit
w_p = plasticity limit
w_n = natural water content

Hungr proposed the following criteria (table 5.2) :

Cohesion	Liquefaction	Sorted material	Unsorted material
IP>5% ?	IL>0.5 ?		
No	No	**Gravel, sand, silt**	**Debris**
No	Yes	non existant	non existant
Yes	No	**Clay**	**Earth**
Yes	Yes	**Quick-clay**	**Mud**

Table 5.3 : Summary of the criteria used to define the material in flow movements (after Hungr 2001).

5.5.1. Subtype : Non-liquefied sand (silt, gravel, debris) flow

Translation
F = coulée dans des sables, limons, graviers, débris non liquéfiés
D = nicht flüssiger Sand – Silt – Kies – Gehängeschutt Fliessen

Definition
Dry sand and silt flow are a common phenomena which control the limit slope of lee sides of dunes in deserts. When the eolian transport overpass the stability angle of the dry sand or silt, rupture begins with a planar slide upwards, continuing by a typical flow form (fig 5.5.1). The friction angle of the material is the dominant variable.

Figure 5.5.2 : Flow movement on the slope of a sand dune.

Such a movement in saturated coarse deposits on the front of deltas present the same morphology and a similar dynamics. The movements does not involve excess pore pressure. They are small scale movements which should not be confounded with the large subaqueous flows leading to the formation of the deep sea fan.

Protecting measures
In the case of dunes, vegetal colonization of the slope (if the climate makes it possible) can reduce the risk of such flow.

5.5.2. Subtype : Sand (silt, debris, weak rock) flow slide

Translation
F = coulée dans des sables, limons, débris, roches tendres
D = Sand – Silt – Gehängeschutt – verwitterter Gestein Fliessen

Definition
In saturated conditions, some uncohesive soils can lead to very rapid flow movements by liquefaction and / or excess pore pressure. Before the flow movement, the material is in a meta-stable equilibrium due to internal structuring. A trigger event (increase of water pressure or a slight seismic vibration) causes an instantaneous collapse of the structure and the liquefaction. Pore pressure can increase up to the total stress. This mean that the effective stress tends to zero as well as the contact between grains. Such conditions may exist only in a basal layer which cause the rupture. In that case, the phenomenon is identified indirectly by the behaviour of the slope. The liquefaction can occur only after a first displacement of the mass (the term flow slide means that an initial slide phenomenon evolves into a flow).
The flow slide is very rapid and can affect large masses on very gentle slopes. Thus it is very dangerous (see case studies in Italy and Wales).

Such flow slides are observed in present lacustrine or marine talus. In terrestrial deposits, loess are very vulnerable. Porous rocks such as chalk or pyroclastic rocks are concerned by the same type of phenomenon (case study 5.5.2.A). Even artificial uncohesive deposits like waste or mine tailings are affected (case study 5.5.2.B). Quick clays form also flow slides but will be treated in the group of cohesive soils (see §5.5.9).

Protecting measures
A preventive measure is the detection of such potential instable zones by mapping and mechanical tests on probes. In such identified zones, drainage is the only way to reduce failure potential.

Case studies

Case study 5.5.2.A : "Campania", Southern Italy
Soft ash deposits around volcanoes are very vulnerable to liquefaction. During strong rainfall, shallow rotational landslides occur at the upper part of the slope when the permeable ash is deposited on an impermeable bedrock. As the ashes have generally a very low cohesion, such landslides evolve often into flow slides which can be catastrophic. For example, on May 5th to 6th 1998, prolonged rainfall triggered numerous landslides in a 70 km^2 mountain area of the Campagnia region, causing a lot of damages. This type of landslide involves pyroclastic fall deposits of the Somma-Vesuvius volcanic system. Flow slides in this area initiate as a debris slide, involving pyroclastic and colluvial soils (0.5-2 m thick), on steep and vegetated slopes at the head of gullies.
a) The region concerned eastern of Vesuvio.
b) Map of the landslides and of the flow slides
c) Initiation of the movement by landsliding, then flow slides inside the channels.
d) Detail of the stratified deposits of ashes in place.
e) Scarp showing superficial sliding of the ash cover including vegetation
f) Damage to the villages down the flow slide paths.
References of images :

b) Guadagno and al. in Landslide News n°12, june 1999.
c) Modified from Guadagno and al. in Landslide News n°12, june 1999.
a)+ d) + e) + f) Del Prete, Guadagno, Hawkins in Bulletin of Engineering Geology and the Environnement n°57, September 1998.

Case study 5.5.2.B : "Aberfan colliery", South Wales
The main mountains in Wales are artificial : slag heap of mines. That is one of these anthropogenic hill that caused the dramatic flow slide of Aberfan colliery (on 21 October 1966). One of the tips near of the village of Abefan collapsed. These rather coarse and uncohesive material from coal extraction slid and became liquefied. Its velocities was of about 30 km/h. The liquefied tongue invaded the village with a thickness of 7 to 9 metres. Thus it destroyed some houses and a school. 147 people were killed including 116 children. Some elements are to be considered about the causes of such instability : rainy climate, erratic management of the waste brought on the heaps, slope angle controlled by the tipping of waste, low shear strength between waste elements due to clay interstrata and graphite on the faces of blocks. We can think that this last factor is decisive in this case because many mine heap exist in so humid zones as Aberfan and they are generally poorly managed. Slow rotational landslides of small amplitude are very frequent but the behaviour of Aberfan tip remains exceptional.

5.5.3. Subtype : Debris flow

Translation
F = lave torrentielle
D = Murgang

Definition
Debris flow corresponds to the very rapid (several m/s) movement of saturated not plastic material inside a torrential channel. Material is eroded in steep channels (slope generally > 15 degrees) and sedimented on a depositional fan (fig 5.5.3 and fig 5.5.4)). The material which is susceptible to lead to a debris flow is comprised between two grain size distribution curves (fig 5.5.4). These flows are discontinuous : surges, separated by flood interludes. This kind of recurrent event is an ordinary process of mountainous stream bed evolution.

Figure 5.5.3 : Debris flow on Transhimalyan Road, North India, which cut the only road to Ladakh and destroyed some houses near the channel. The deposit show that the boulders are not rounded and enveloped by a non-abundant silty and sandy matrix.

Figure 5.5.4 : Some events of debris flow can transport coarse material only, without any fine matrix. This photo illustrates a case of debris flow in a granite region western of Katmandu (Nepal), near of the village of Daman. The granitic catchment is covered by ball of granite, which is the ordinary form of weathering in such rock. During a recent event, a debris flow formed a cone of rounded boulders of granite at the confluence with the main river.

Figure 5.5.5 : Domain of grains size distribution of soils in the French Alps, which are vulnerable to debris flow, after Bonnet Staub

The condition of an established channel shows the dominant role of surface water brought by the catchment for the locomotion of the debris. So, it differs fundamentally from debris avalanches which is more the response to a hydrogeological pressure (see §5.5.4).

There are intermediate cases where hydrogeological overpressure are developed under a stream bed (Case study Les Clées). Strong upward gradient inside fine stream sediments lead to a sudden erosion of the alluvium.

Protecting measures
As debris flow is a current phenomenon, it is common to reduce their impacts by building cascade of dams inside the channel in order to reduce the kinetic energy and retain the solid material (Case study Pissot). This measure is possible at various scales, for example timber construction for small brooks.

Case studies

Case study 5.5.3.A : "Illgraben", Canton of Valais
The case of Illgraben is one of the most active zone of erosion and debris flow. This is due to a very deep erosion trough in quartzite and dolomites which are much deformed and weathered (photo B). The sediment transport is so important that the cone at the outlet of the trough was several time devastated by debris flow (photo A). In the middle of XXth century, a series of dams was built in the talweg to reduce the velocity of the creek. These works were much efficient but were rapidly filled by sediments and some of them bypassed by the creek. This catchment is now instrumented by WSL to study the propagation of debris flows with many monitors and a video camera. Some very interesting events were so registered. Photo C : front of a surge of the debris flow on June 28th, 2000 (approximately 15 km/h and 60' 000 m3).

Case study 5.5.3.B : "Pissot", Canton of Vaud
On August 13th 1995, at about midnight, a sudden debris flow occurred in the Pissot creek (photo A), due to a very intense rainfall into the very steep mountainous catchment (photo B). The fluid material (about 50'000 m^3) left the perched channel built to cross the highway and invaded the road. Some cars collide with the debris mass (photo C). By chance, there was no fatality. The highway was cut during 2 days, diverting all the traffic of the Simplon axis through the city of Montreux. At the time of conception of this highway (end of the years sixties), the debris flow hazard was not at all considered. Only a peak discharge of water was taken into account for the dimensioning of the channel. After the event, a very large basin was excavated in order to retain sediments upwards the highway (photo D).

5.5.4. Subtype : Debris avalanche

Translation
F = coulées boueuses (the term **"ovailles"** is used in Valais for this phenomenon)
D = Hangmur

Definition
Very rapid to extremely rapid flow of debris issues from the cover material of a slope, outside the hydrographical channels. The soft material, of low plasticity, becomes unstable due to groundwater pressures in underground, often in fissured bedrock. The condition for such movement is a permeability contrast between soft cover and the aquifer : the aquifer must be permeable to induce a strong response to pluvial events. The cover must be low permeable to allow confinement of hydraulic pressure below it. High hydraulic ascendant gradient appear in the cover leading to suffusion of grains, and a sudden flow of fluid material down the slope (fig 5.5.6).

Figure 5.5.6 : Mechanism of debris avalanche due to permeability contrast between aquifer and cover.

The material can be more or less the same as the one for debris flow, from different origin : weathering mantel of non argillaceous rocks, moraines, slope debris or sometimes simply topsoil (fig 5.5.7). For example, molassic rocks of the Swiss Plateau show often such conditions : the sandstones are fissured and react strongly to rainfalls. In the slopes, sandstones are covers by sandy and silty uncohesive colluviums, which are rather impermeable and near their equilibrium limit. In some cases, despite the low volume of material, the debris avalanche can be dangerous due to their velocity (fig 5.5.8).

Figure 5.5.8 : Two persons died in this house at Orsieres in Canton Valais, when the debris avalanche destroyed the backside of the house (photo A). The avalanche was originated in sandy layers of a glacial terrace (photo B). After heavy rains and snow melt, the sandy layers became confined below the colluvial cover. The victims were sleeping in a room built at the rear side of the house. This extension, build with light structures, could not resist to the impact of the flow (photo C).

The phenomenon is generally not recurrent and thus more difficult to forecast than debris flows. The behaviour of groundwater is also more difficult to observe than superficial water. After reaching a stream bed, debris avalanche can evolve into a debris flow.

Protecting measures
As forecasting is difficult in a large territory, the systematic protection is impossible. In sites where this hazard could occur, threatening important objects, a good prevention can be obtained by draining slopes with subhorizontal boreholes. They avoid a pressure heave in the underground during rainy season.

Case studies

Case study 5.5.4.A : "Debris avalanche of Gondo", south of Canton Valais
In October 2000, the southern side of the Alps lived an exceptional rainfall event. A kind of mini-monsoon coming form North Africa and crossing the Mediterranean Sea brought about 700 to 900 mm rain in five days. The village of Gondo is built at the foot of a huge cliff. A retaining wall was constructed to stop the numerous blocks falling of the cliff (see scheme). At the foot of the cliff, a debris cone is superposed to till deposits on which the village was built. During this event, a maximum of water penetrated the permeable cone of debris due

to the infiltration of runoff on the cliff. The base of the debris is rather impermeable. Thus, this perched formation, generally drained intensively at its foot, became saturated up to exceptional piezometric level. The percolation forces at the outcrop of the groundwater table lead to a rapid landslide of these uncohesive terrains. The slide leant against the retaining wall, which was not dimensioned for such a stress. After some minutes, in conjunction with erosion of its foundation by runoff water, the wall collapsed. The wall and the debris destroyed ten houses in the centre of the village and killed 14 persons (photos A and B).

Case study 5.5.4.B : "Les Clées", Orbe Gorge, Canton Vaud
The flow that occurred on 2001, on the left side of the Orbe Valley, in an intermediate case between debris avalanche and a debris flow. If we consider the root of the phenomenon, its is a debris avalanche because the movement was initiated by a hydrogeological pressure in a spring zone. Fluvio-glacial gravels and sands were clogged below a colluvium cover of low permeability. Due to intensive rainfall, this silty and sandy mantel collapsed suddenly and flew down the small talweg downwards the spring. The rests of the flow on the sides on the talweg and on the trees show that the wave was about 5 m high and the velocity about 10 m/s. The wave impacted and ejected a car parked in the talweg.

5.5.5. Subtype : Debris flood

Translation
F = transport solide hyperconcentré
D = hyperkonzentrierte Ströme

Definition
According to Hungr et al (2001), debris flood is a very rapid, surging flow of water heavily charged with debris, in a steep channel. The word "flood" show clearly that this phenomenon is more corresponding to stream flow than to landslides. This is an intermediate between debris flow, where the solid mass is predominant, and a flood. The ratio solid/liquid can be used theoretically to distinguish these phenomena. A limit of 80% of solid concentration is proposed to separate what is also called hyperconcentrated flow and debris flow. In practice, it is difficult to use such criterion to distinguish these two transport processes and in fact there is no clear physical limit. Debris flood is sometimes directly issued from landslide areas (fig 5.5.8)
Two main differences are more usable in the field. If we have chance to observe the event, the peak velocity will be the best way : the debris floods have velocities which are similar to main floods (some m/s); on the contrary, debris flow can show maximum velocities up to ten times higher. A difference is also usable by studying the general form of the deposits : more regular and flat for debris flood, more erratic for debris flow.
It is common that debris flow evolve progressively into debris flood in the lower part of the stream course or of the fan, when the slope is decreasing.

Protecting measures
Debris floods are in principle less destructive than debris flow because the kinetic energy of boulders is not so high (except exceptional floods issued from dam rupture or glacier outburst or other major catastrophic event). The sediments invade the buildings without destroying them. The prevention of this risk is the same as for debris flows.

Case studies

Case study 5.5.5.A : "Debris flood on Krishnabir Landslide", Nepal
Debris flood is frequent in the catchment of Krishnabir landslide, which cut the main road between Katmandu and India. Runoff at the surface of landslide transports a large amount of debris, which sediment partially on the only flat zone of this slope : the road itself. This stops regularly trucks that try to cross the landslide and then stops the entire traffic for some days.

5.5.6. Subtype : Earth flow

Translation
F = coulée de terre
D = plastisches Fliessen

Definition

Earth flow is a movement of clayey material in its plastic and viscous behaviour. The velocity can vary in time from slow to rapid during acceleration phases, due to pore overpressures. The material is similar to the one of earth slides (over-consolidated clays, weathered soft rocks etc.) but with a greater mobility, a more elongate form like a tongue. The internal distortion of the material is also much greater, even if in the earth flow also the main shearing deformation are observed at the limit of the mass (see Example of landslide Cornalle – Luges which corresponds to deep earth flow from its middle part to its toe, fig 5.3.4).

As earth flows can form rather long tongues, the arrival of the toe in a stream bed creates a obstacle to the river flow. Because the material is cohesive, it is not easily eroded and a large dam can seal the talweg and form a large lake behind it. This corresponds to a very critical situation if it is not possible to maintain with machines the passage of water. Such an example of river invasion was spectacular in the case of Champlin landslide in Canada with a clay flow slide (see case study "Champlin landslide").

Earth flow are often very superficial and affect only vegetated soil cover of temporary of permanently frozen slopes. Two case must be distinguished in such situation :

Reptation or surface creep (F = reptation, D = Hangkriechen)

The superficial soil is homogeneously creeping without any landform (fig 5.5.9). These movement are recognized by their effect on all superficial structures on the slope (walls and poles tilting).

Figure 5.5.9 : Frost action on superficial soil induce a slow translation of the particles composing the soil. This movement is the resultant of freezing of superficial soil at each freezing – thawing cycle : freezing induce a soil heave perpendicular to the slope (arrow 1). When thawing, the surface is lowered vertically (arrow 2). The resultant is a translation along the slope (arrow 3).

Solifluction (F = solifluxion, D = Solifluktion)

If soil freezing – thawing cycle implies high water content (impermeable underground), the creeping movement becomes heterogeneous. Liquefied soil push down the cohesive vegetated cover creating a series of tongues (several meter to some decametres) very typical morphologically (fig 5.5.10)

Figure 5.5.10 : Solifluxion tongues on a the northern slope in the Alps. Furka Pass, height = 2450 m

Oversaturated fine soils in arctic regions can flow on the permafrost due to the impermeable property of such underground (fig 5.5.11).

Figure 5.5.11 : A solifluxion tongue on permafrost in northern Siberia, which broke out during the slide movement and making visible the liquefied material.

Protecting measures

Except during surges due to pore overpressure propagating like waves inside the mass, the earth flows themselves are not dangerous for man. But they are difficult to stabilize because the viscous behaviour of the material (difficulty to retain it mechanically) and its low permeability (difficulty to drain it efficiently). The best prevention is the collection of runoff waters with ditches using deformable matters.

Case studies

Case study 5.5.6.A : “Pavillon Earth flow”, Canada

5.5.7. Subtype : Peat flow

Translation

F = coulée de tourbe
D = Torf Fleissen

Definition

The organic structure of peat leads to a very frictional behaviour. Despite this property, peat can move rapidly when groundwater overpressure occur below the layer. The overpressure can be originated by hydrogeological conditions at the limit of the palustrine area. As the specific weight of vegetal fibres are more or less the same as water, it is very easy to make peat floating on an oversaturated layer. When the rupture is achieved, the movement can take place on slopes of some degrees only (Case study Vraconne).

Protecting measures
If this problem is detected, drainage of the layer below the peat is efficient. But sometimes, such a measure is not sustainable environmentally. It leads also to important settlement. A better way is to control the hydrogeological contact with the formations of the flanks of the swamp zone and to cut overpressures in these aquifers during pluvial events only, in order to maintain the palustrine character of the site.

Case studies

Case study 5.5.7.A : “Peat flow of La Vraconne”, Jura, Canton Vaud

5.5.8. Subtype : Mud flow

Translation
F = coulée de boue
D = Schlamm Fliessen

Definition

Inside stream beds, clayey plastic material (Ip>5%) is placed in presence of a very high amount of water. It can reach or even exceed the liquidity limit. The material becomes semi-liquid (mud) and flows very rapidly. This phenomenon was observed particularly in arid climate where clay passes suddenly from a dry state to saturation during storms.

Mud flow is the geodynamic equivalent of debris flow (see §5.5.3) but with cohesive and plastic material. The velocity regime is thus a bit smoothed in comparison with debris flows.

Liquefaction in mud flows needs surface water, what is not the case of clay flow slide (see §5.5.9).

Protecting measures

As the material is difficult to drain because the low permeability, the only way to tend to reduce the hazard is the collection of surface water (see also §5.5.4).

5.5.9. Subtype : Clay flow slide

Translation
F = coulée dans les argiles sensibles
D = Fliessen von empfindlischen Töne

Definition
Clay flow slide is a very rapid to extremely rapid flow of sensitive clays (“quick clays”) at or close to their original water content. Generally the clays have a glacio-marine origin and contain sodium ions in the fluid between clay particles. Sodium affinity for clay particles

create a very porous but strongly aggregated structure. Even over-consolidation is sometimes observed. Due to isostatic uplift of ancient glacial areas as Scandinavia and Canada, these deposits are exposed since some thousand years to pluvial regime. Progressively the hydrogen cations replace sodium by leaching. The internal structure of clay becomes meta-stable. A very light stimulus (for example a mechanical remoulding or a small landslide) can break the aggregation and make the clay very liquid if it is saturated. The process is reversible in laboratory : adding salt to the mud make it stiff again.

Quick clay event are generally spectacular and catastrophic. The famous film made by a amateur photographer in Rissa, inside a fjord of Norway, is an impressive testimony of such destruction (fig 5.5.12). An initial landslide expend retrogressively in a for of channel where clay is flowing with angles of some degrees. On the side of the channel, raft of clays are detached and move in mass at speed of some tens of km/h, transporting more or less intact houses. After some distance, the raft looses its integrity when clay becomes fluid and flows in the channel. Eastern Canada have been also largely exposed to this hazard.

Figure 5.5.12 : Rissa photo.

Some clay flow slides have occurred in non sensitive clays. The process controlling this phenomenon remains unknown.

Protecting measures
Prevention is needed in suspect zones. The clays are collected by boreholes and are tested in laboratory. A hazard map is made on the base of these recognitions. But the phenomenon remains dangerous because it is difficult to forecast when a failure will occur.
In vulnerable zones, works conception must be very careful. Locally, for a special working place, sodium can be injected in boreholes before excavation. However, due to the small permeability of clays, the efficiency of injection is very local around the borehole. Mechanical preventing stabilisation is more practicable in order to prevent any remoulding of the clay.

Case studies

Case study 5.5.9.A : “Ch”, Champlin landslide”, Ontario, Canada

5.5.10. Subtype : Rock avalanche

Translation
F = écroulement
D = Sturtzstrom

Definition
In §5.1, we presented the slope instability by fall movements. According to the size of particles, we could separate rock-particle fall and rock-mass fall. When the mass of falling

rock or sliding rock becomes very important, other mechanisms lead to an exceptional widespread distribution of the debris. This kind of phenomenon was first treated and defined by Albert Heim in the Alps in 1932. He studied several historical Strurzstrom events as reported in chap 1. The very large kinetic intensity due to collisions between particles (velocities up to several hundreds m/s) allow them to be transported very far from the source massive. The common h/l ratio have exceptionally low values (fig 5.5.13). For such movements, a minimum of 7 million of cubic meters source material is needed, according to Shu.
Some authors pretend that a vapour pillow formed at the base of the debris, generated by the large internal energy and then water vaporisation, should explain this long flow distance.
Rock avalanches concern mainly elastic rocks of various petrography (limestones in Mt-Granier, conglomerates in Arth-Goldau etc.), while weathered rocks lead to more common rock falls.

Figure 5.5.13 : Compilation of the ratio fall height / horizontal extension (h/l) for the main events. After Hutchitson 1988.

Protecting measures
Rock avalanches are generally unpredictable. It is difficult to distinguish cliffs that could evolve into a common rock fall or into a rock avalanche. Potential instable masses are so huge that stabilization works are unthinkable. Protection against debris is also rather impossible due to the high kinetic energy.

Case studies

Case study 5.5.10.A : “Elm Sturzstrom”, Central Switzerland

Case study 5.5.10.B : “Frank slide”, Canada

5.6. Collapse

Translation
F = effondrement D = Absenkungs und Einsturtzphänomene

Definition
Collapse of the ceiling of karstic or artificial cavities. The ceiling can be made of rocks or cohesive soils. The collapse can be sudden, creating a open hole up to the surface, or progressive, leading to soil subsidence and closed topographical depressions, without superficial drainage (fig xxxx). Notice that subsidence due to consolidation of porous soils is not included in this phenomenon.

Schéma à prendre dans ECA

Figure xxx : Collapse typology.

Typical geological material
- Karstic rocks, mainly gypsum and carbonates, with or without soil cover
- Every kind of rocks concerned by underground building and mining

Mechanism
- Dissolution of soluble rocks, weakening of the ceiling of cavities by tectonic joints and weathering processes, underground particular erosion (piping) during heavy infiltration rates.
- in artificial cavities, weakening of ceiling and pillars by mechanical crushing and weathering, hydrogeological modifications.

Geodynamic behaviour
Sudden collapse is often (but not always) occurring during heavy infiltration events, thaw of frost soils, or seismic vibrations (earth quake or traffic). Sometimes, the collapse is announced by an increase of soil subsidence, foundations ruptures, or noises.
More or less regular subsidence can evolve very gently, with or without evolution into a complete collapse of the cavity.
Velocity : the very sudden collapse have a duration of some seconds, for example in the case of fragile rock ceiling such as massive limestones. It can also take a much longer time if a soil cover is present.

Intensity quantification
For the risk of rapid collapse, quantification is given in terms of the probability of sudden event, the surface of land concerned and the depth of the hole expected.
Subsidence is quantified by the surface affected and the rate of subsidence measured by topographical measurements (fig xxx)

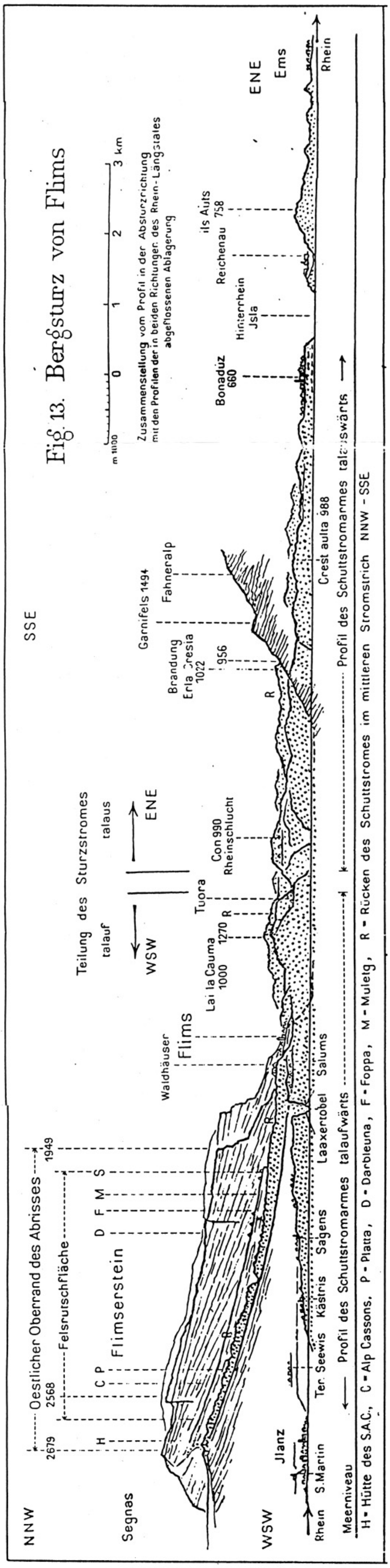
Schéma à prendre dans ECA

Figure xxx : Subsidence rates defined for the building insurance company in the Vaud Canton.

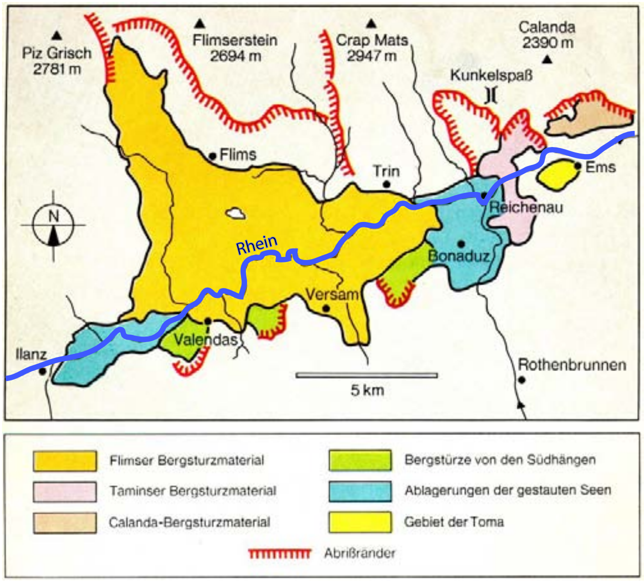
Case studies

Case study 5.6.A : “Bex”, Canton Vaud

Fig. 1.1 : Flims in Graubünden Canton



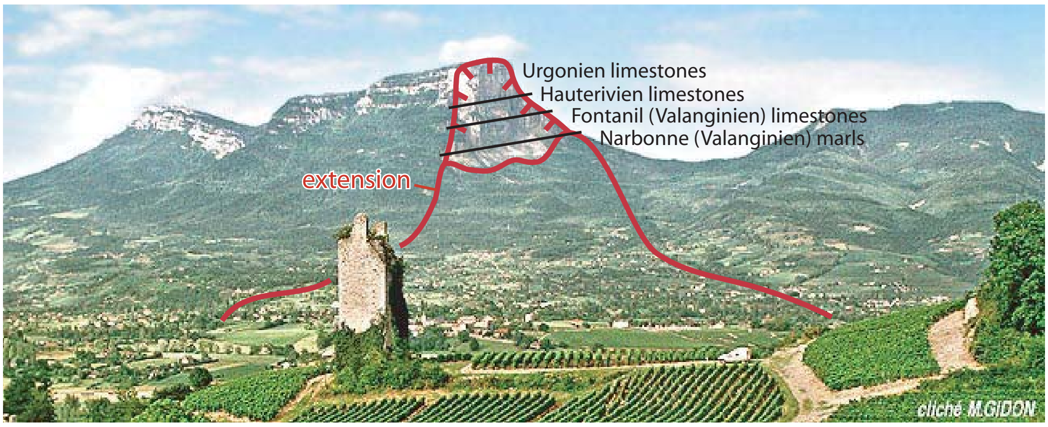
Heim, 1932

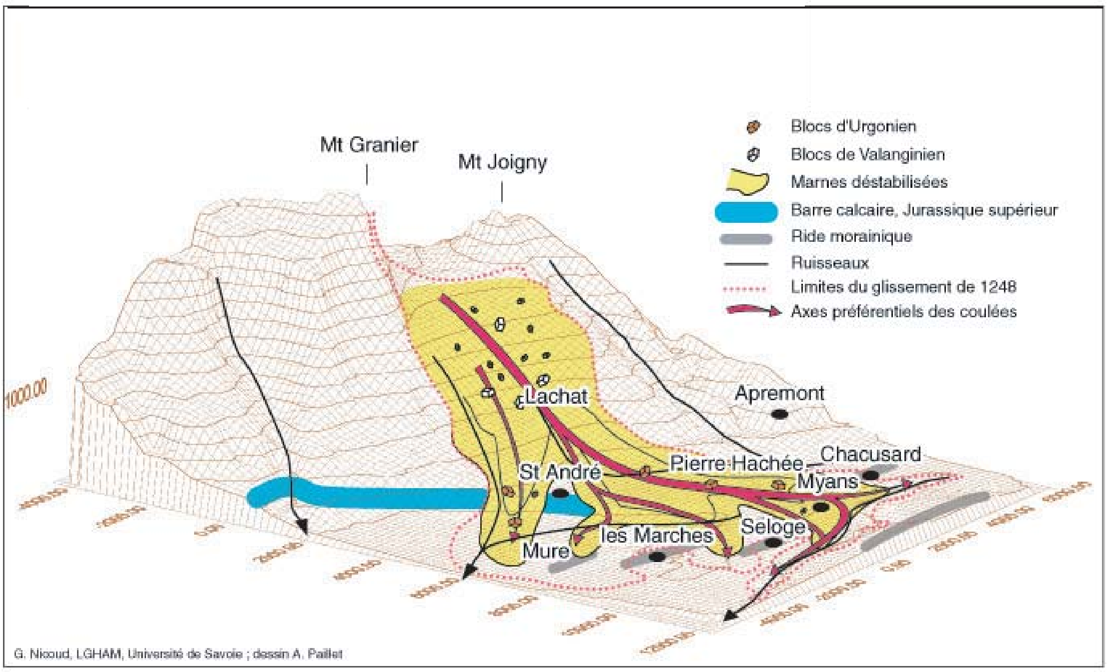


Heierli, 1977

Photo taken in www.geo.unizh.ch

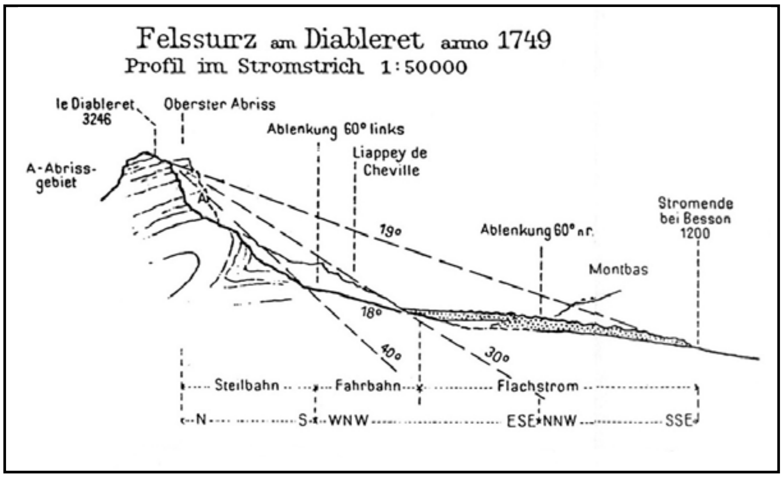
Fig. 1.2 : Mont-Granier (Chartreuse Massif, French Alps)





Nicoud, 1999

Fig. 1.3 : Derborence in Valais Canton



Heim, 1932

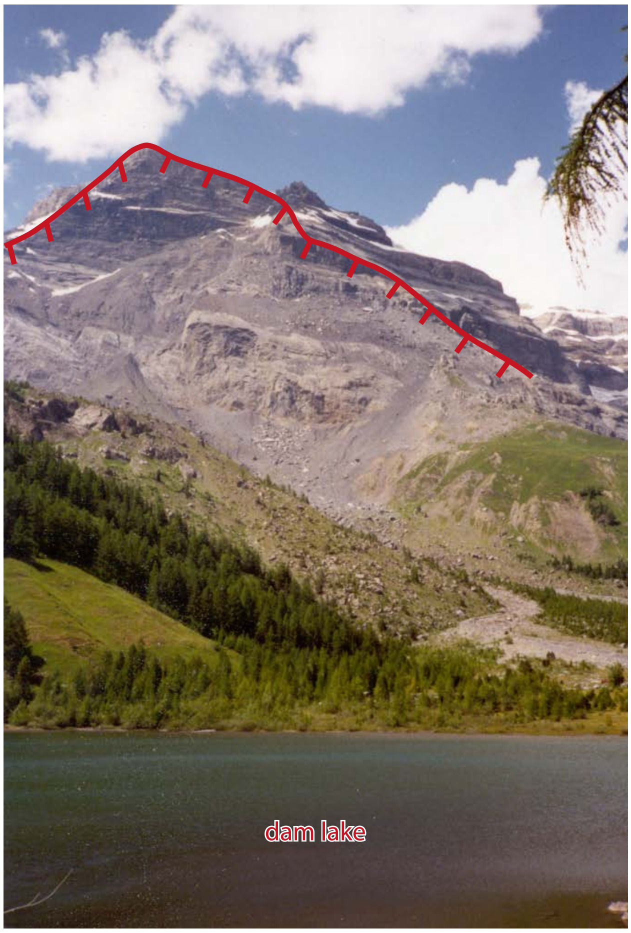


Photo Parriaux

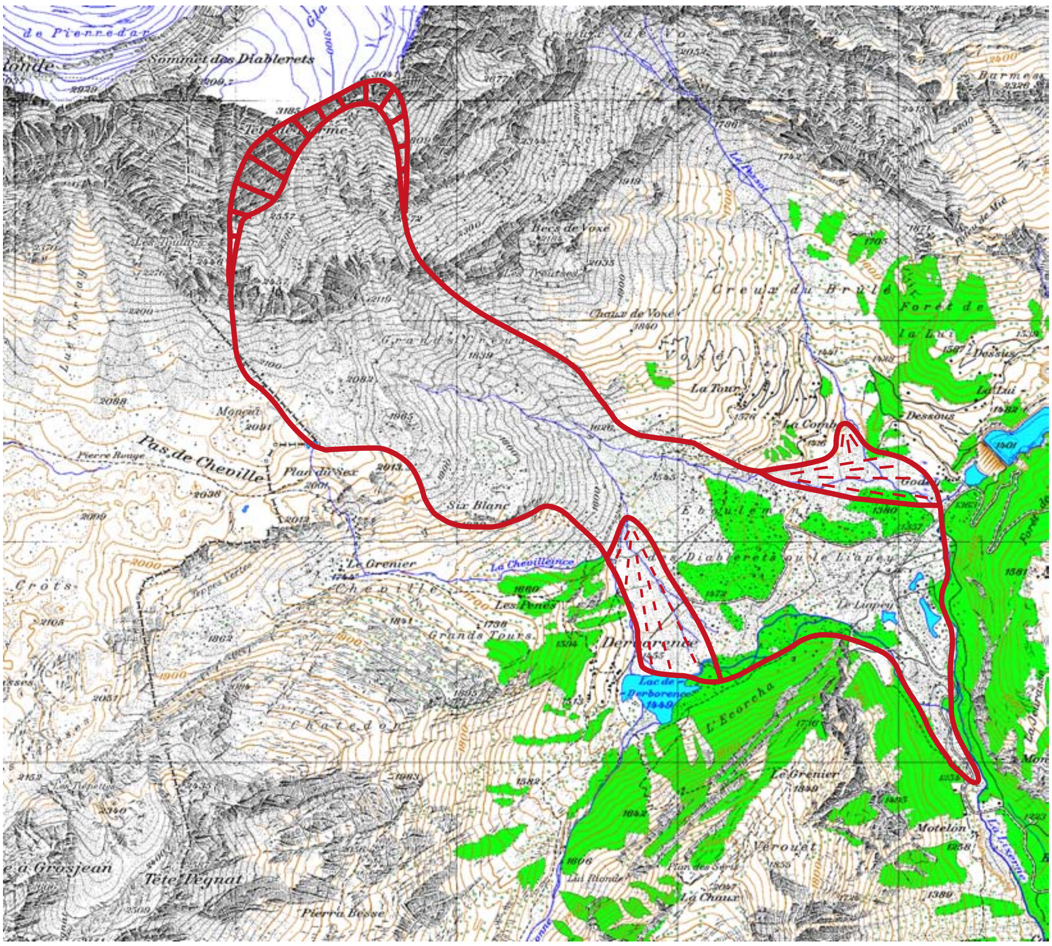
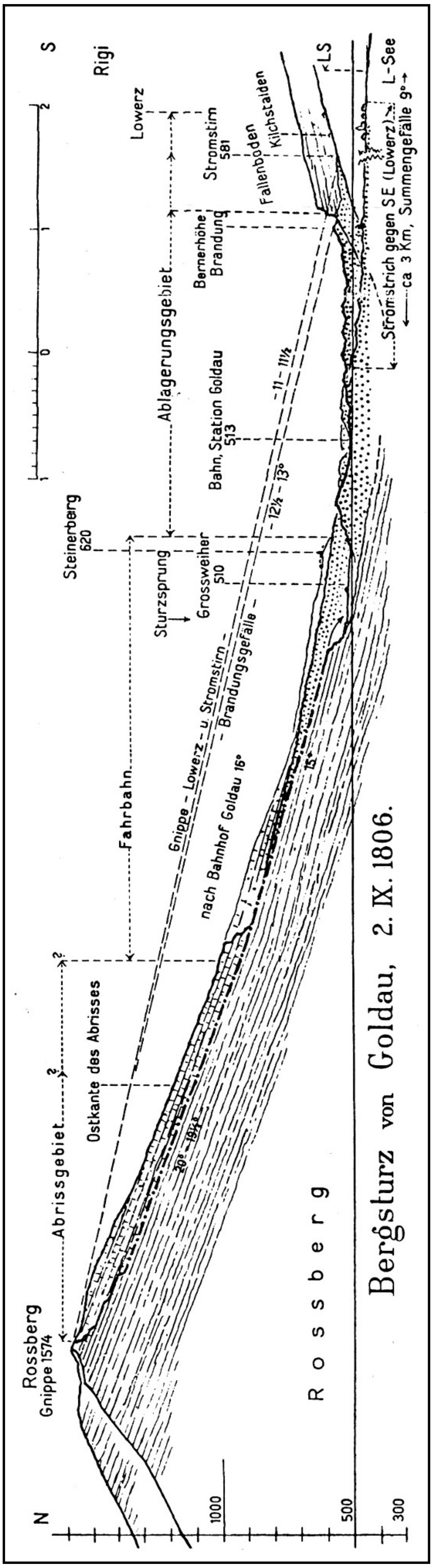


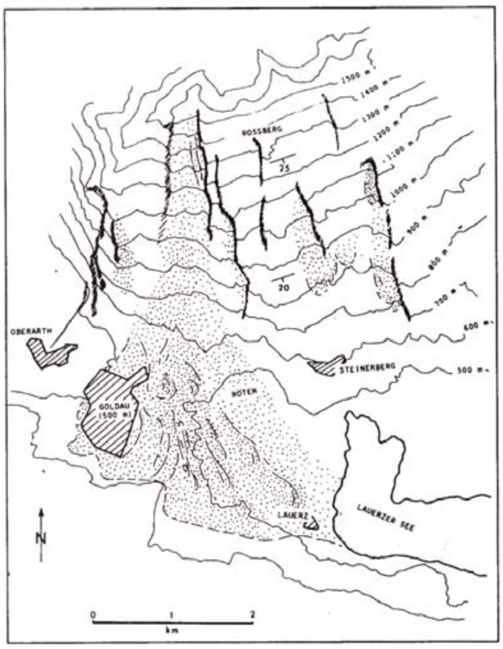
Fig. 1.4 : Arth-Goldau in Schwytz Canton



Heim, 1932

Photo Parriaux

Photo Parriaux



Map of the rock avalanche, Turner & Schuster, 1996

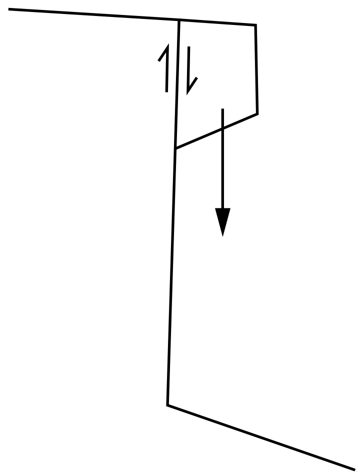


Fig. 2.1 : Fall

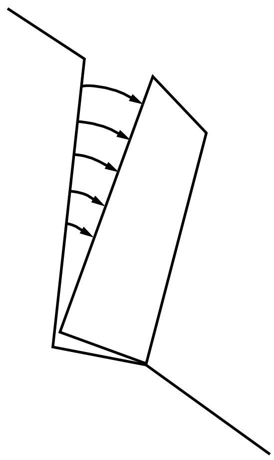


Fig. 2.2 : Toppling

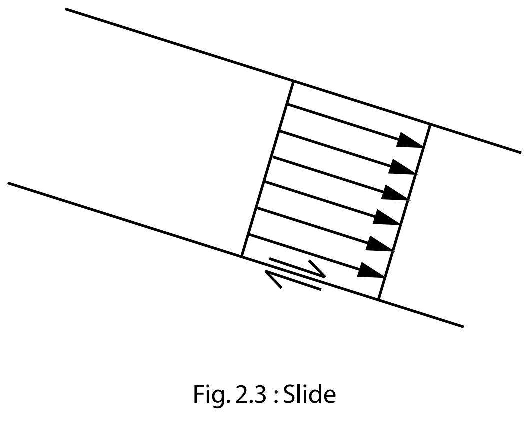


Fig. 2.3 : Slide

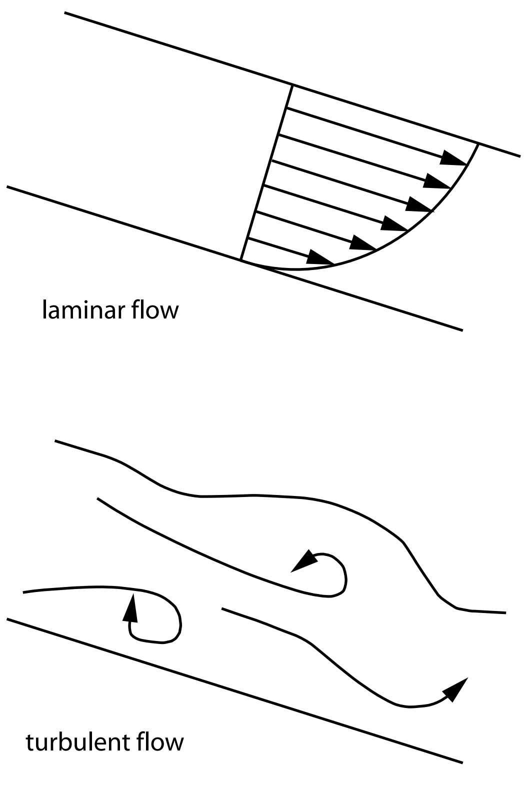


Fig. 2.4 : Flow

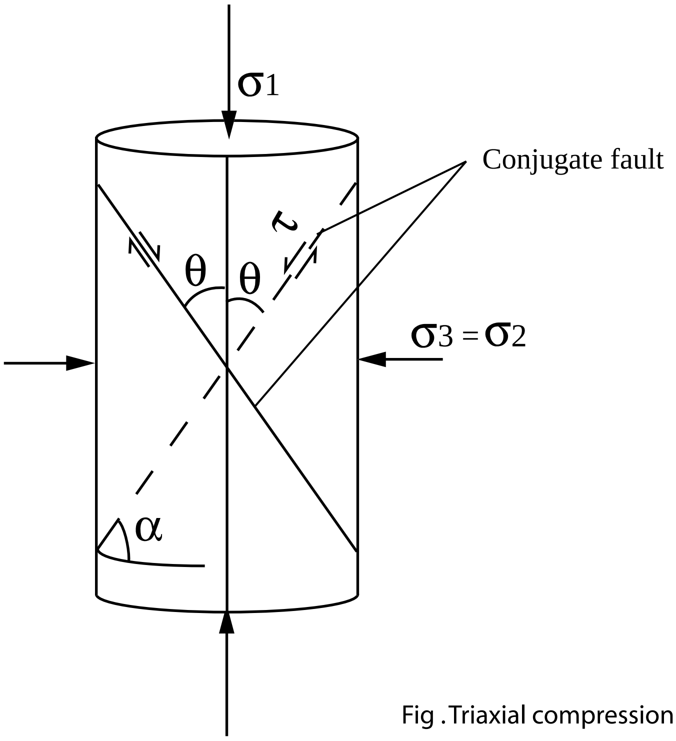


Fig .Triaxial compression test.

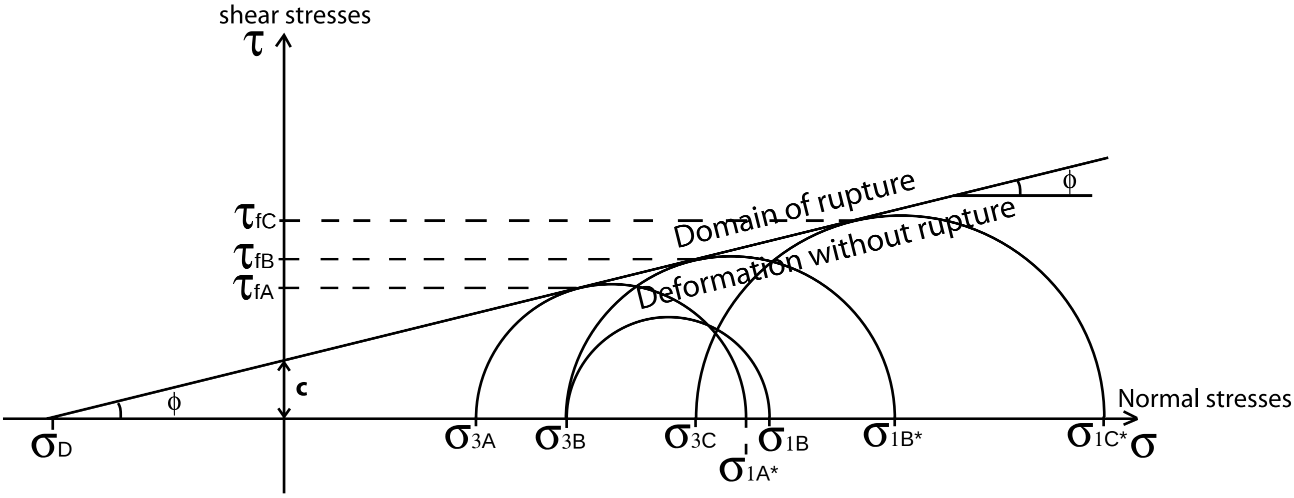
Cases :

A : test at low confining stress $\sigma_3 = \sigma_2$

B : test at middle confining stress $\sigma_3 = \sigma_2$

C : test at high confining stress $\sigma_3 = \sigma_2$

D : traction strength



σ_{1*} = maximum normal stress at failure

τ_f = shear stress at failure

σ_D = traction strength

c = cohesion

ϕ = friction angle

Fig. 2.5 : Mohr diagram with determination of the angle of friction and cohesion by using triaxial test.

Driving force:
$T_M = M * \sin\beta$

Resisting force: T_R

Limit shear strength:
$\tau_f = c * L + N_M * tg\ \varphi$

If $T_M < \tau_f$ => equilibrium

If $T_M > \tau_f$ => failure

$$\frac{\tau_f}{T_M} = F = \text{factor of safety}$$

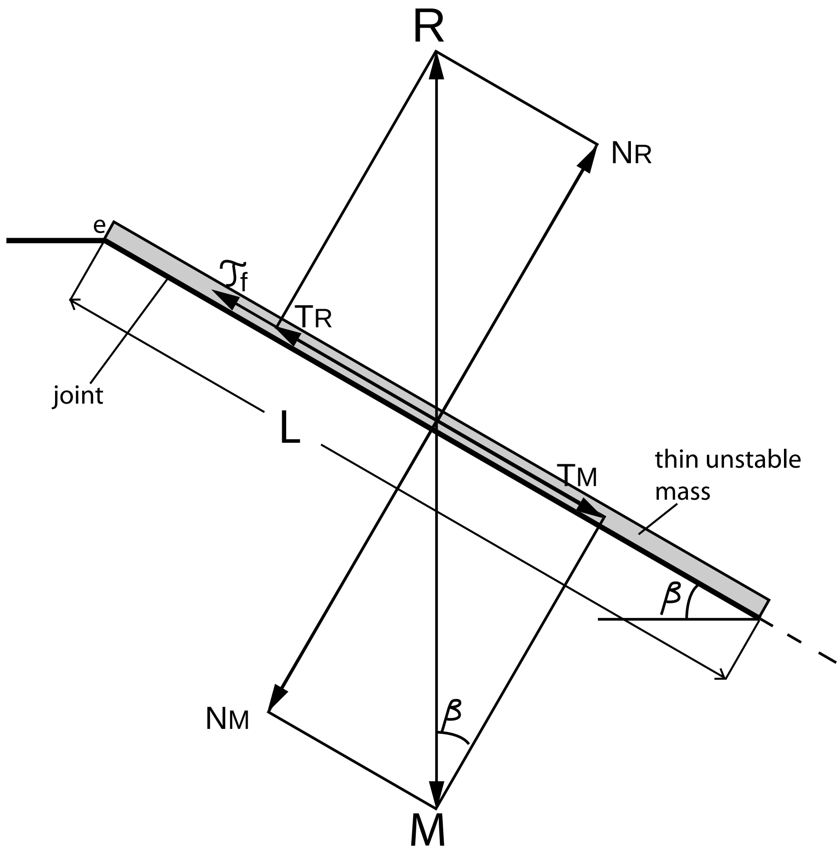


Fig. 2.6 : Limit equilibrium of a slope containing a planar discontinuity (without water).

Hydrostatic pressure:

$$U = \frac{\gamma_w * h}{2} * h$$

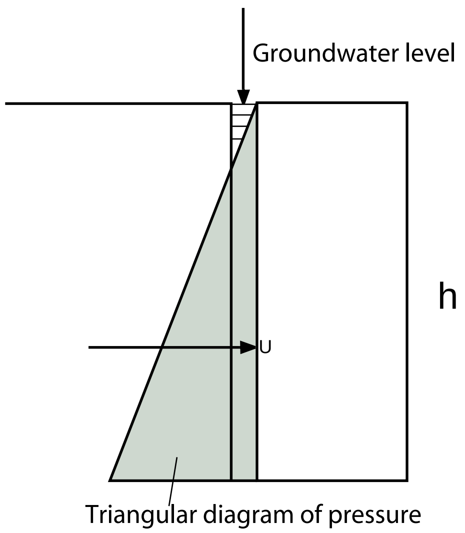
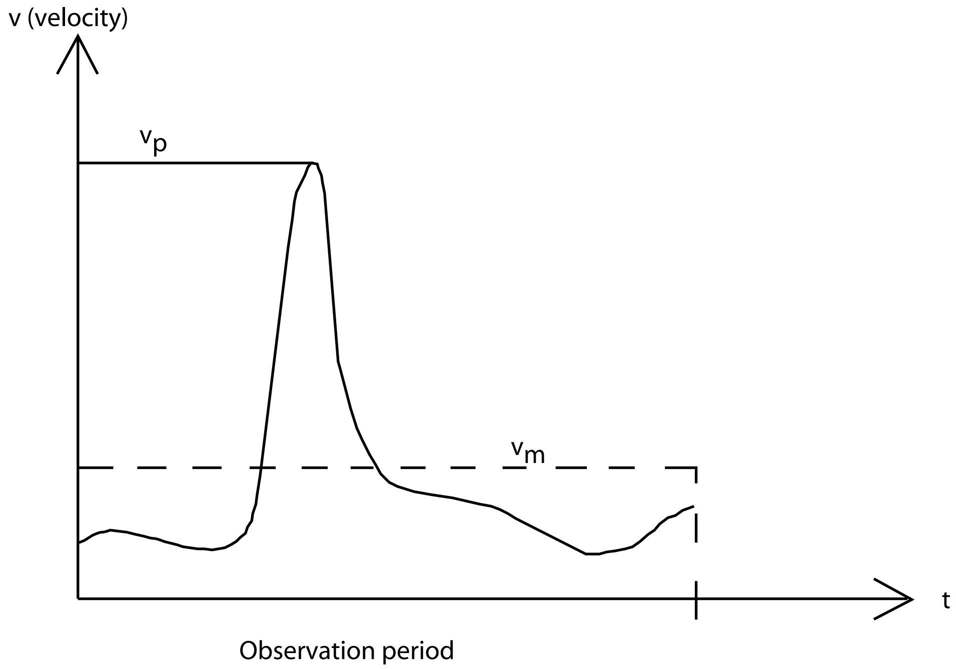


Fig. 2.7 : The filling up of an open fissure in a rock massif.



v_p = peak velocity

v_m = mean velociy during an observation period

$v_p / v_m \cong \infty$: fall, flow, fast landslide		
$v_p / v_m > 100$	Landslide	Very irregular
$100 > v_p / v_m > 10$	Landslide	Irregular
$10 > v_p / v_m > 5$	Landslide	Moderatly irregular
$5 > v_p / v_m > 2$	Landslide	Moderatly regular
$2 > v_p / v_m > 1$	Landslide	Very regular

Fig. 3.1 : Velocity regime of unstable slopes for the different phenomena.

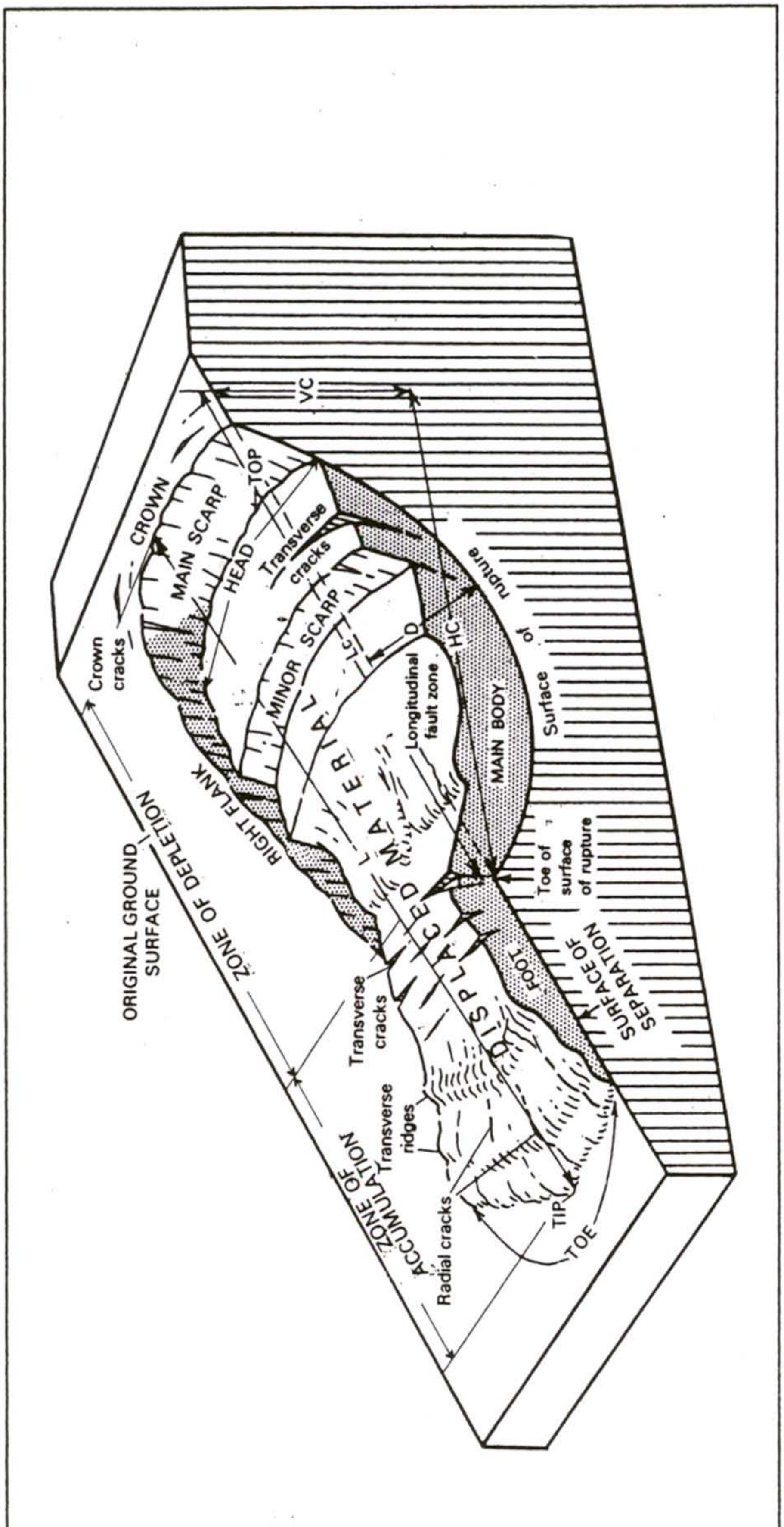


Fig. 3.2 : Main geomorphological terms of idealized complex earth slide-earth flow (Varnes 1978, fig. 2.1t).

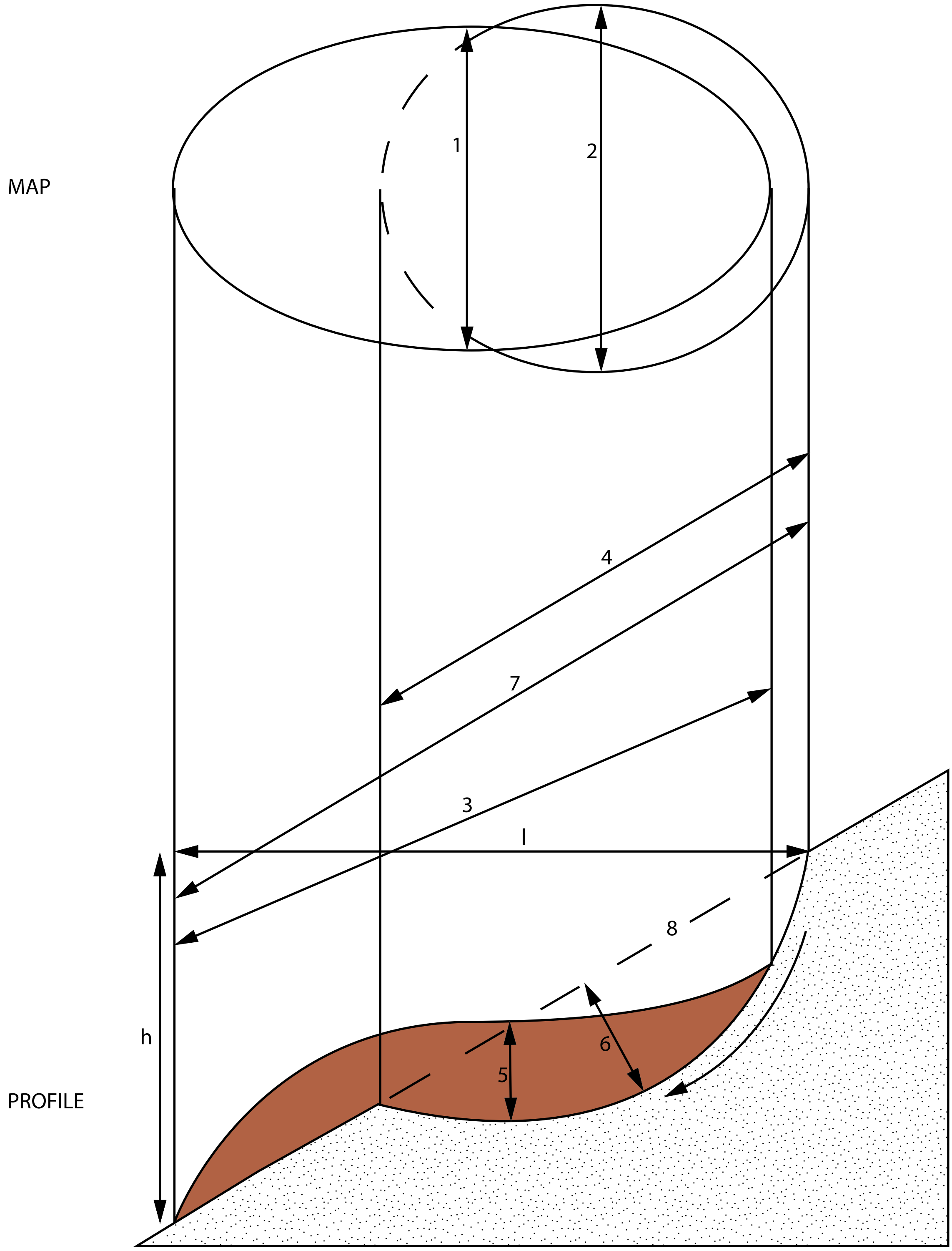


Fig. 3.3 : Geomorphological parameters of a landslide (modified from Cruden and Varnes).

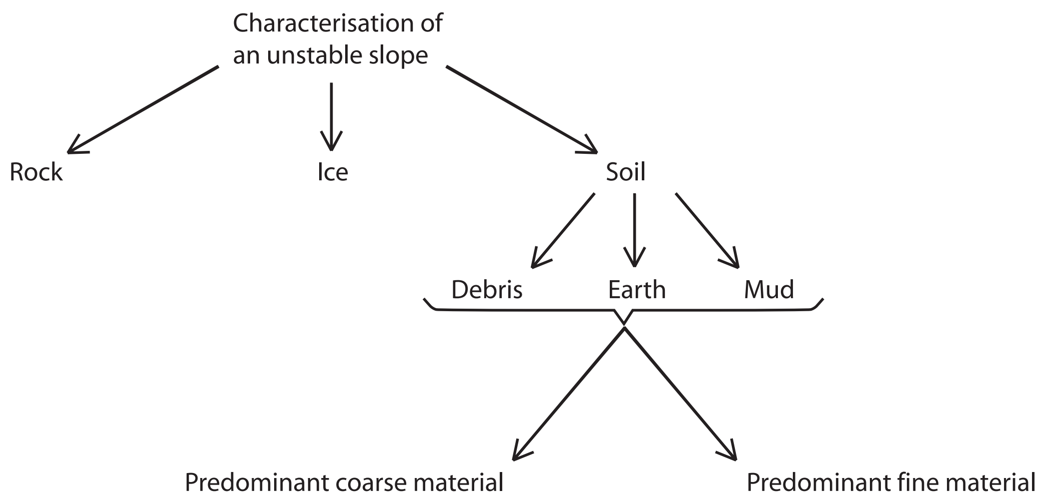
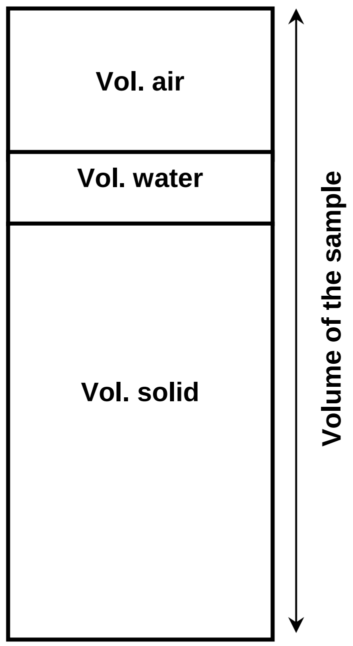


Fig. 3.4 : General categories of geological material moving in unstable slopes

Fig. 3.5 : Solid-liquid-air contents



After the four trials laboratory we know :

- Specific weight of the sample γ
- Water content w
- Specific weight of soil particules γ_s
- Specific weight of water γ_w

N.B. In a first approximation we have :

- γ_s = 26.7 [KN/m3]
- γ_w = 10 [KN/m3]

By means of these manipulations we have measured too :

- W = weight of the sample
- V = volume of the sample
- W_s = weight of the skeleton

We have also calculated W_w, the weight of water.

With some of these eight values we can calculate the volumes of the three phases; then all the identification parameters of a soil:

1) Volume of solid Vs:

$$W = \frac{W - W_s}{W_s} = \frac{\gamma \cdot V - \gamma_s \cdot V_s}{\gamma_s \cdot V_s}$$

V_s is unknown; w is expressed in unit, not in %.

$$w \cdot \gamma_s \cdot V_s = \gamma \cdot V - \gamma_s \cdot V_s$$

$$w \cdot \gamma_s = \frac{(\gamma \cdot V)}{V_s} - \gamma_s$$

$$\frac{V_s}{\gamma \cdot V} = \frac{1}{\gamma_s \cdot (w+1)}$$

$$\boxed{V_s = \frac{\gamma \cdot V}{\gamma_s \cdot (w+1)}}$$

2) Volume of the liquide V_w:

$$W = W_s + W_w \qquad (W_a = 0)$$

$$\gamma \cdot V = \gamma_s \cdot V_s + \gamma_w \cdot V_w$$

V_w is unknown.

$$\gamma_w \cdot V_w = \gamma \cdot V - \gamma_s \cdot V_s$$

$$\boxed{V_w = \frac{\gamma \cdot V - \gamma_s \cdot V_s}{\gamma_w}}$$

3) Volume of the air V_a:

$$V_a + V_w + V_s = V$$

V_a is unknown.

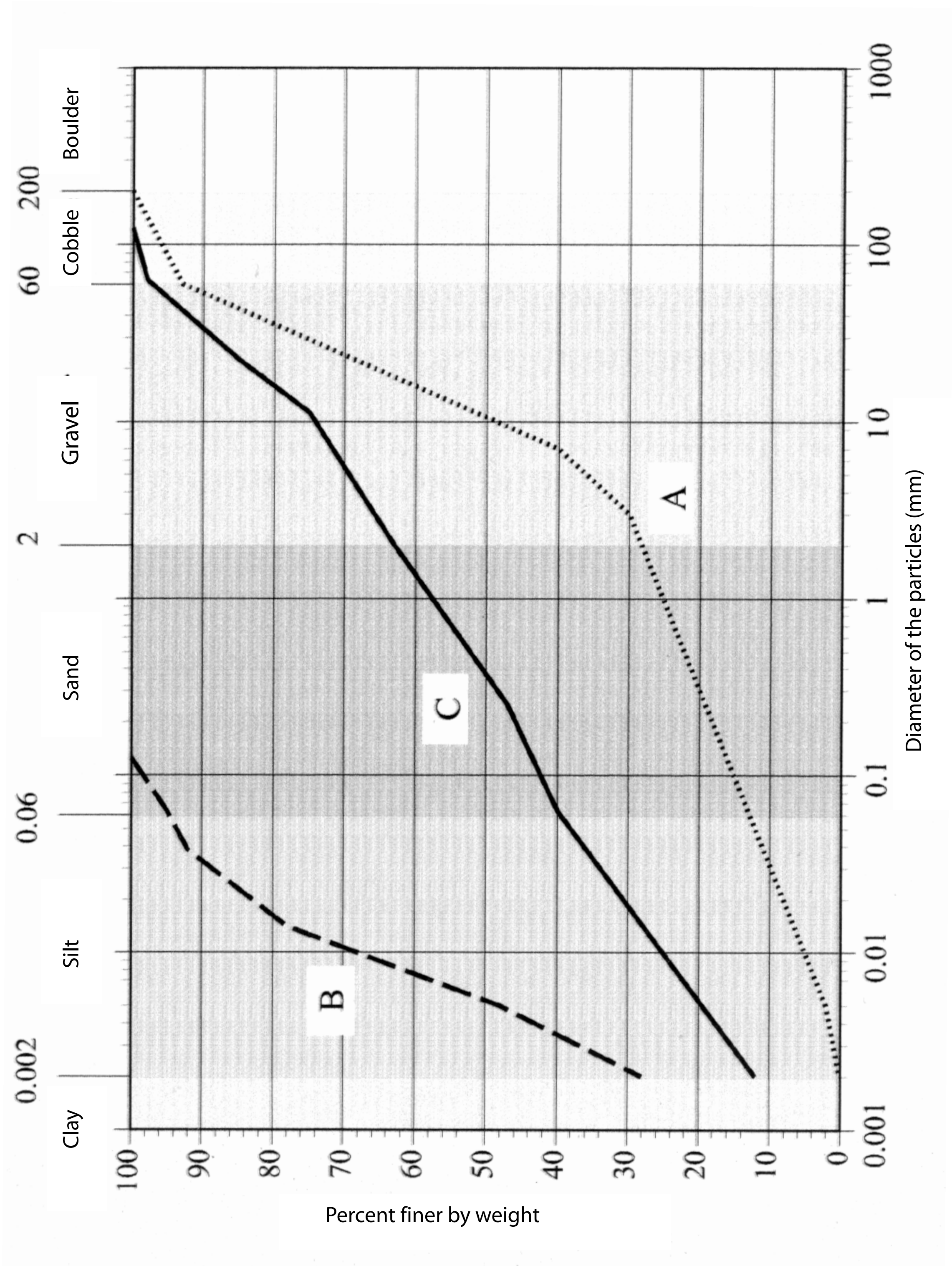
$$\boxed{V_a = V - V_w - V_s}$$

Now we can calculate the other parameters :

- Specific dry weight:

- Specific saturated weight:

- Specific weight of soil particules γ_s
- Specific weight of water γ_w

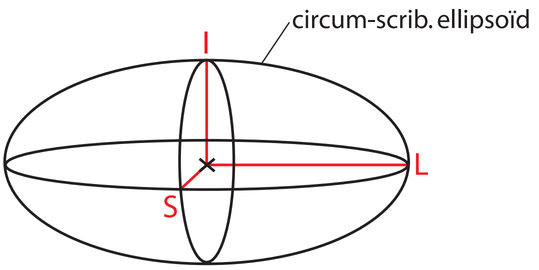


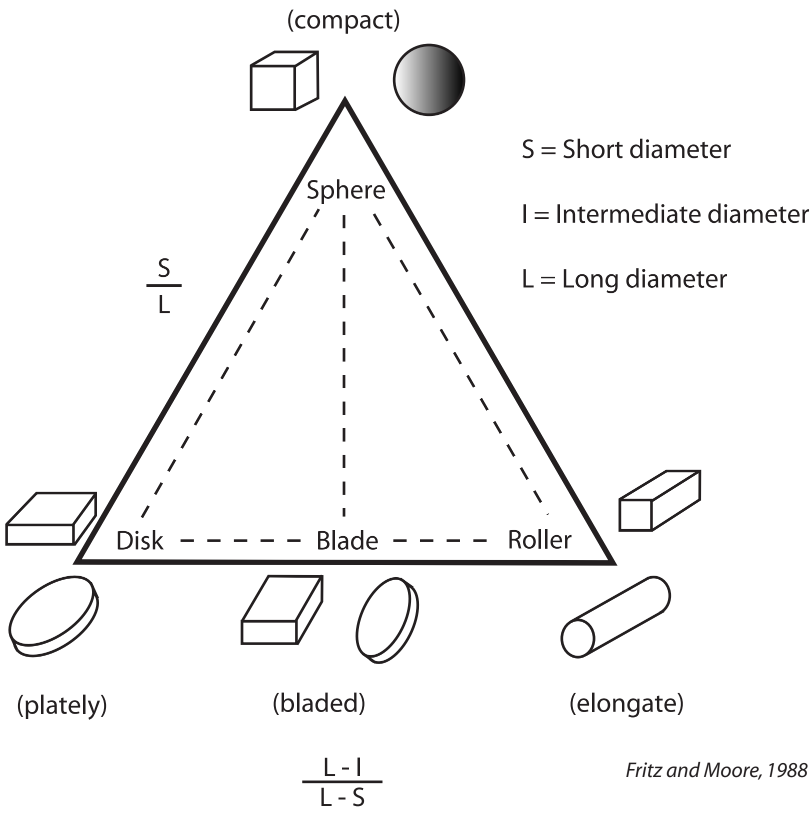
Soil type	A	B	C
Uniformity coefficient $Cu = \frac{D_{60}}{D_{10}}$	35	14	200
Skewness $Cc = \frac{\overline{D_{30}}^{2}}{D_{10}D_{60}}$	1.62	1.28	0.89

Fig. 3.6 : Grain size distribution of clastic rocks and the amount of fine matrix (USCS).

Fig. 3.7 : Shape of coarse elements.

SOURCE MATERIAL



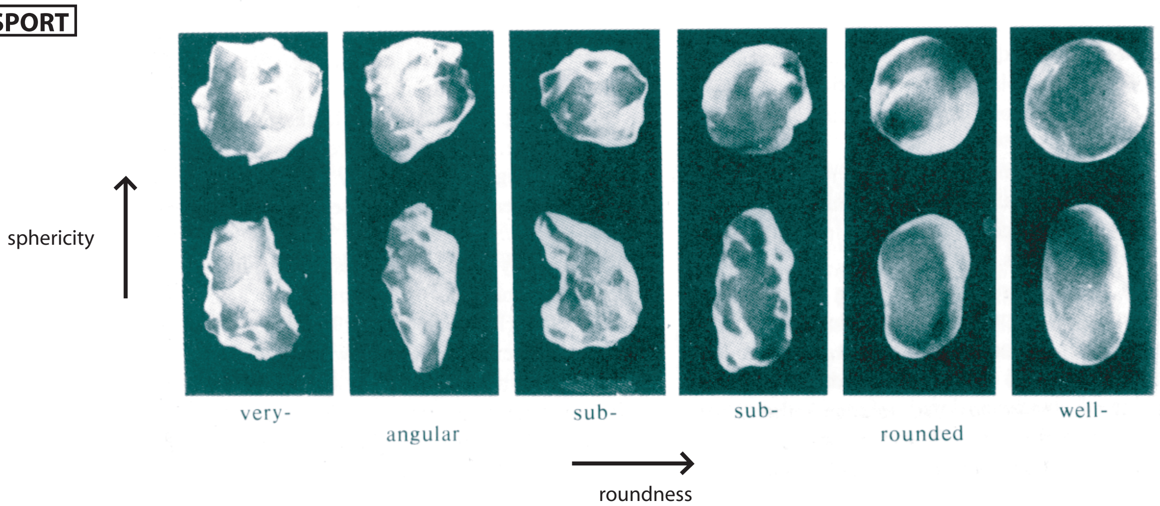


Fritz and Moore, 1988

sphericity = $\sqrt[3]{\text{(Volume of a particule / volume of a circum-scribing sphere)}}$

Sphericity = expression of the degree to which its shape approaches the form of a sphere, Wadell (1933). For large numbers of particules, it is easier to group them into convenient shape of classifications (triangular diagram for example). This shape classification is related to the sphercity of a particule in terms of particules intercepts, assuming the partices shape as a triaxial -ellipsoid. Bourgeois J. , Fairbridge R, 1978, "The encyclopedia of sedimentology", Dowden, Hutchinson & Ross Inc., Pennsylvania.

TRANSPORT

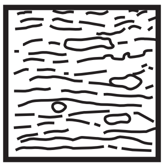
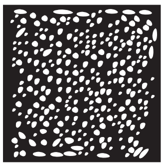
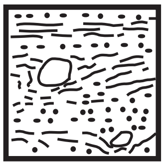
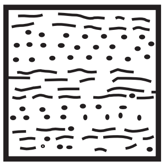
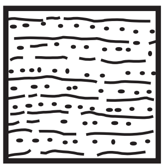


roundness = av. radius of corners and edges / radius of max. inscribed circle.

Roundness = describes the degree of abrasion of a clastic fragment as shown by the sharpness of its edges and corners, independant of shape (Wadell, 1932). Thus spherical paticules are perfectly rounded, but well-rounded objects need not to be spherical. Roundness may provide evidence of time or distance of transport. Bourgeois J. , Fairbridge R, 1978, "The encyclopedia of sedimentology", Dowden, Hutchinson & Ross Inc., Pennsylvania.

DEPOSIT

Fig. 3.8 : Textural arrangement of the deposit

	Description	Environnement of formation
	Striated angular pebbles texture	Lodgment till
	Shear texture	Infra-morainic shearing pillow
	Isotropic texture	Waterlain till
	Laminated texture with drop-stones	Glacio-lacustrine
	Thickly bedded laminations texture	Lacustrine
	Finely bedded laminations texture	Lacustrine
	Turbiditic texture (balls, slumps,...)	Lacustrine

Legend :

 gravel, cobble

 sand

 silt

 clay

Fig. 3.9 : Plasticity and liquidity limit

LIQUIDITY

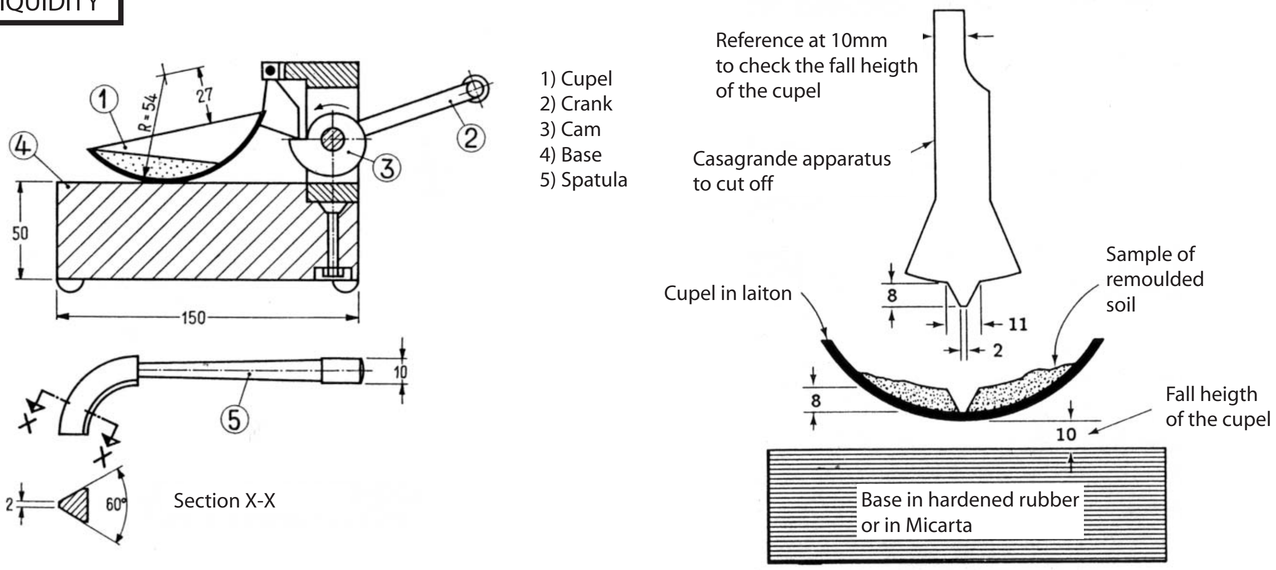
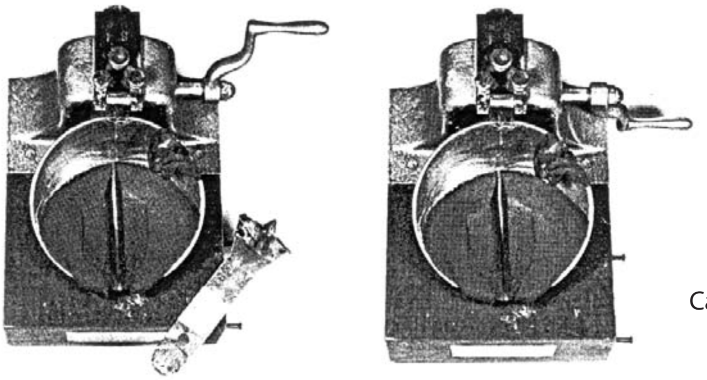


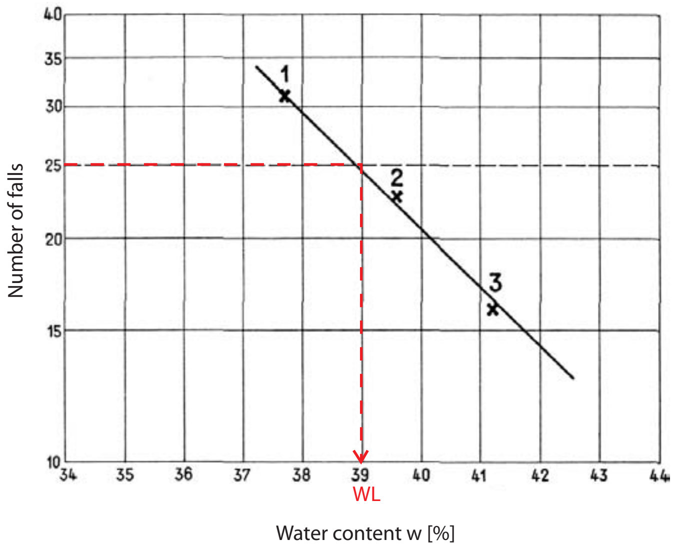
Diagram of Casagrande apparatus (SNV)



a) b)

Casagrande apparatus and instrument to notch

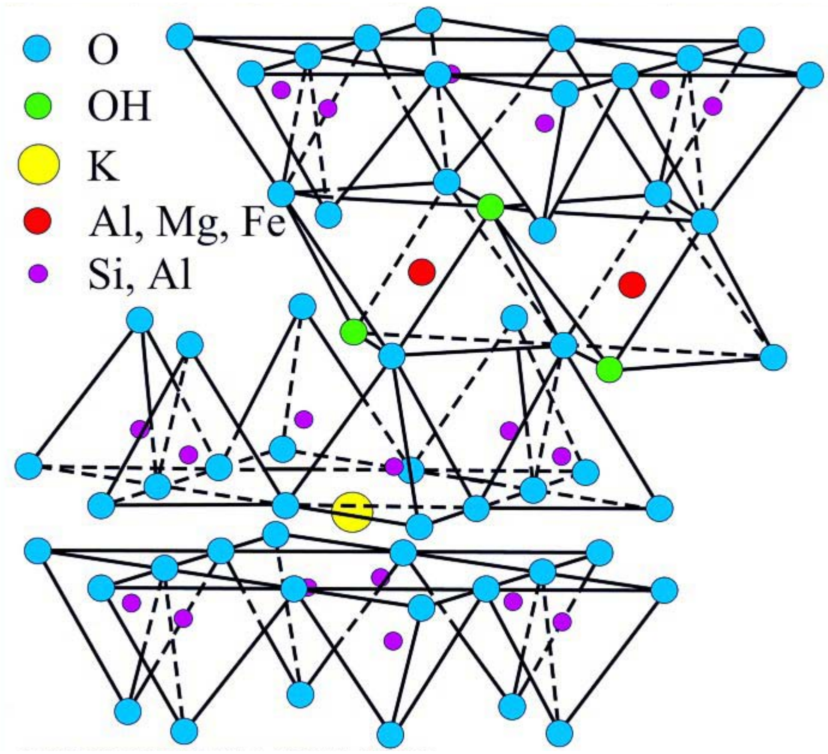
The liquidity limit is determined by measuring the water content and the number of blows required to close a specific width groove for a specific length in a standard liquid limit device. Lambe & Whitman, 1969.



PLASTICITY

The plastic limit is determined by measuring the water content of the soil when threads of 1/8 in. in diameter begin to crumble. Lambe & Whitman, 1969.

c)



Structure of illite, modified from Grim (1962)

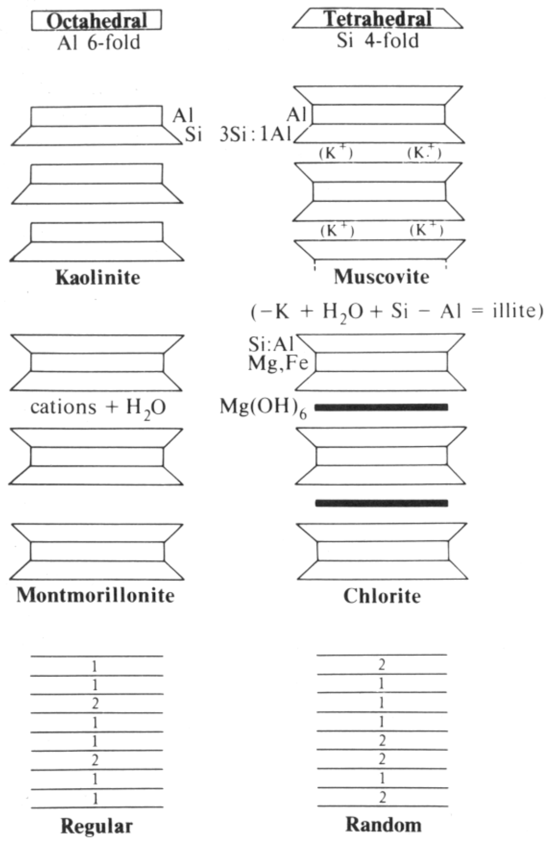


Fig. 3.10 : Mineralogy of clay material (after Pettijohn et al. 1972)

Table 3.3 : Characterisation matrix of "geotypes" for field mapping of unstable slopes in quaternary deposits.
Observations on a representative measuring site.

DETAILED GEOTYPE :

HAZARDS MAP (1 : 5'000)

LITHOLOGICAL CHARACTERISTICS																				
Granulometry [%]					Dominant shape of the coarse elements							Proportions of other components [%]		Overconsolidation				Cementing		
					average diameter of the gravels, rollers and blocks	sphericity			roundness											
clay (< 2 microns)	silt	sand	gravel	cobbles & boulders		low	average	high	low	average	high	organic matter	chalk	null	average	strong	pocket penetr.	null	average	strong

STRUCTURAL CHARACTERISTICS					
Macro-isotropy		Dip *(if anisotropic)*			Average azimuth of plunging *(if anisotropic)*
isotropic	anisotropic	low <5°	average 5-10°	high >10°	

Evaluation of the present stability																			
Slides					Saggings			Topples			Collapses			Permafrost			Activity of dominating phenomenon		
yes			doubtful	no	yes	doubtful	no	yes	doubtful	no	yes	doubtful	no	yes		no	null	weak	strong
superf. < 5m	mid. 5-50m	deep >50m												rock glacier	solifluction				

Degree of colonization/pedological maturity					
Ground very installed	Colonizing ground	No ground/no vegetation	Degree of establishment of vegetation		
			weak	middle	strong

<table>
<tr><td colspan="3" rowspan="3">TYPE OF MOVEMENT</td><td colspan="3">TYPE OF MATERIAL</td></tr>
<tr><td rowspan="2">BEDROCK</td><td colspan="2">ENGINEERING SOILS</td></tr>
<tr><td>Predominantly coarse</td><td>Predominantly fine</td></tr>
<tr><td colspan="3">FALLS</td><td>Rock fall</td><td>Debris fall</td><td>Earth fall</td></tr>
<tr><td colspan="3">TOPPLES</td><td>Rock topple</td><td>Debris topple</td><td>Earth topple</td></tr>
<tr><td rowspan="3">SLIDES</td><td>ROTATIONAL</td><td rowspan="2">FEW UNITS</td><td>Rock slump</td><td>Debris slump</td><td>Earth slump</td></tr>
<tr><td rowspan="2">TRANSLATIONAL</td><td>Rock block slide</td><td>Debris block slide</td><td>Earth block slide</td></tr>
<tr><td>MANY UNITS</td><td>Rock slide</td><td>Debris slide</td><td>Earth slide</td></tr>
<tr><td colspan="3">LATERAL SPREAD</td><td>Rock spread</td><td>Debris spread</td><td>Earth spread</td></tr>
<tr><td colspan="3">FLOWS</td><td>Rock flow
(deep creep)</td><td>Debris flow</td><td>Earth flow
(soil creep)</td></tr>
<tr><td colspan="3">COMPLEX</td><td colspan="3">Combination of two or more principal types of movement</td></tr>
</table>

Table.4.1: Classification by intersecting geodynamic behaviour and nature of material (Varnes 1978).

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

Fig. 4.1 : The seven classes of velocity for the landslides (Cruden & Varnes, 1996).

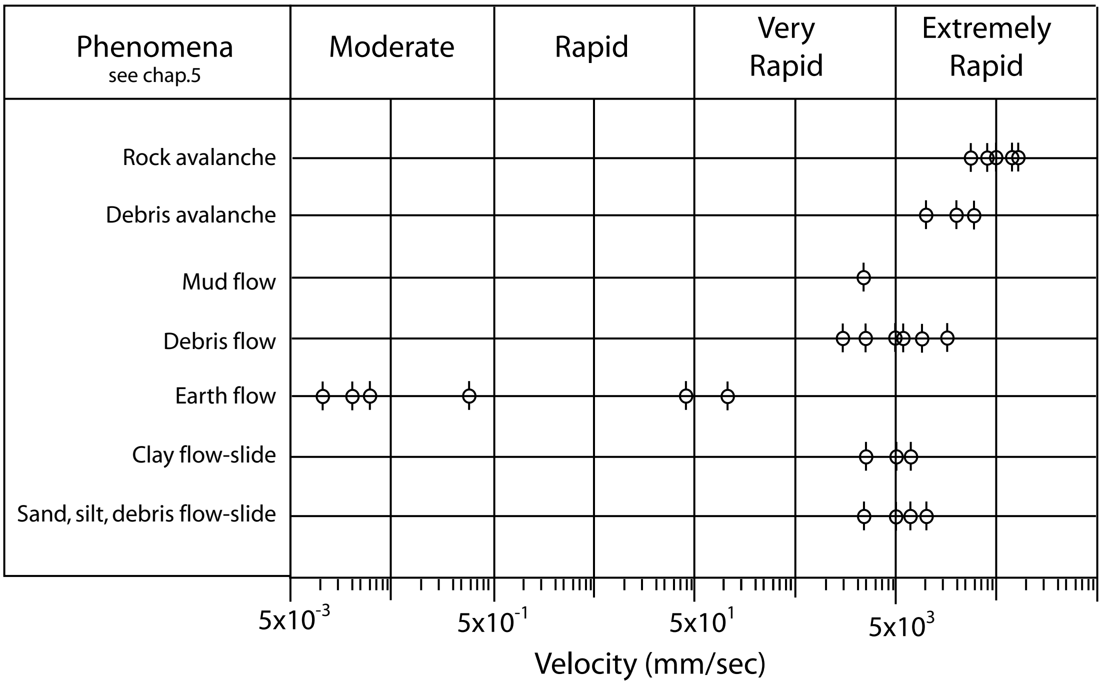


Fig. 4.2 : Maximum velocities of movements for the flow type phenomena (modified from Hungr, 2001).

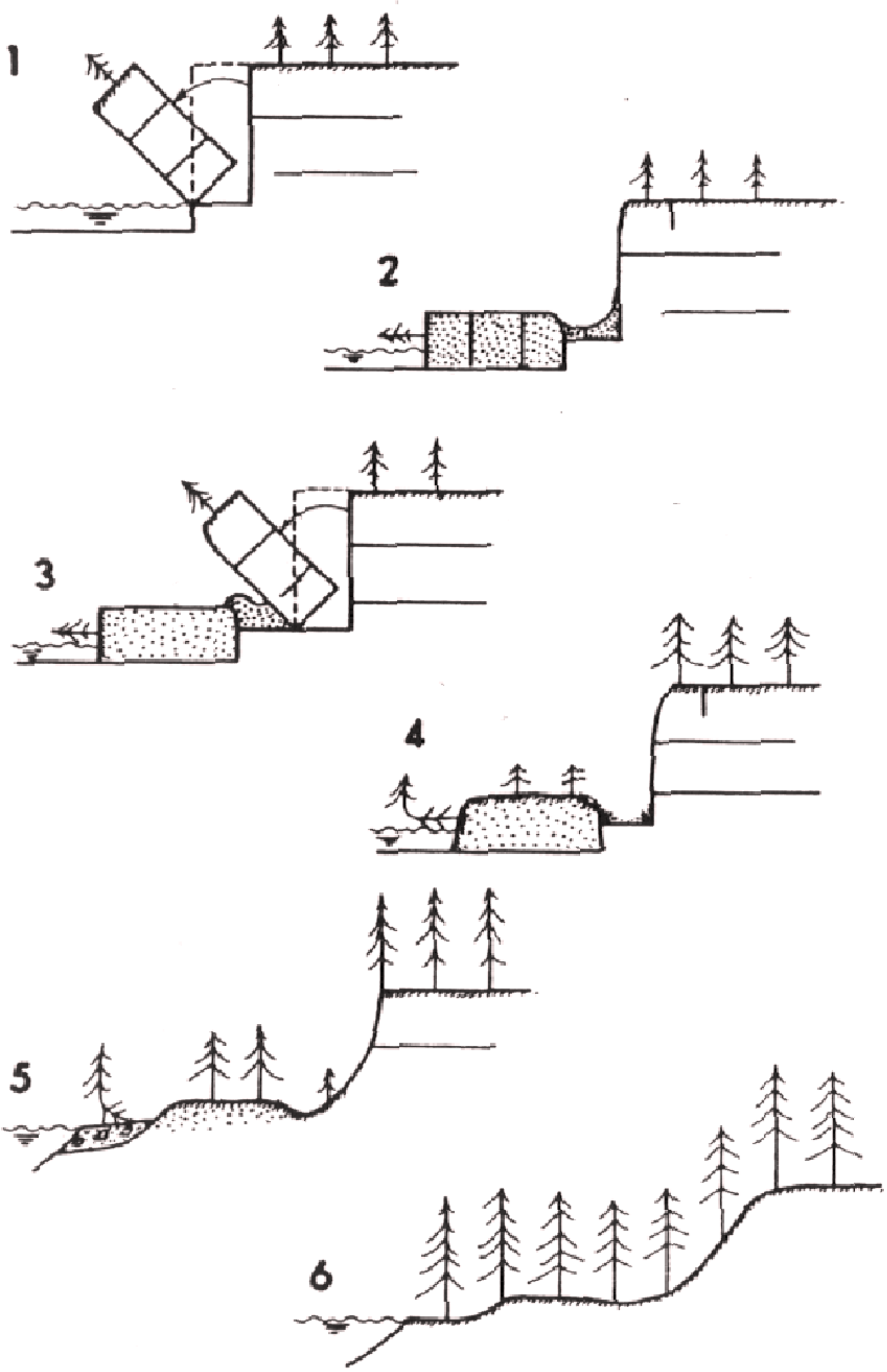


Fig. 4.3 : Degrees of activity of a landslide according to the International Glossary (Cruden and Varnes).

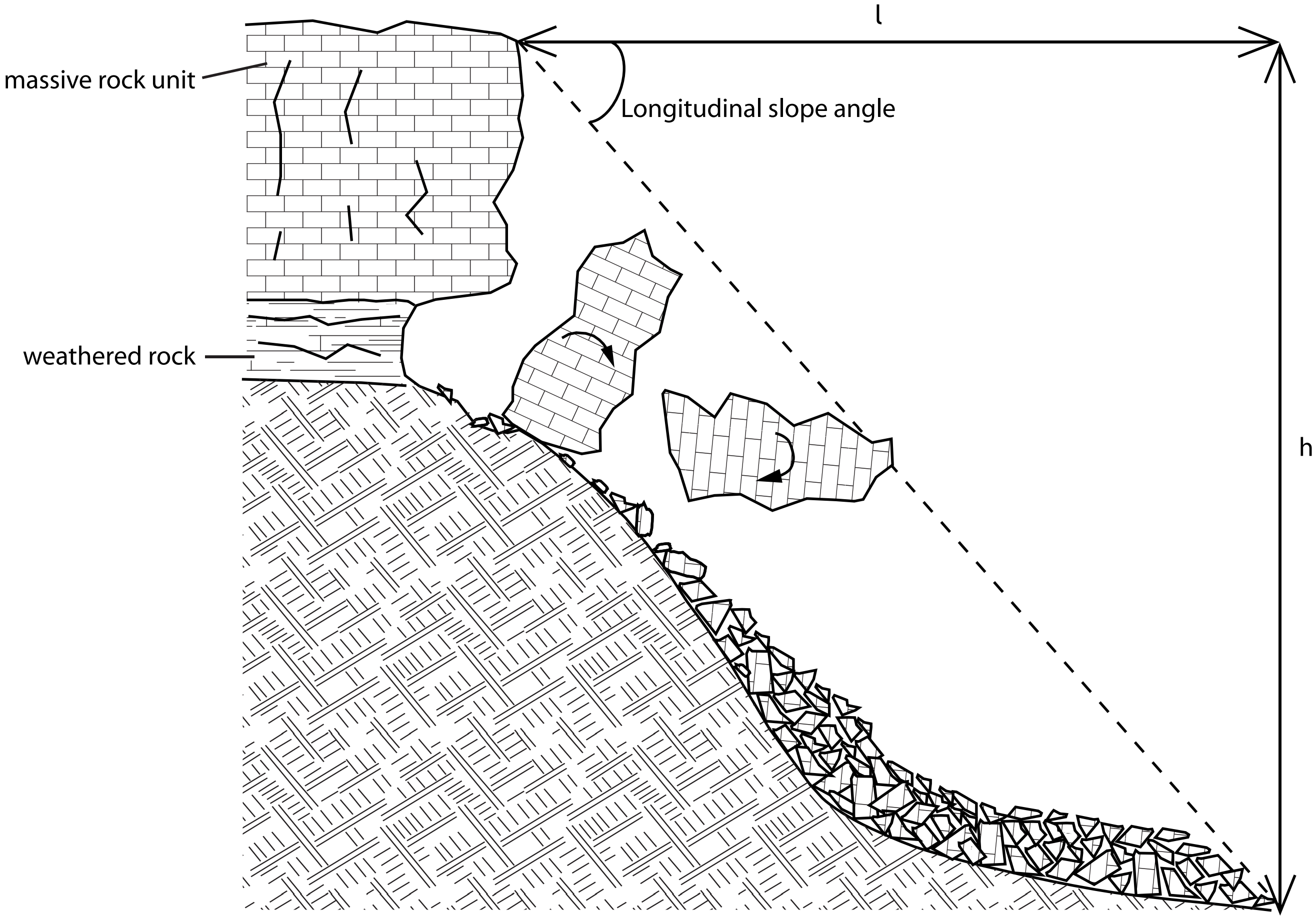


Fig. 5.1.1 : Schematic profile of a rock fall from a cliff.

Fig. 5.1.2 : Stone-fall in the Ladakh mountains. Photo Parriaux.

Fig. 5.1.3 : Single block-fall from a conglomerate formation in Grindelwald, Burglauenen (2.2.1994).
Photo Geotest AG.

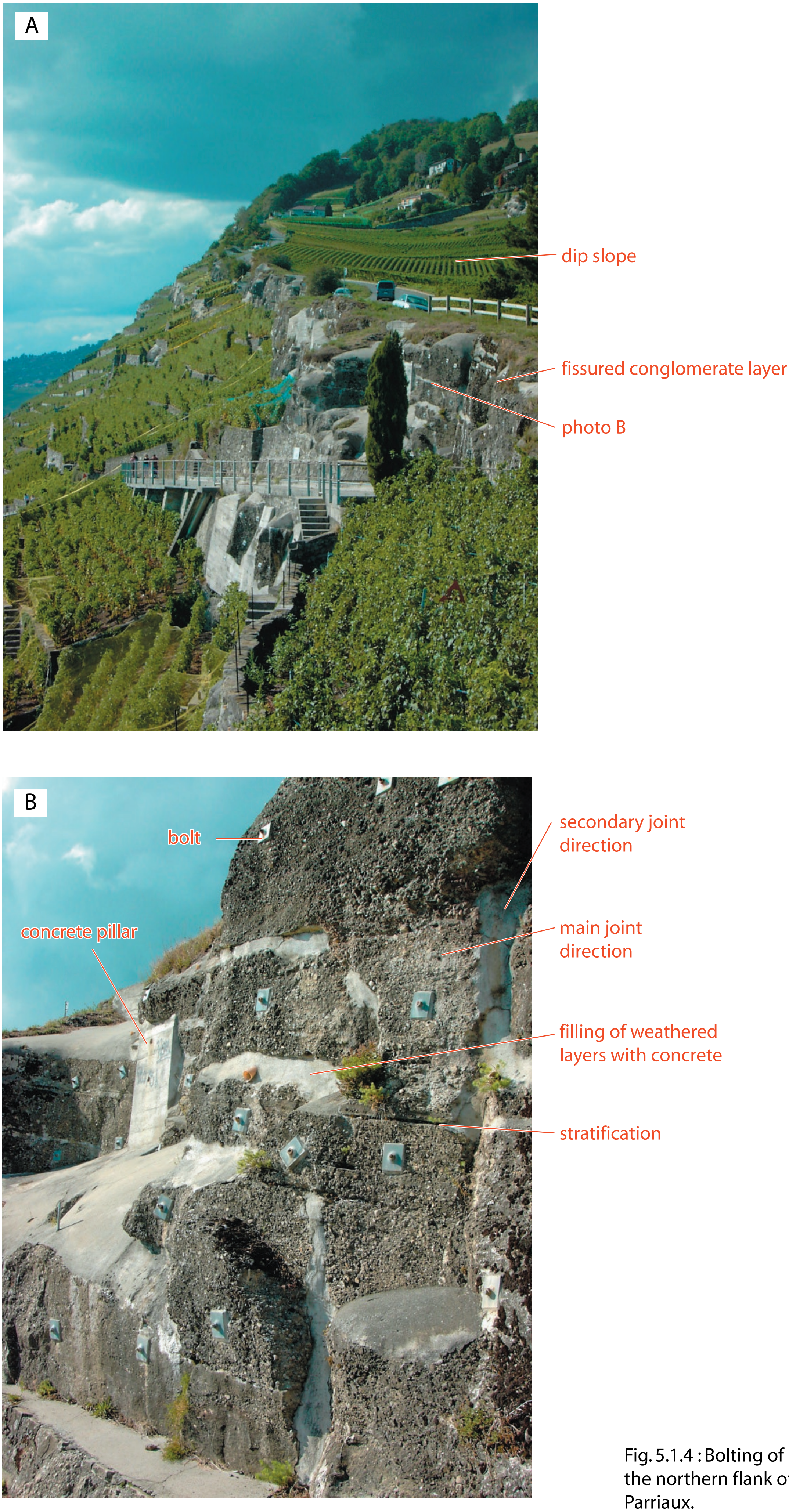


Fig. 5.1.4 : Bolting of Oligocene conglomerates in the northern flank of Geneva Lake (Lavaux). Photo Parriaux.

t1 = 0.00 s ; v1 = 26 m/s

t2 = 0.11 s ; v2 = 27 m/s

t3 = 0.30 s ; v3 = 19 m/s

t4 = 0.44 s ; v4 = 11 m/s

t5 = 0.52 s ; v5 = 0 m/s

t6 = 0.78 m/s ; v6 = -4 m/s

t7 = 1.04 s ; v7 = 0 m/s

Fig. 5.1.5 : Geobrugg net for retaining blocks. Photos Geobrugg AG.

5.1.1 A
Case study of Chasseron, Suisse

Photo Parriaux

Photo Rovina

Photo Parriaux

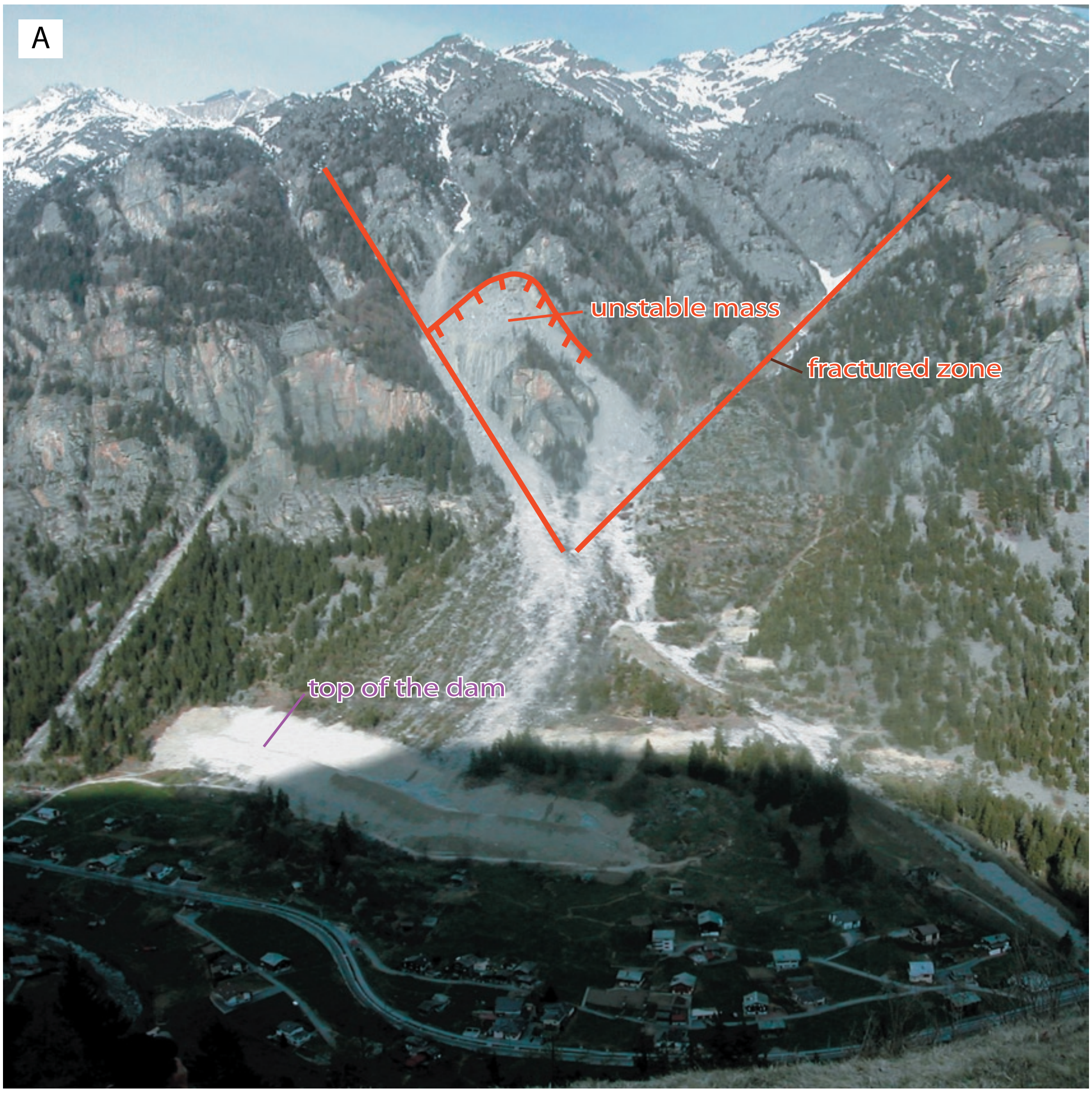
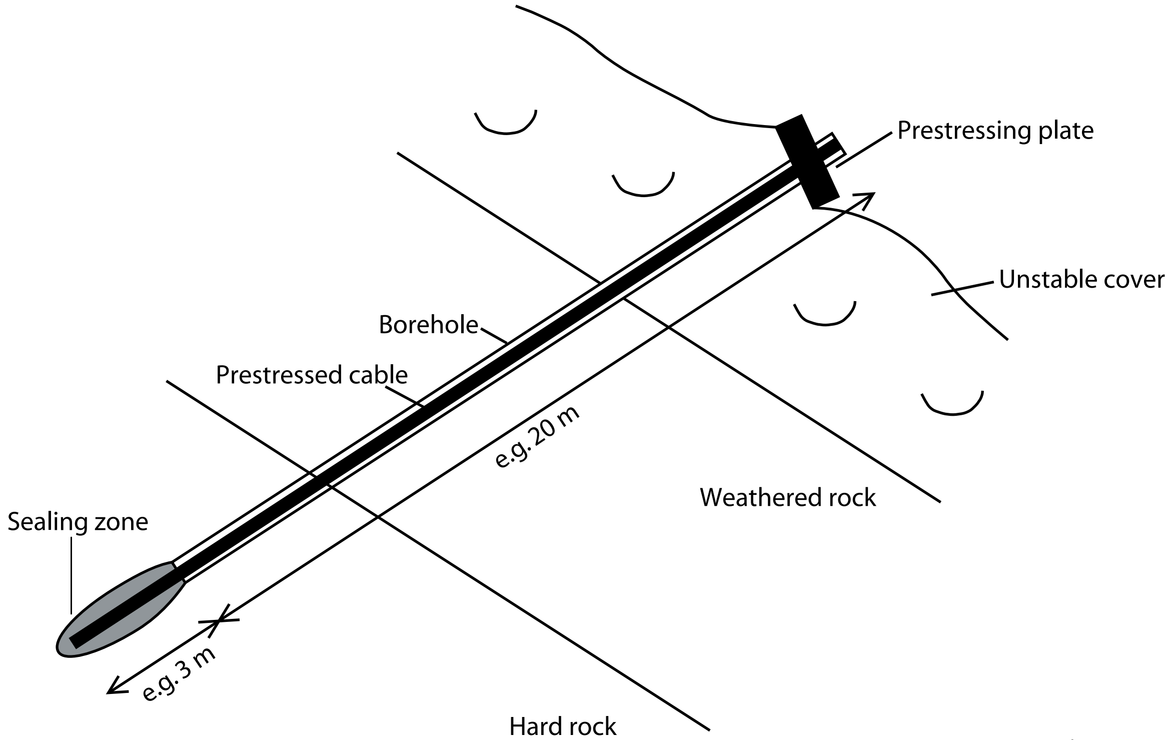


Photo Rovina

Fig. 5.1.6: St-Niklaus, Valais



A)

Road embankment
supported by anchors.

B)

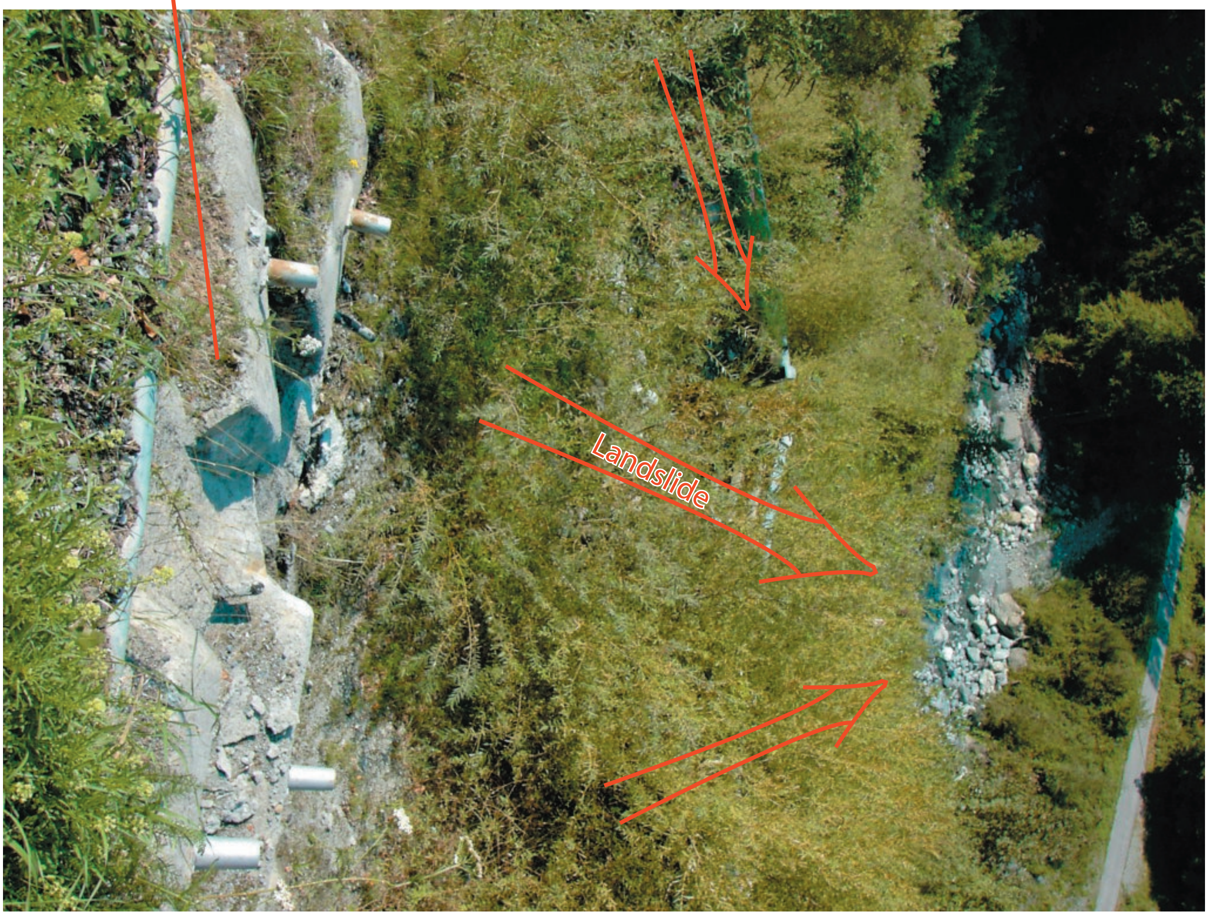


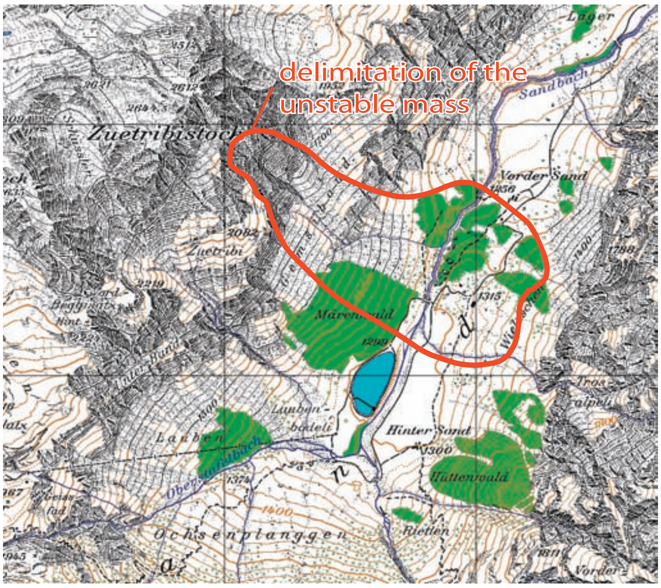
Photo Parriaux

Fig. 5.1.7: Anchors in Chenalette (Canton of Vaud)

Fig. 5.1.8: Anchors

Fig. 5.1.9 : Pillar supporting the foot of a dip-slope limestone series in the Eichwald quarry (west of Brunnen, Canton of Luzern). Photo Parriaux.

5.1.2 A
Case study of Sandalp (Canton of Glaris)



Topographic map before the event

A

Photos Parriaux

5.1.2 b
Case study of Randa (Canton of Valais)

Photos Crealp

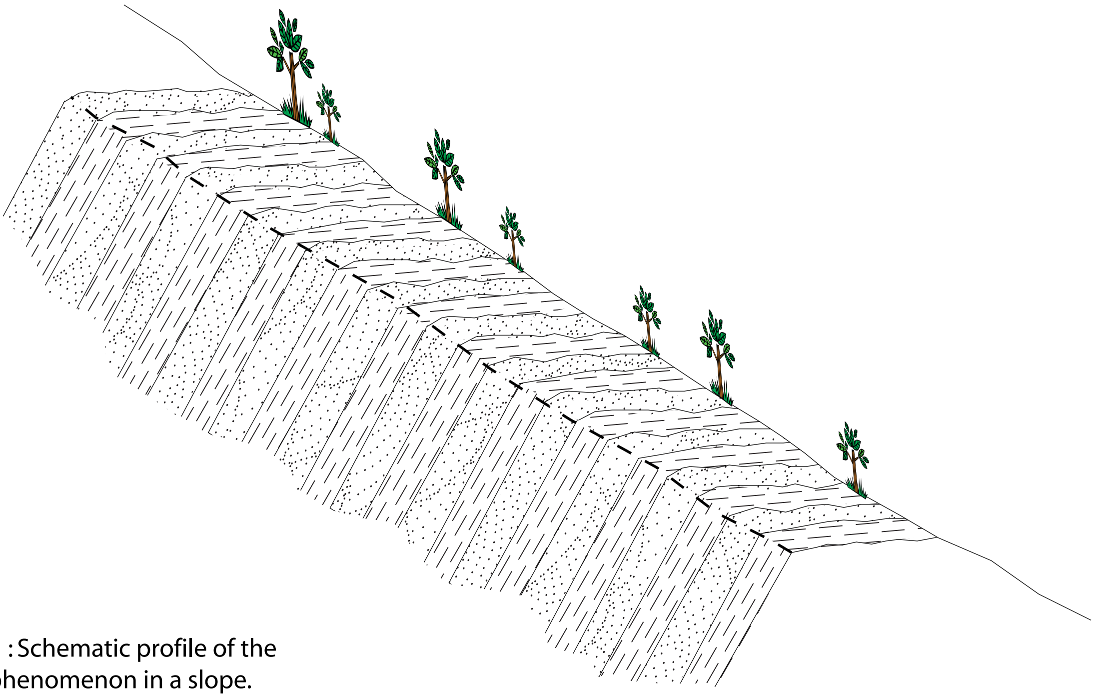
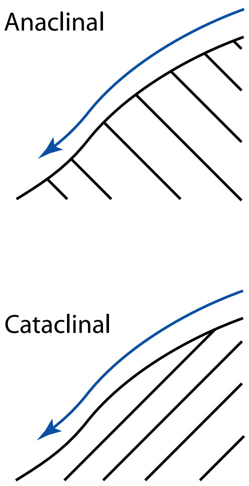
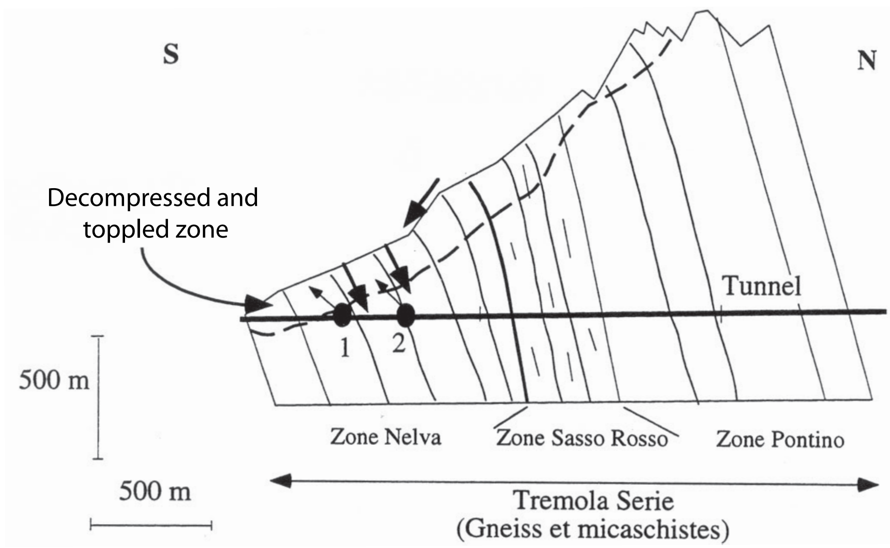


Fig. 5.2.1 : Schematic profile of the topple phenomenon in a slope.





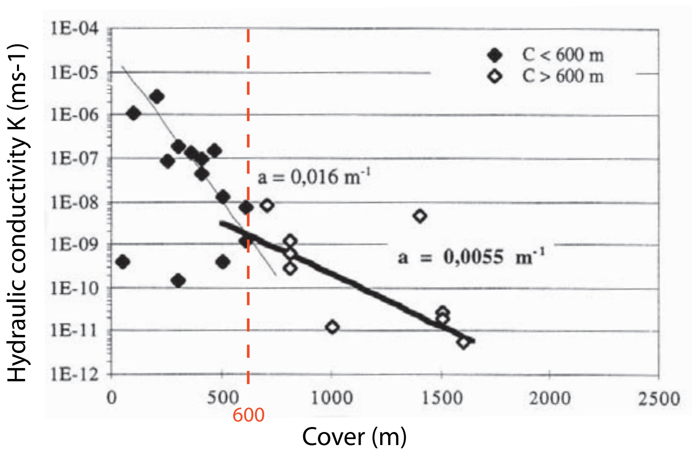
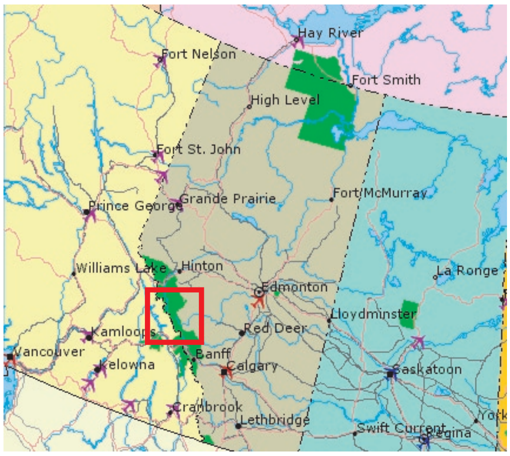
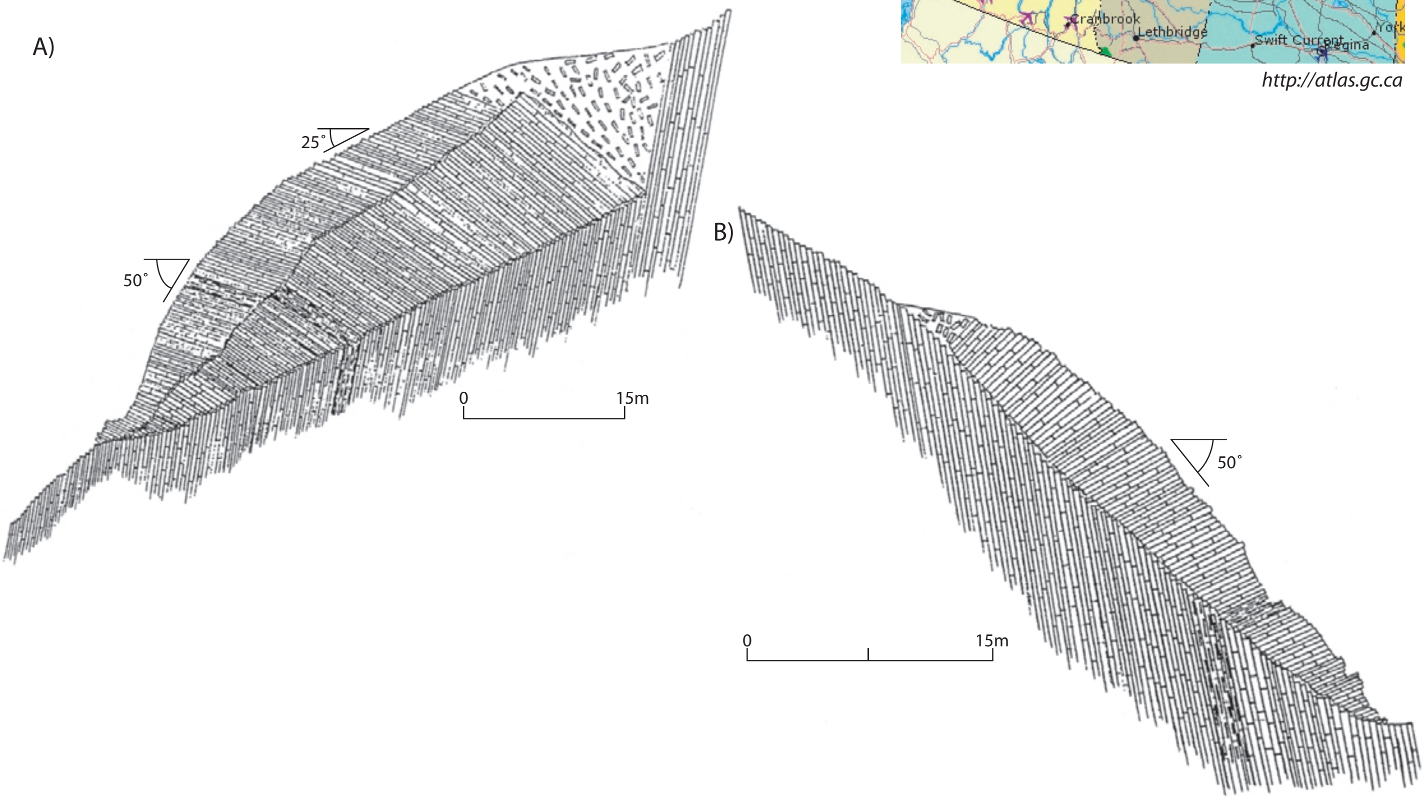


Fig. 5.2.2 : Deep toppling in the south part of the Gothard tunnel. Maréchal, 1998.

5.2 A
Case study of Clairveaux, Canada

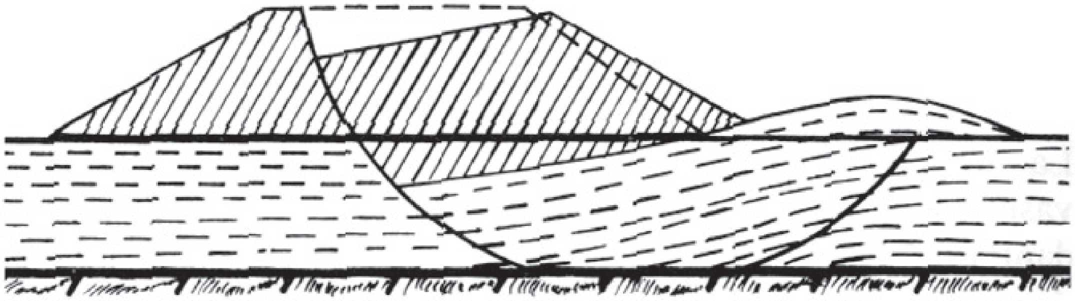


http://atlas.gc.ca



Cruden et al. 1993

Photo Parriaux



a) Standard diagram of circular rupture.

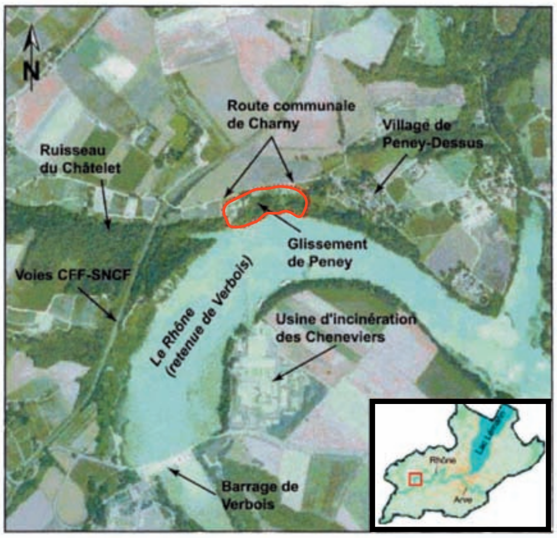
Fig. 5.3.1 : Schematic profil of the slide phenomenon in a slope.

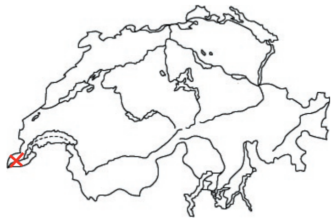
b) General view of an embankment after a circular rupture.

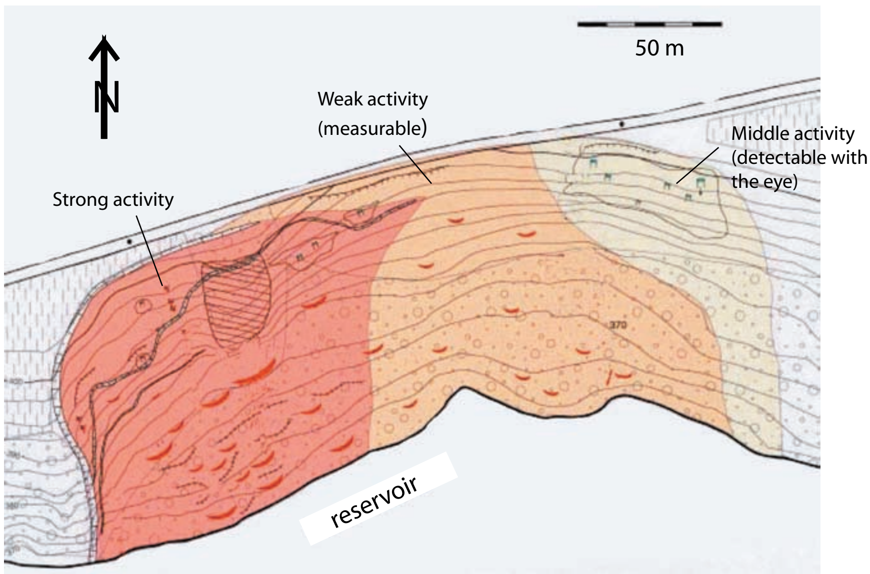
Fig. 5.3.2 : Rotational rupture of an embankment and a part of the foundation soil. LCPC, 1976.

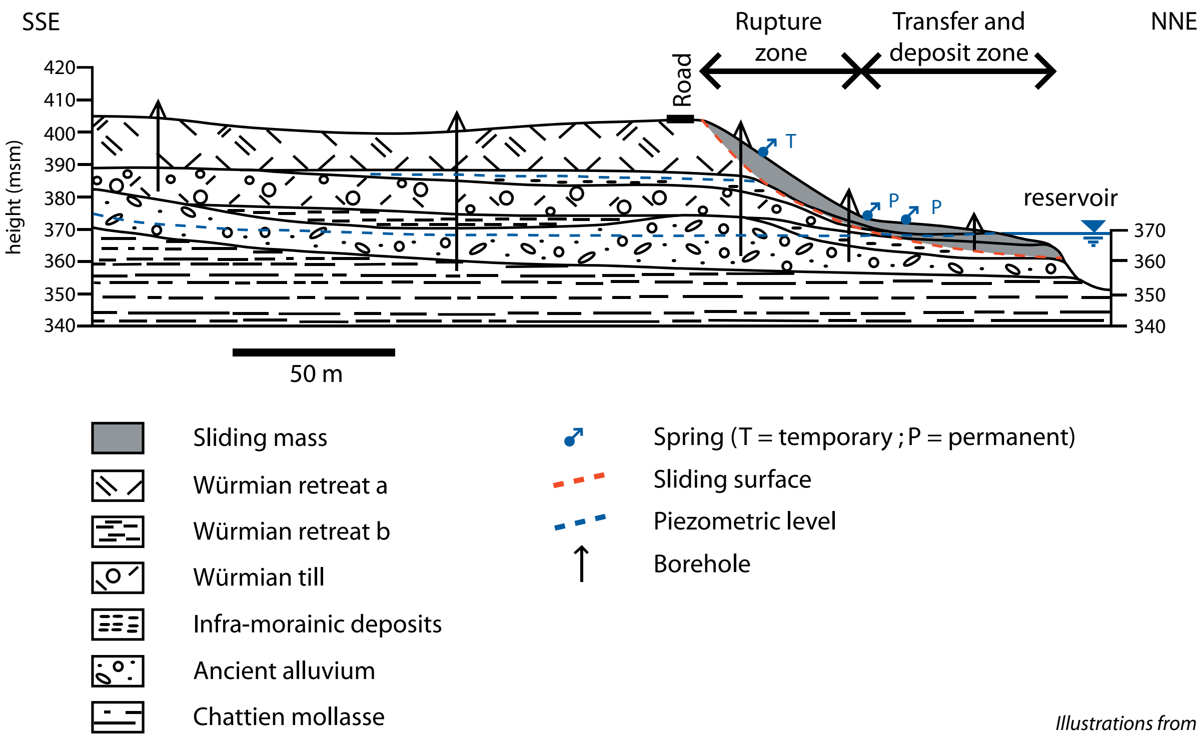
5.3.1 A

Case study of Peney (Canton of Geneva)









Illustrations from Tullen, 2002

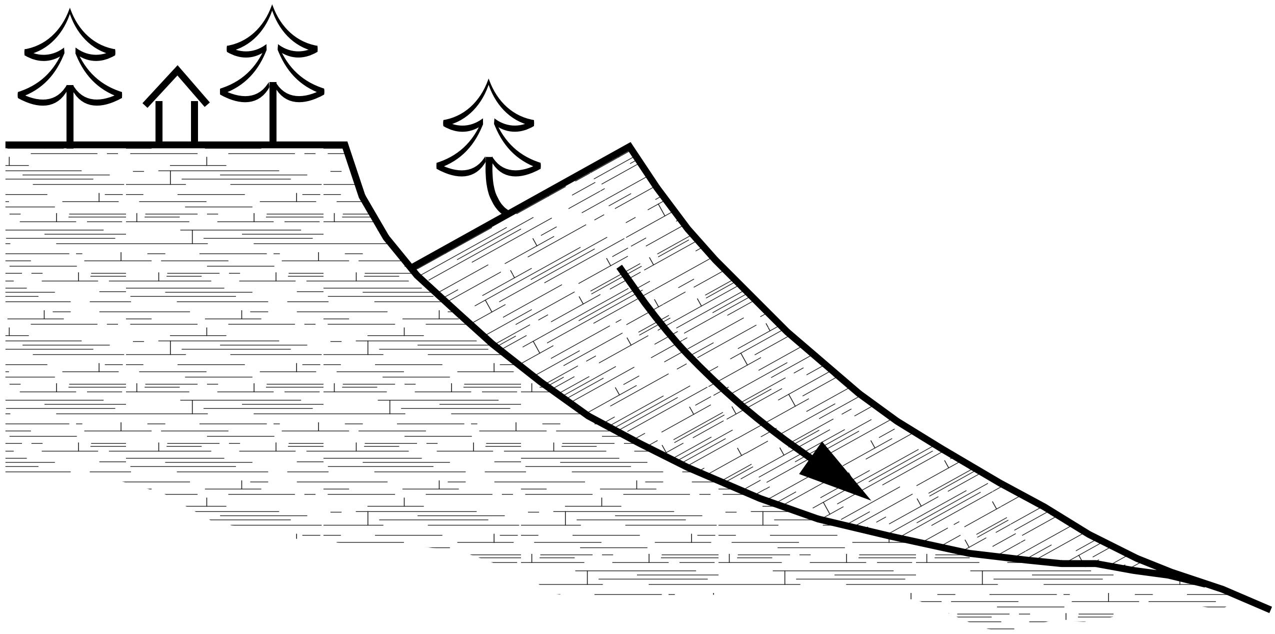
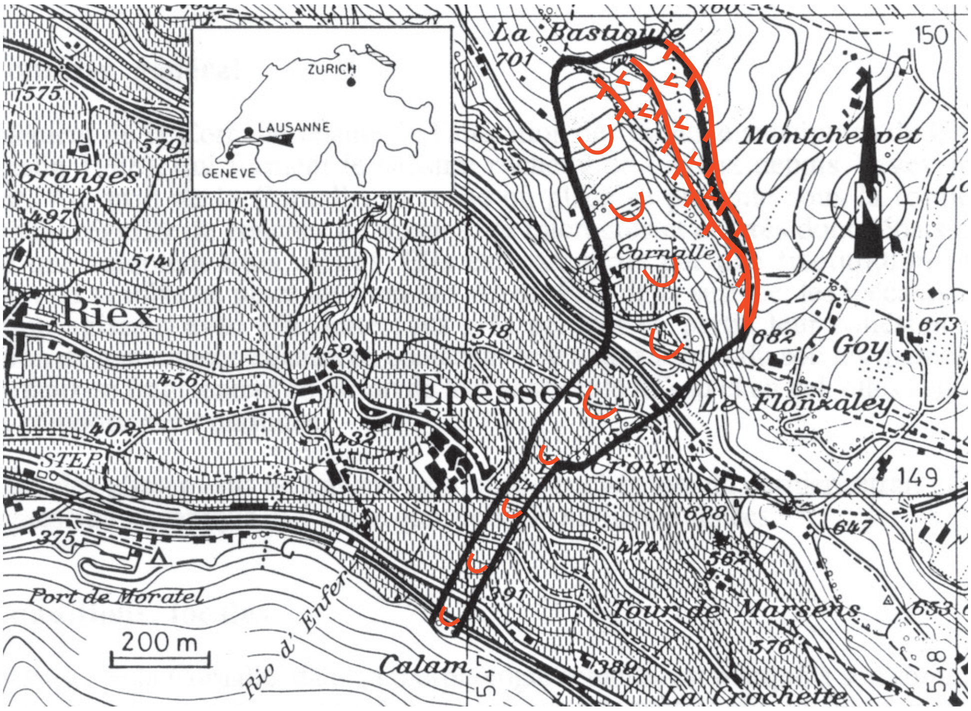


Fig. 5.3.3 : Schematic profile of a deep rotational slide.



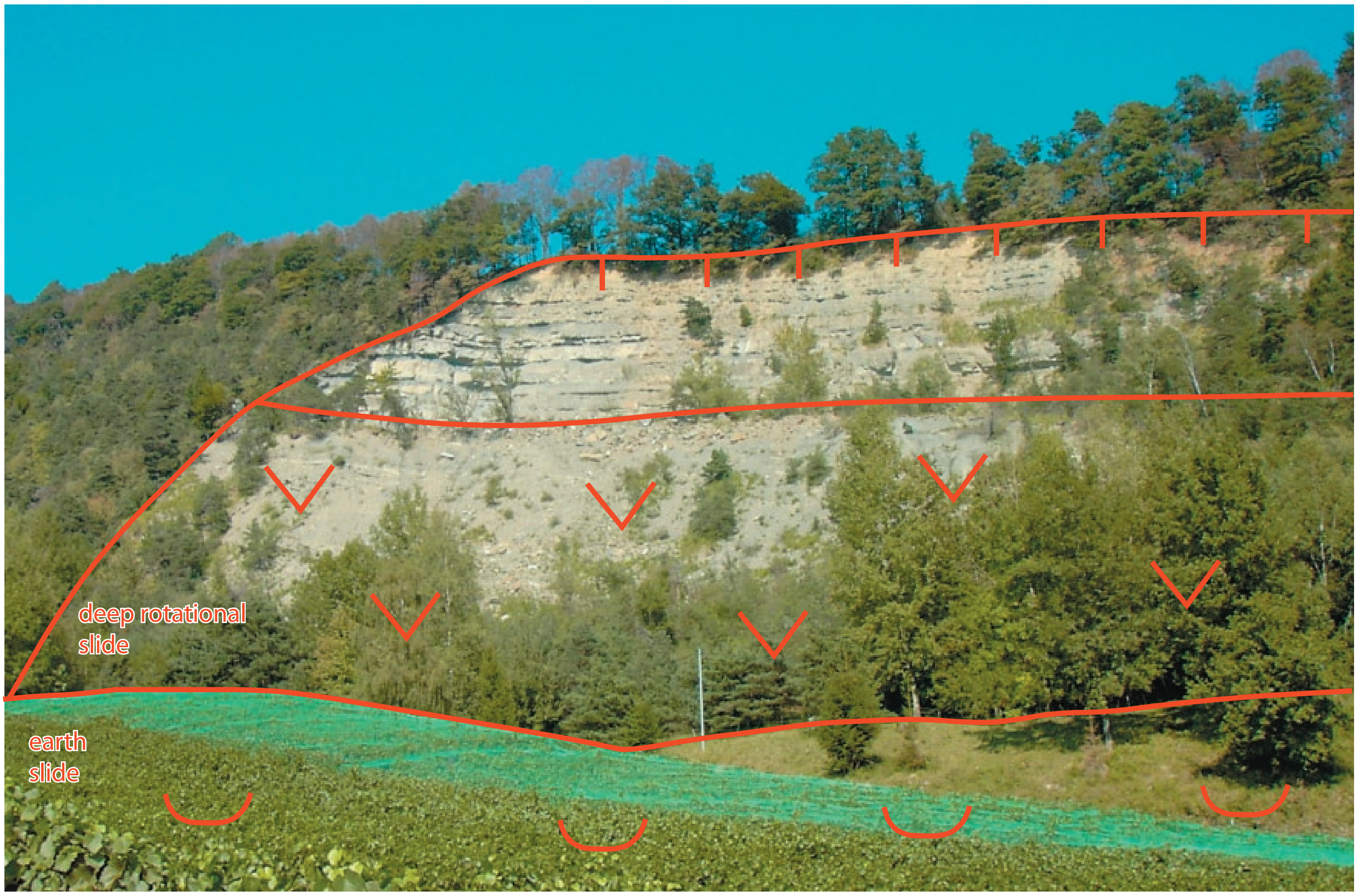
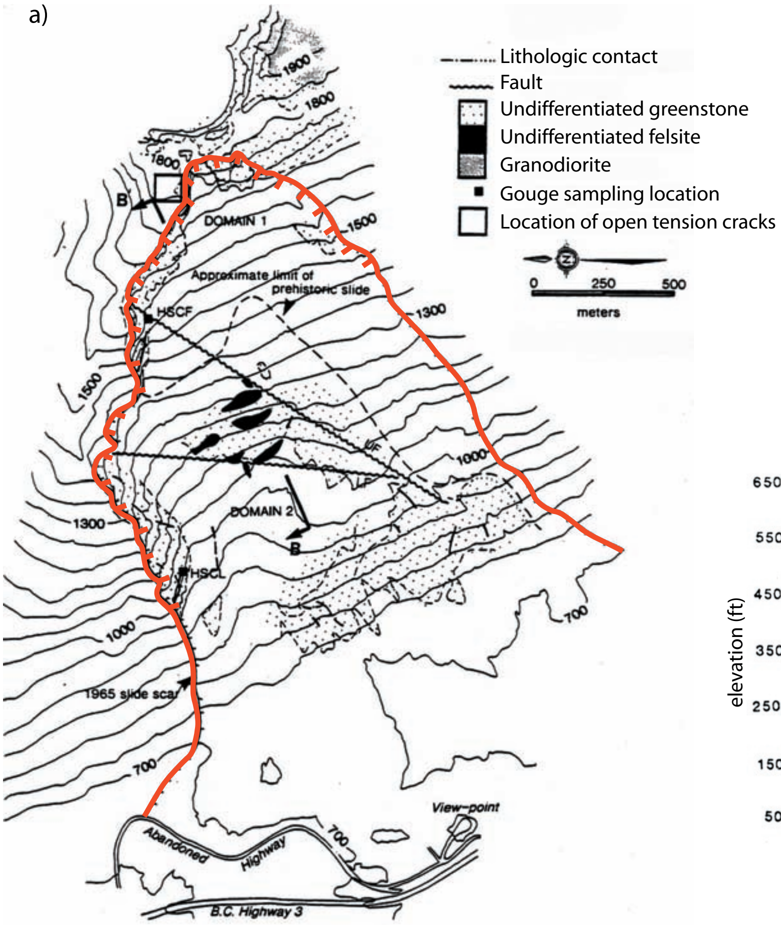
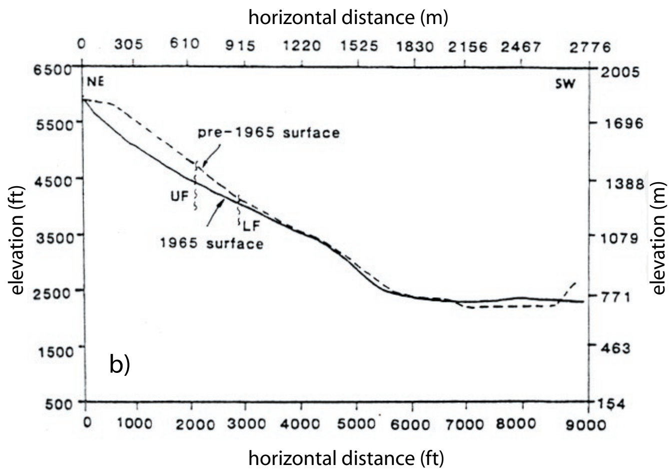


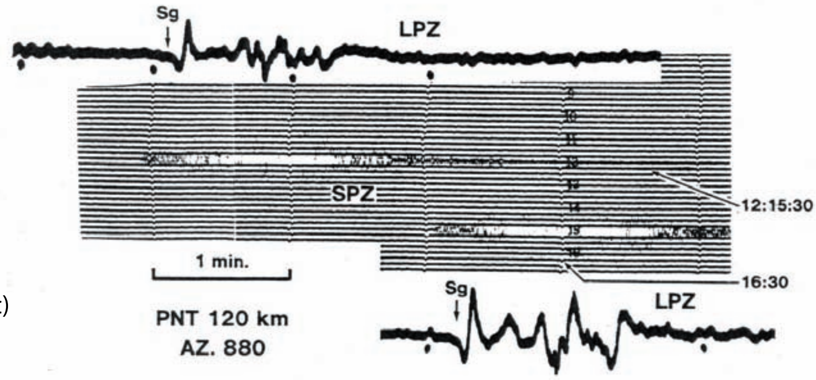
Fig. 5.3.4 : Cornalle landslide in the northern side of Geneva Lake. Photo Parriaux.

5.3.2 A
Case study of Hope Slide, Canada

a)







c)

Photo Parriaux

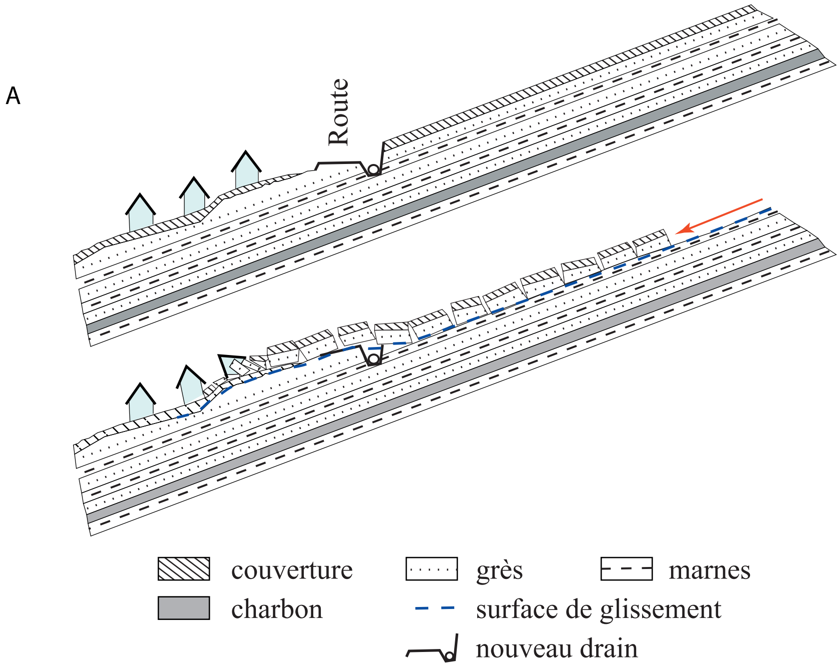
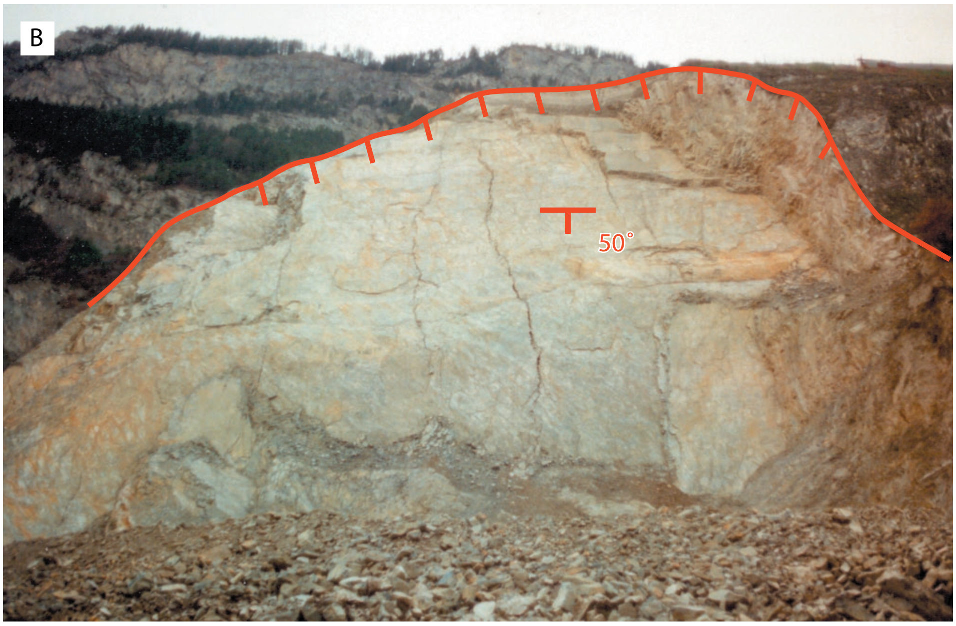


Photo Gabus

Fig. 5.3.5 : Landslide at Ecaravez in Belmont near Lausanne.

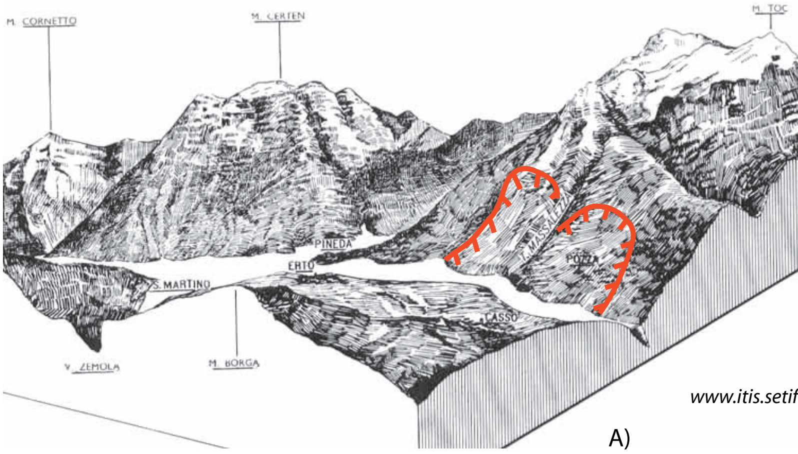
5.3.3 A

Case study of Saillon (Canton of Valais)



Photos Parriaux

5.3.3 B
Case study of Vajont, Italy

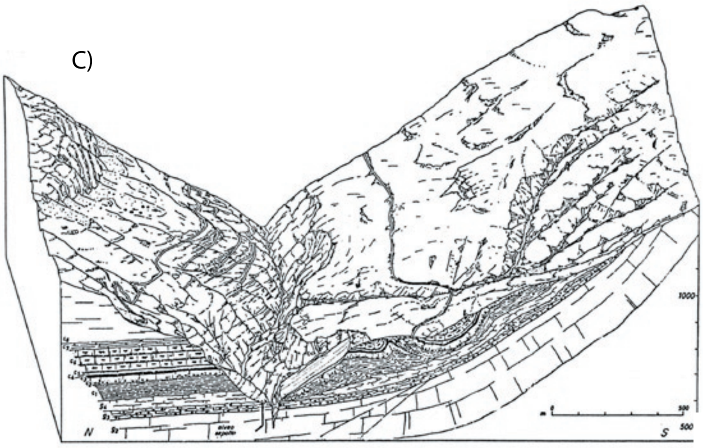


www.itis.setificio.co.it

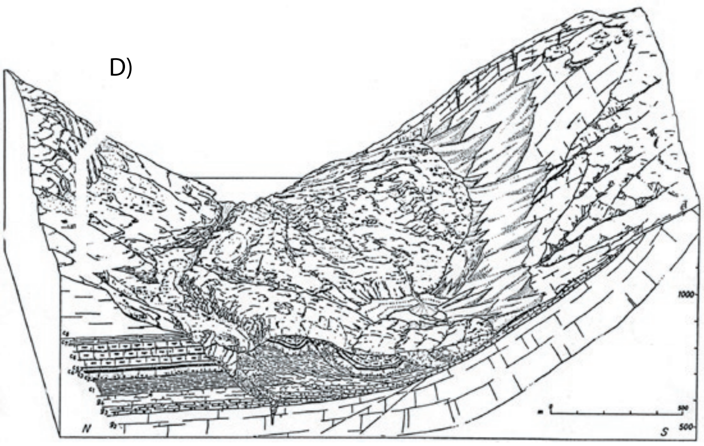
A)

B)

C)

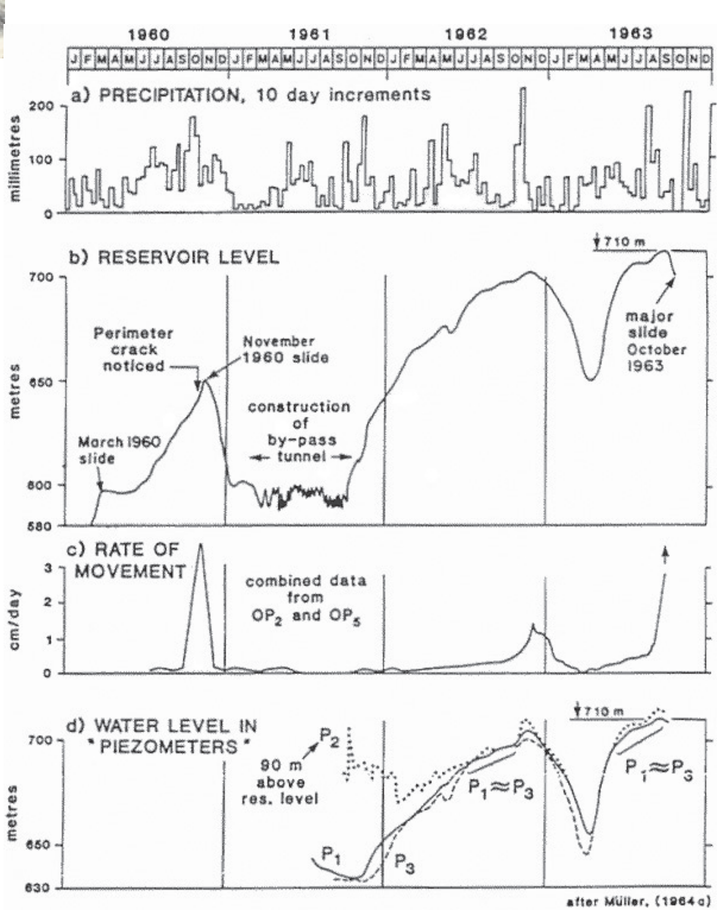


D)



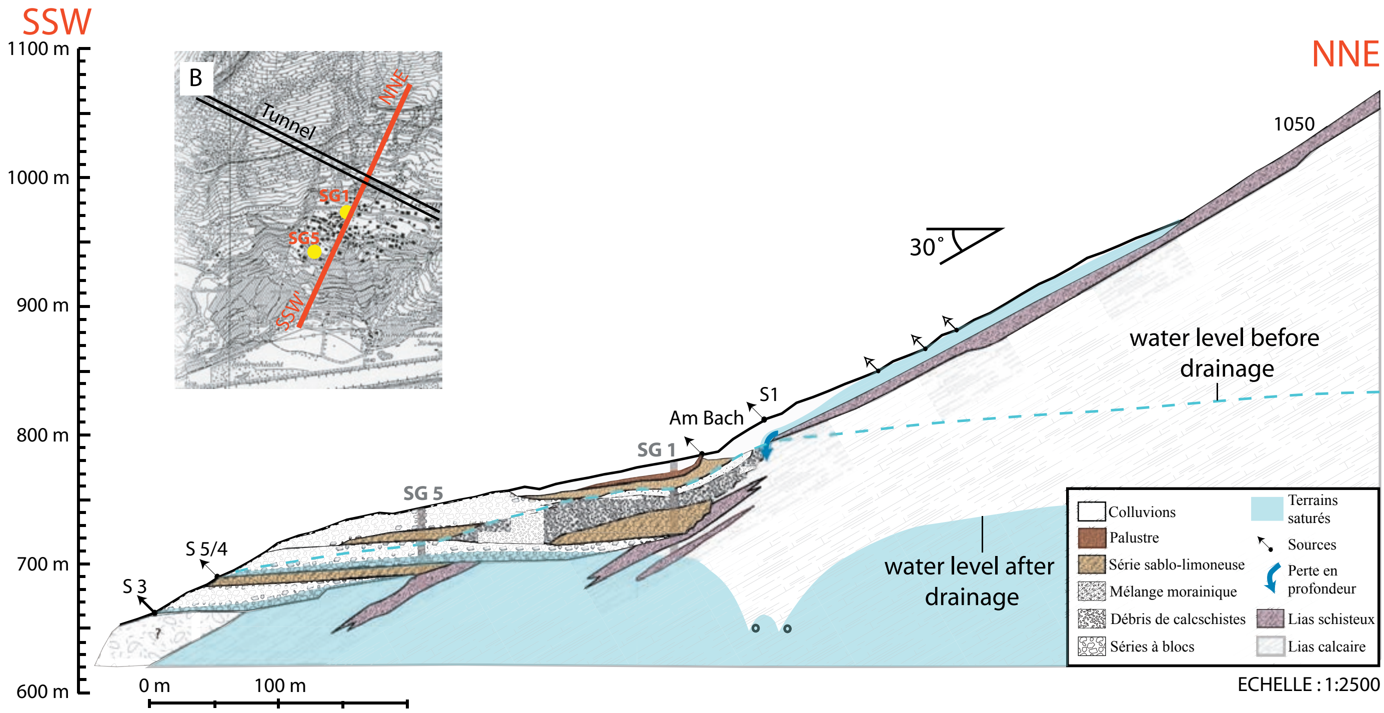
3D blocs from Carloni, 1964

Case study of Vajont, Italy (continuation)

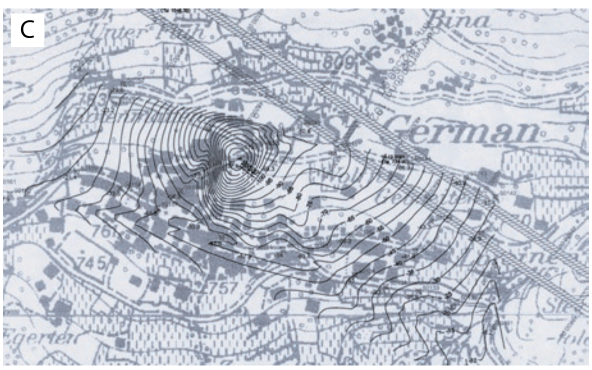


5.3.3 C
Case study of St- German (Canton of Valais)

Photo Bulliard



Cross section from expertise EPFL



Interlines : 5mm
Situation of 10.12.2001
Maximum collapse: 200mm

BSAP Ingenieure u. Berater, 2001

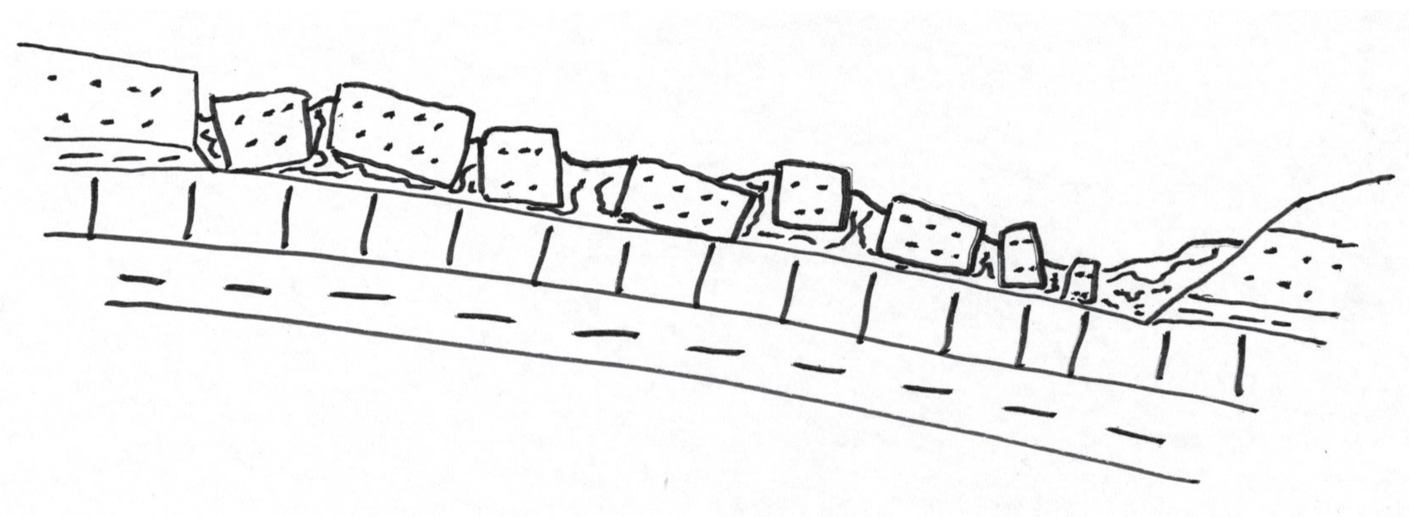
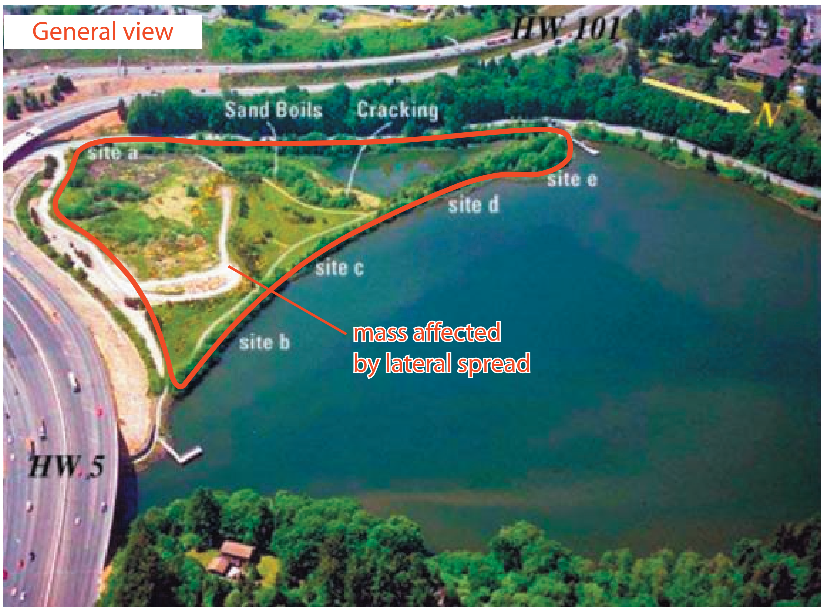
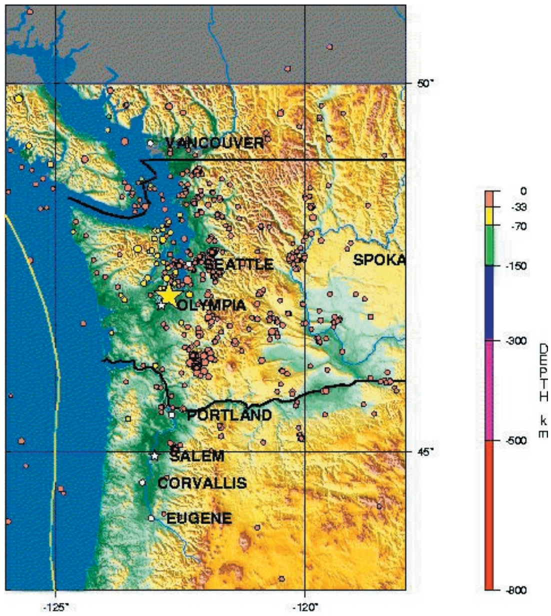


Fig. 5.4.1: Schematic profile of the spread phenomenon in a slope

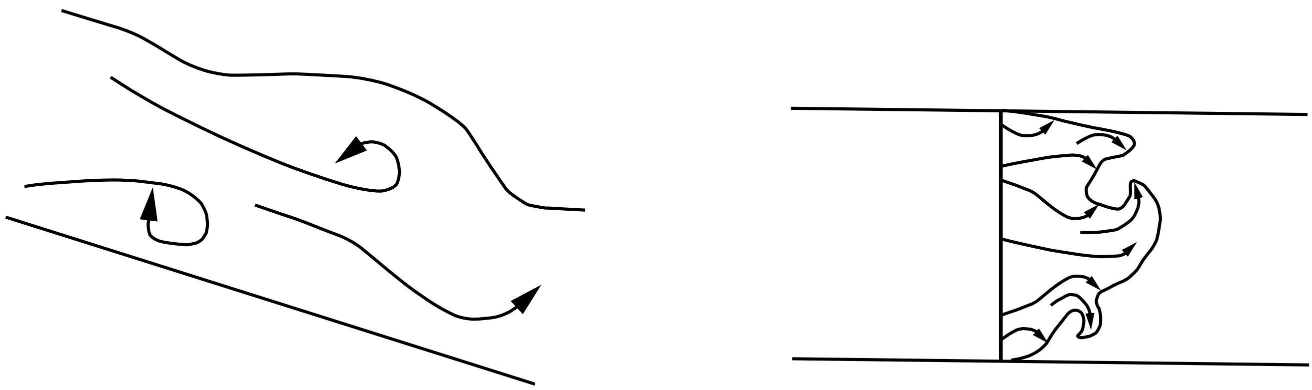
5.3.4 A
Case study of Capitol, USA





State of Washington, seismicity 1977-1997, USGS National Earthquake Information Center

Photos from Bray and others, USGS, 2001 laminar flow



turbulent flow

Fig. 5.5.1 : Schematic cross-section and map view of a flow phenomenon.

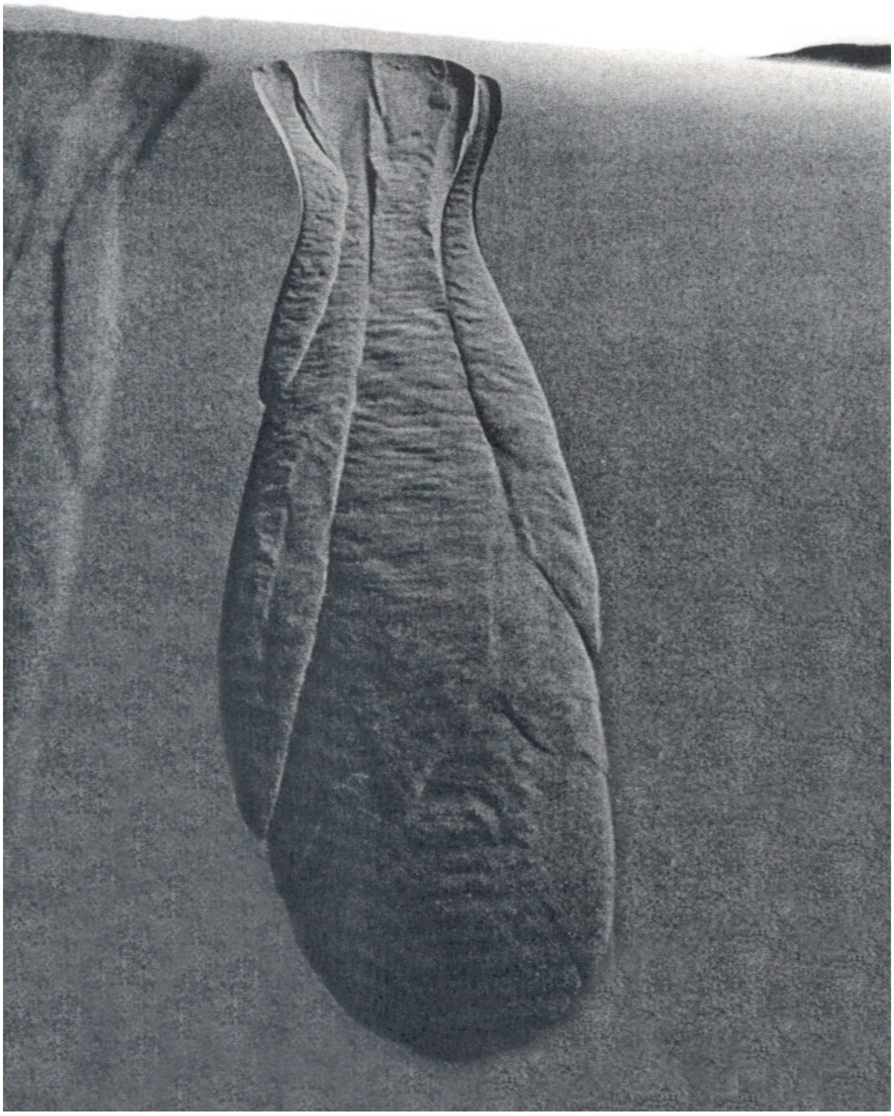
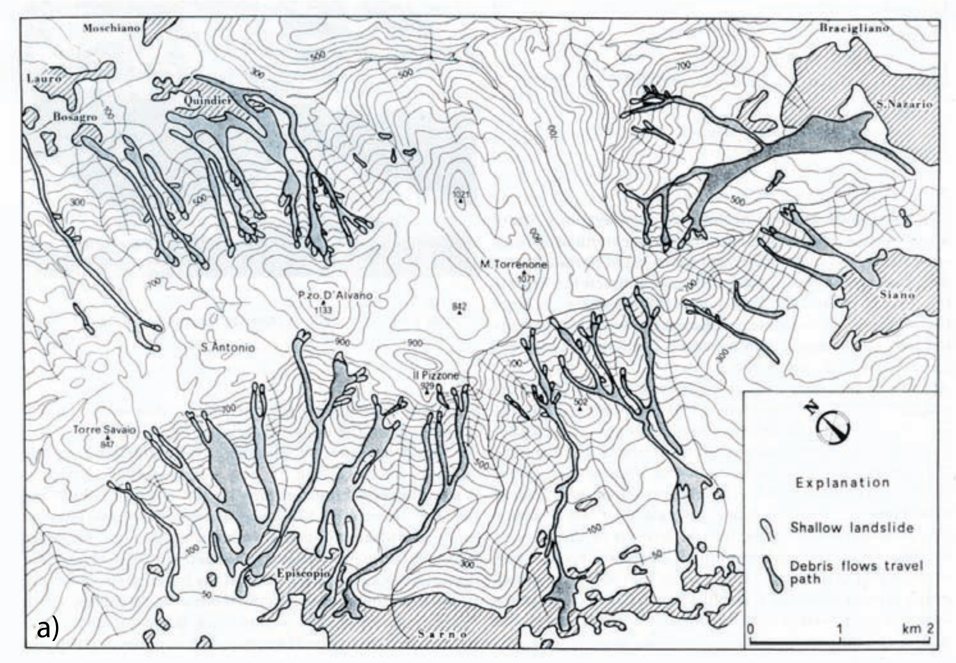
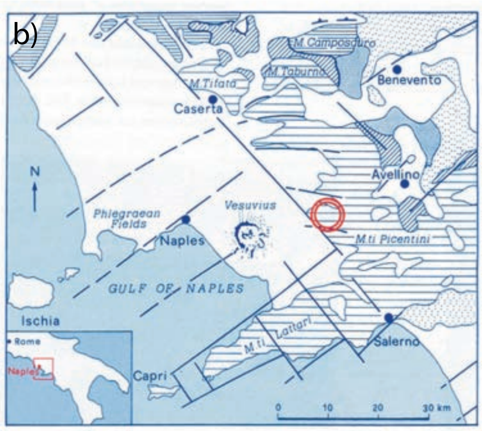
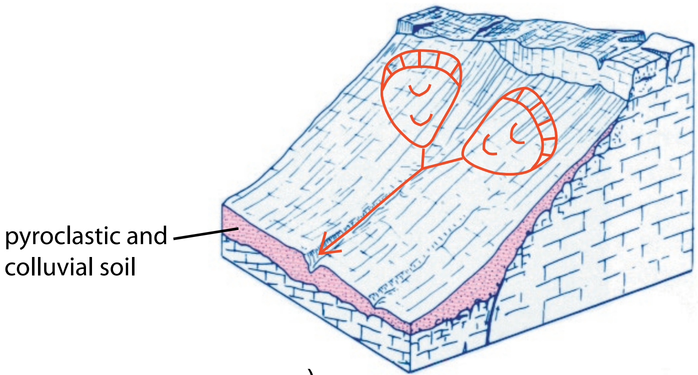


Fig. 5.5.2 : Sand flow on the lee slope of a sand dune in the Namib Desert. *Photo G. D. Plage*

5.5.2 A
Case study of Campania, Italy

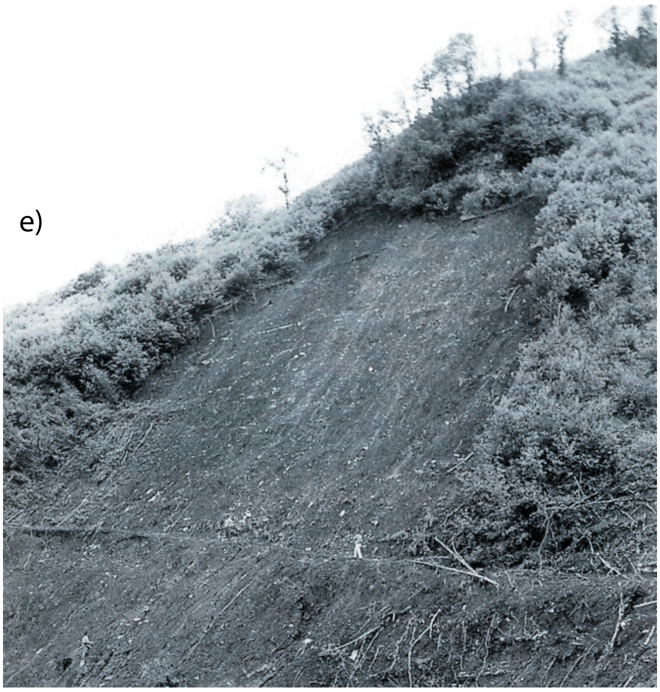






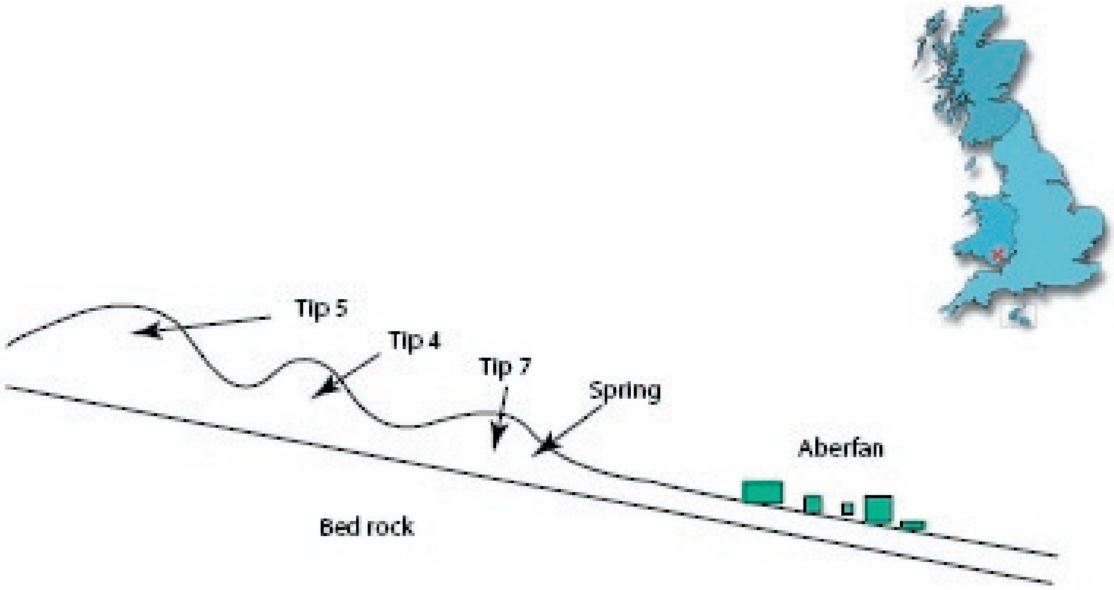
c)

e)



5.5.2 B

Example of real case of flow slide: Aberfan, South Wales, Great Britain

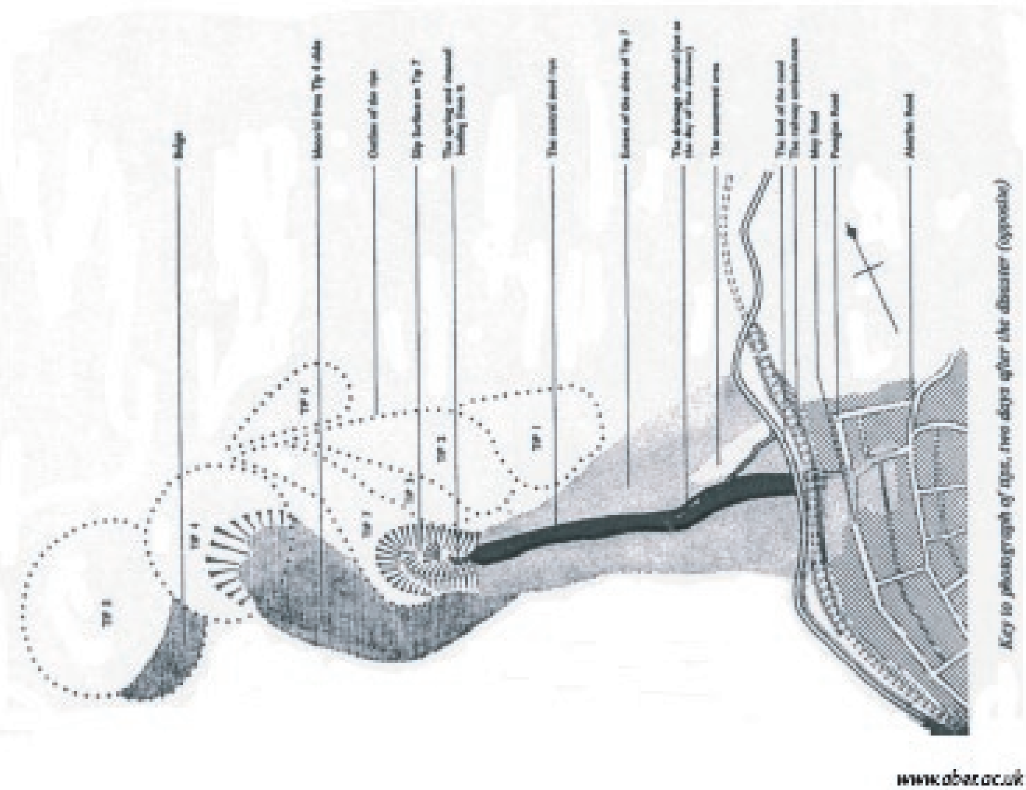


www.slamtschoolage.org.uk

www.slamtschoolage.org.uk

Example of real case of flow slide: Aberfan, South Wales, Great Britain (continuation)

Bignell et al, 1977
www.aber.ac.uk



www.aber.ac.uk

Photo Parriaux

Fig. 5.5.3: Debris flow in Ladakh, India

Fig. 5.5.4 : Debris flow of granite balls, Nepal. Photo Parriaux.

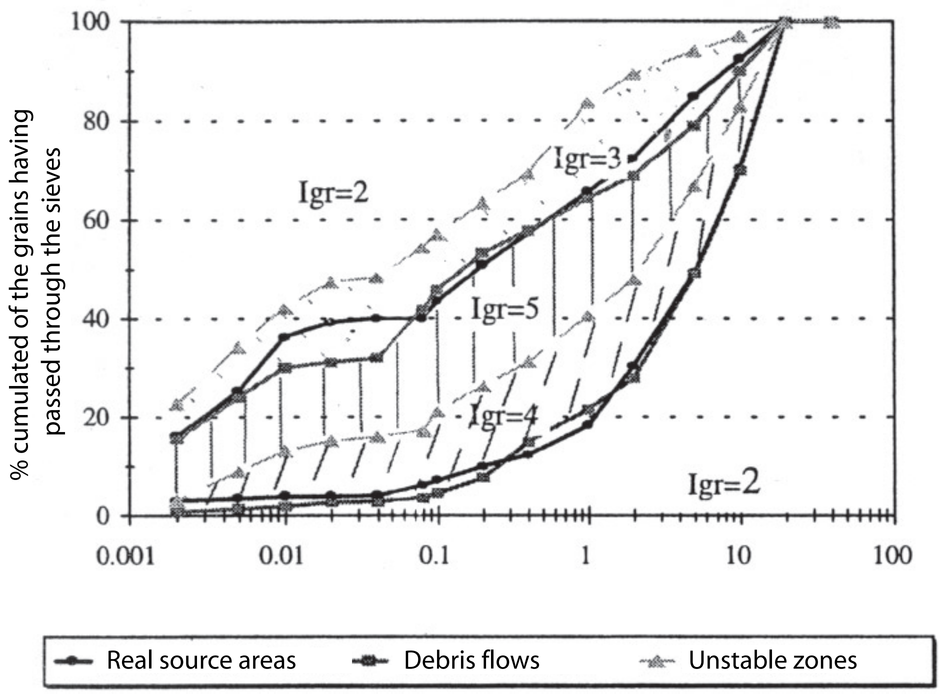


Fig. 5.5.5 : Domain of grain size distribution of unstable soils in the French Alps (Bonnet-Staub, 1999).

5.5.3 A
Case study of Illgraben (Canton of Valais)

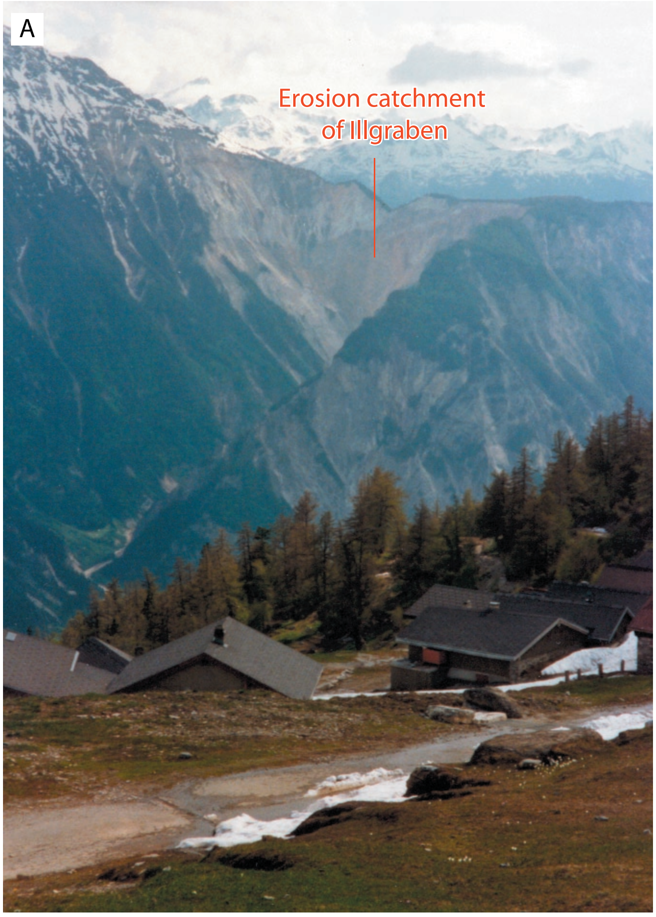


Photo Parriaux

Photo Parriaux

Photo SLF_ENA Valais

5.5.3 B

Case study of Le Pissot (Canton of Vaud)

Photo 24 Heures

Photo Parriaux

Photo Karakas & Français

Photo Karakas & Français

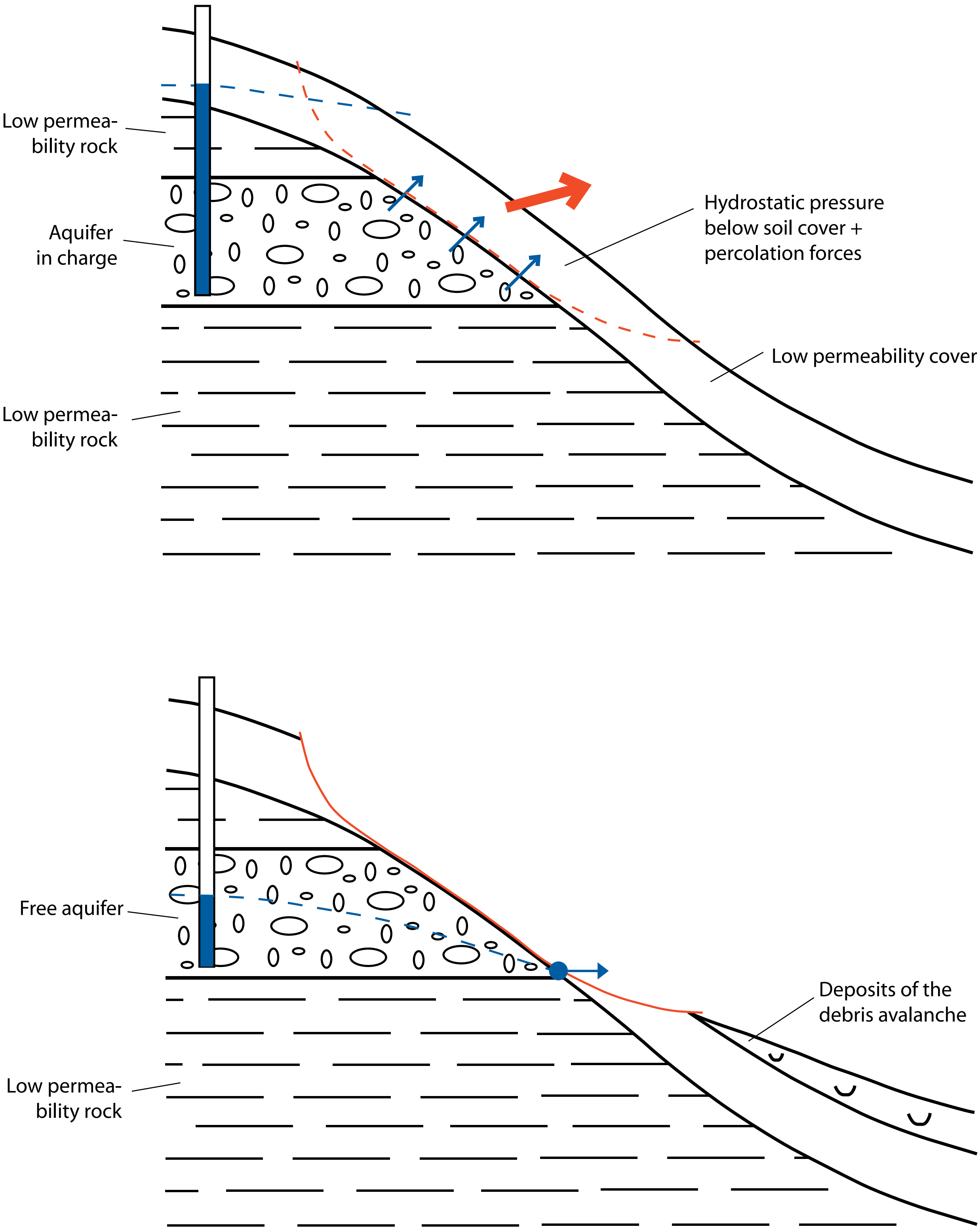


Fig. 5.5.6 : Mechanism of a debris avalanche.

Photo Parriaux

Fig. 5.5.7: Debris avalanche in Himalaya

A)

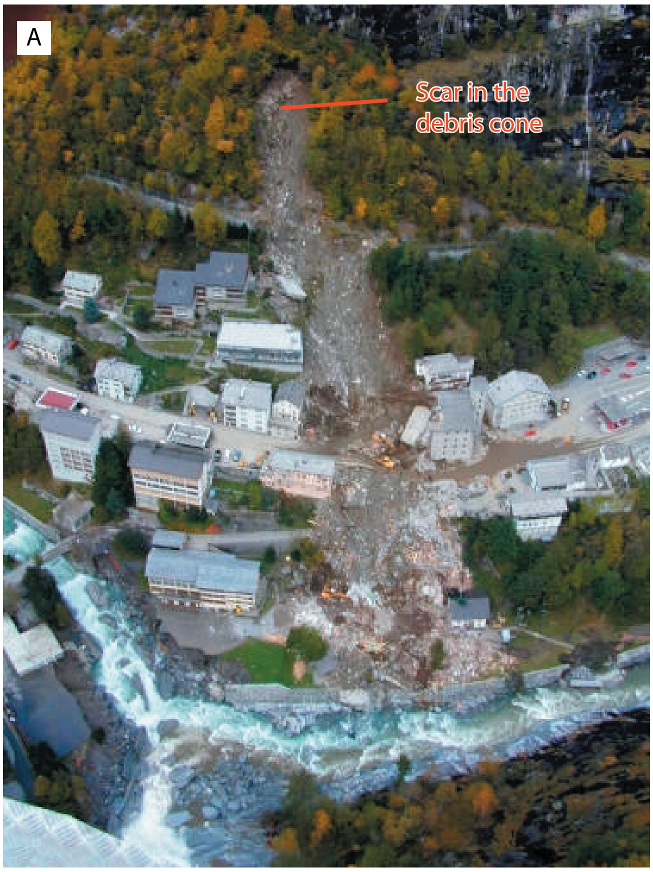
B)

C)

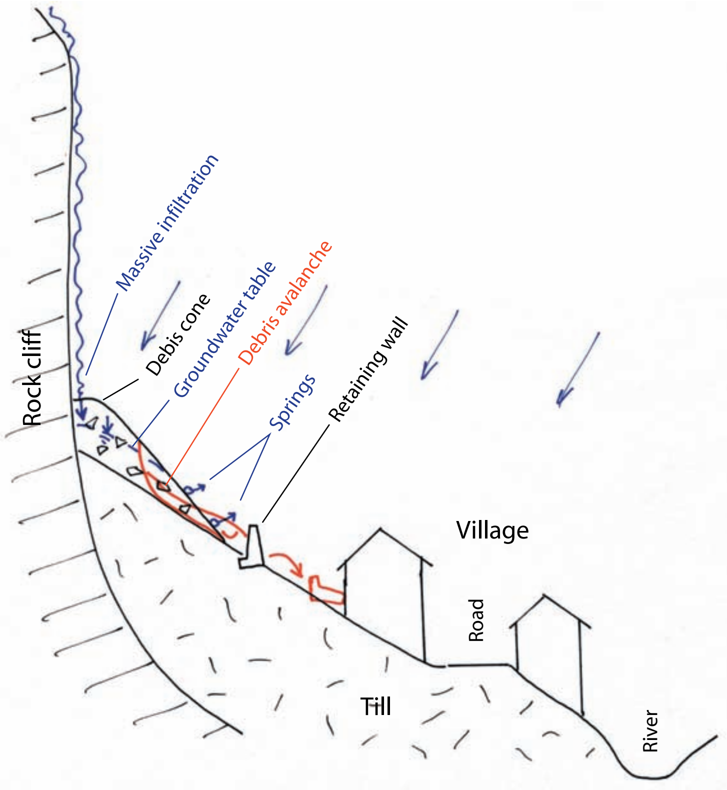
Photos Parriaux

Fig. 5.5.8 : Debris avalanche at Orsières, Valais

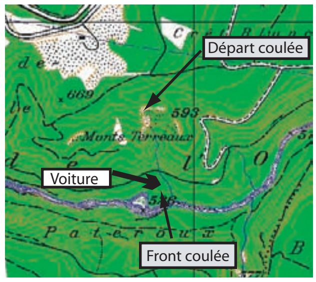
5.5.4 A
Case study of Gondo (Canton of Valais)



Photos from CREALP

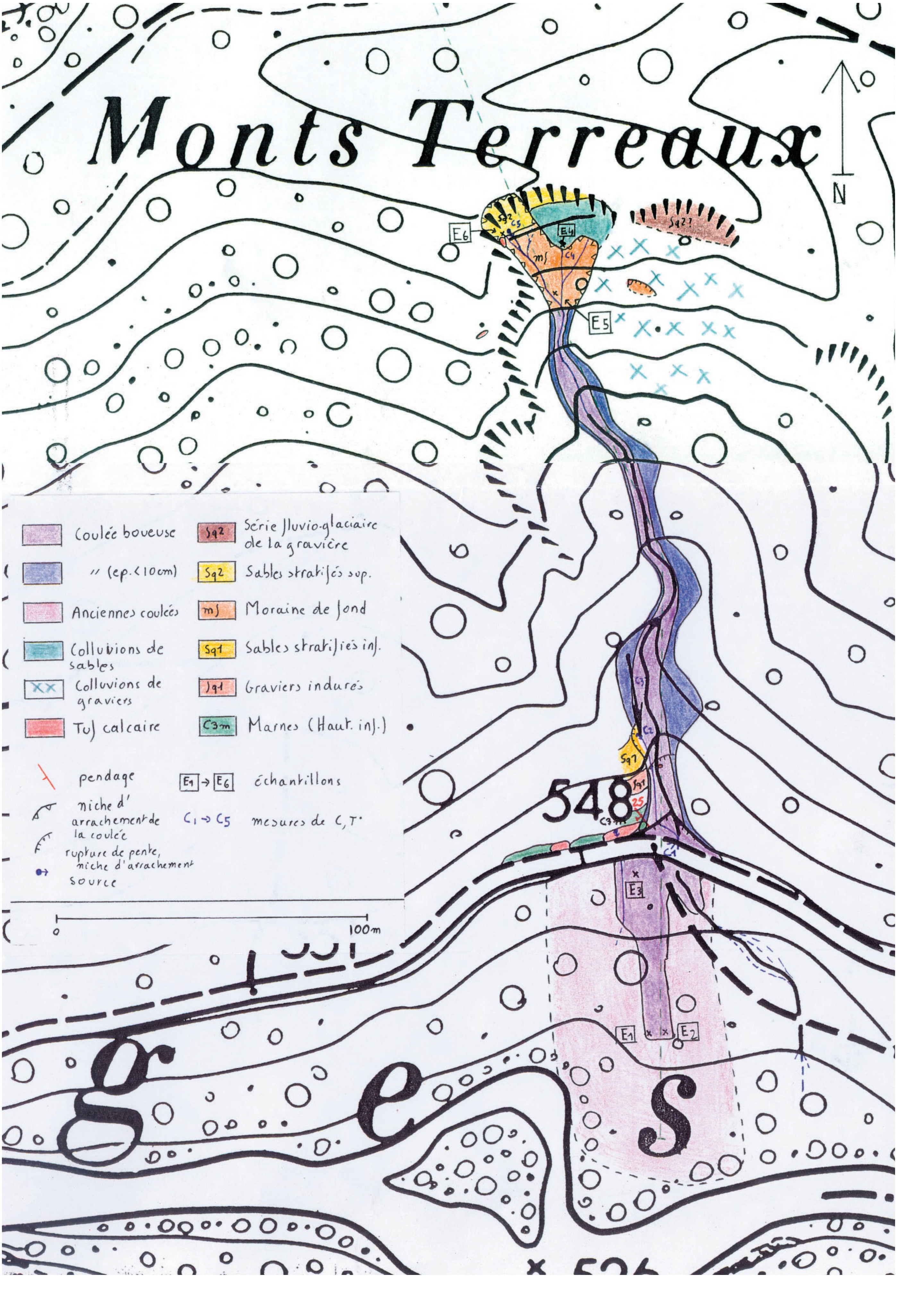


5.5.4 B
Case study of Les Clées (Cantoon of Vaud)



Photos Parriaux

Case study of Les Clées



5.5.5 A
Case study of Krisnabyr, Nepal

Photos Parriaux

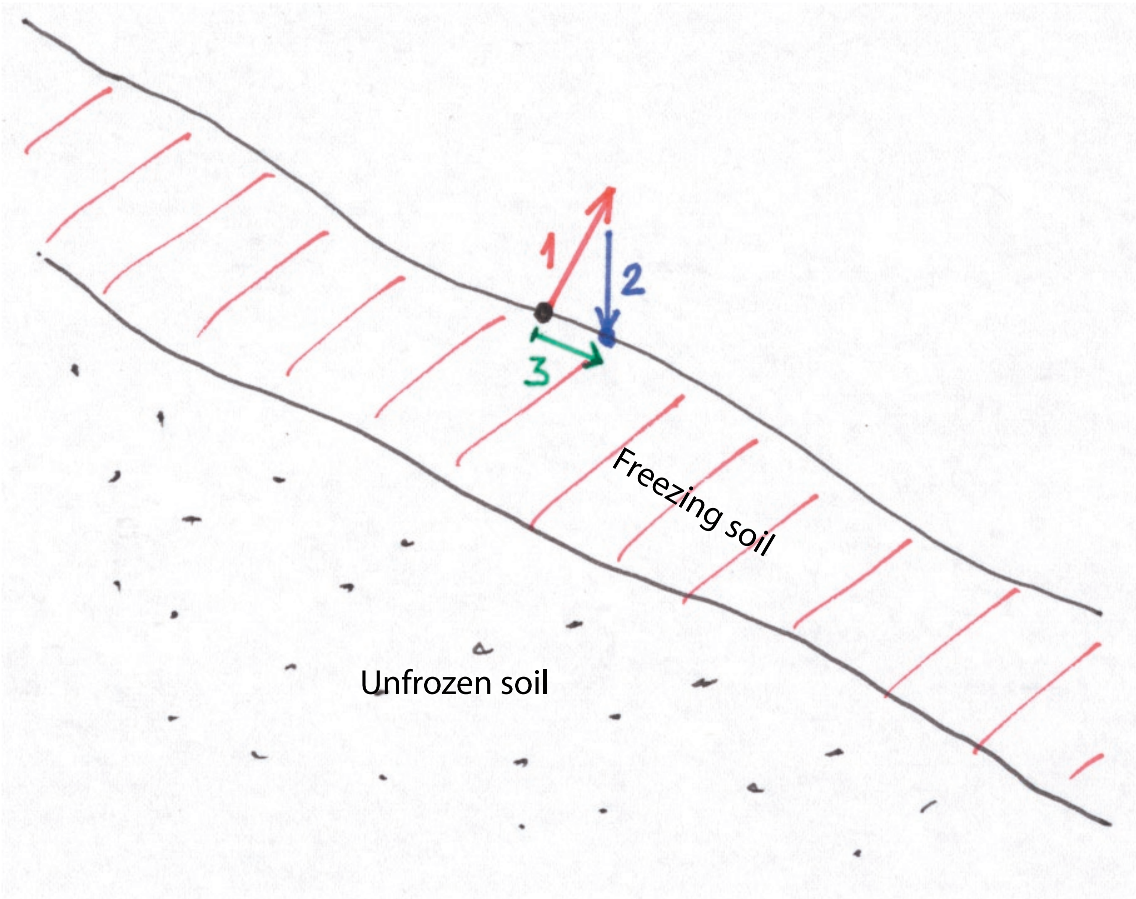
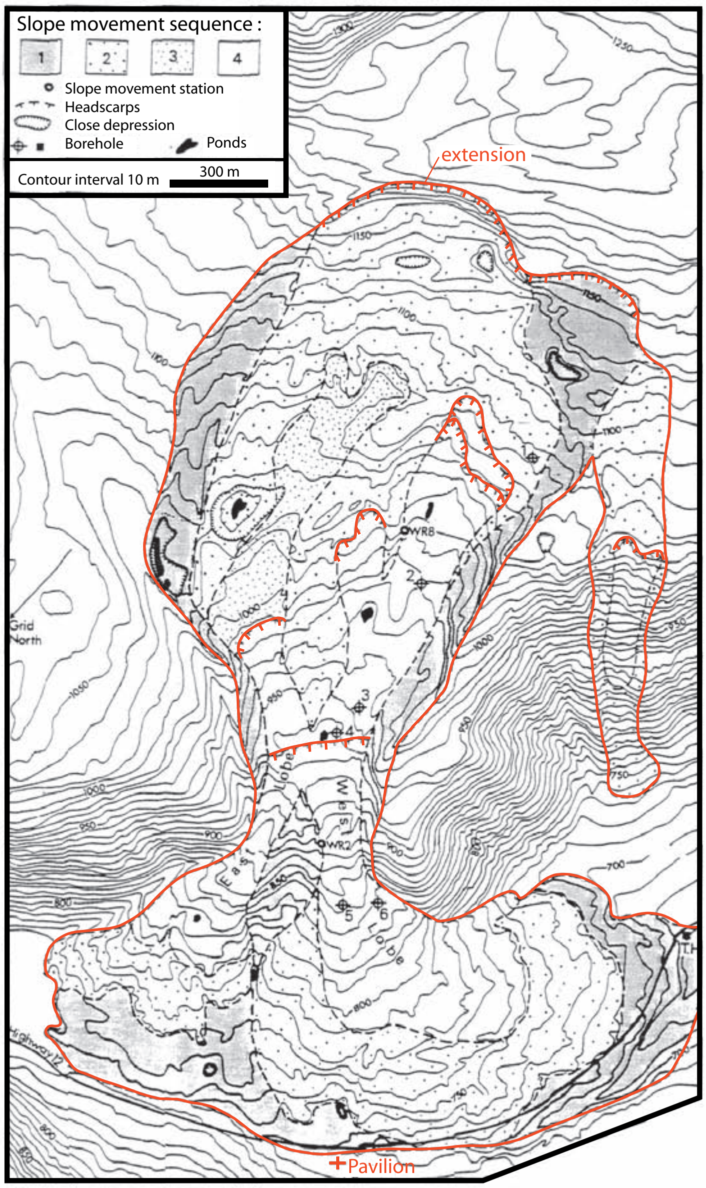


Fig. 5.5.9: Reptation process

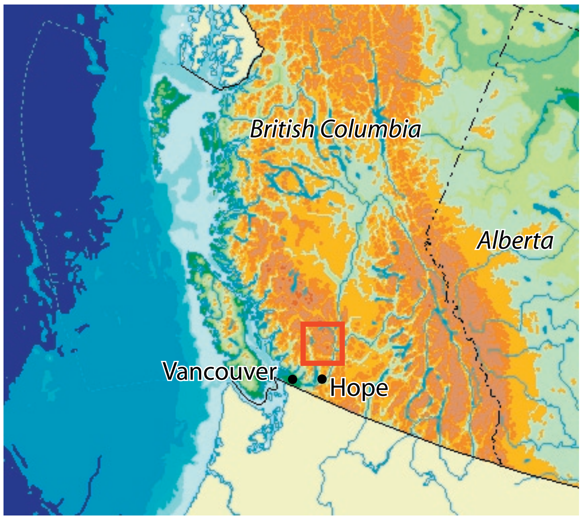
Fig. 5.5.10 : Solifluction in Furka pass, Switzerland. *Photo Parriaux.*

Fig. 5.5.11 : Earth flow in Ienissei, Siberia. *Photo Parriaux*.

5.5.6 A
Case study of Pavilion, Canada



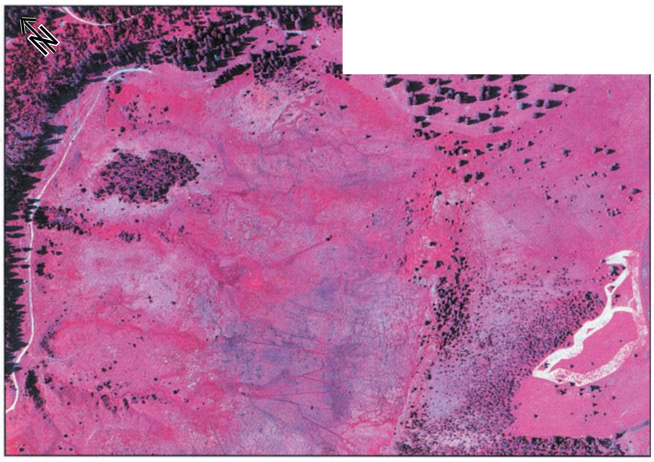
Modified from Couture, 2001

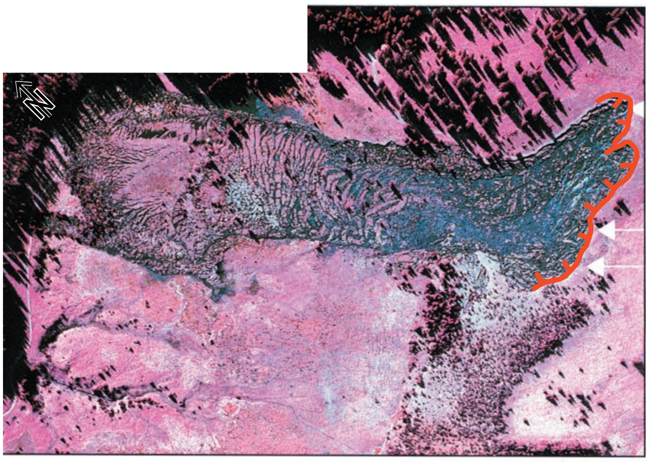


http://atlas.gc.ca

Photo Parriaux

5.5.7 A
Case study of La Vraconnaz (Canton of vaud)





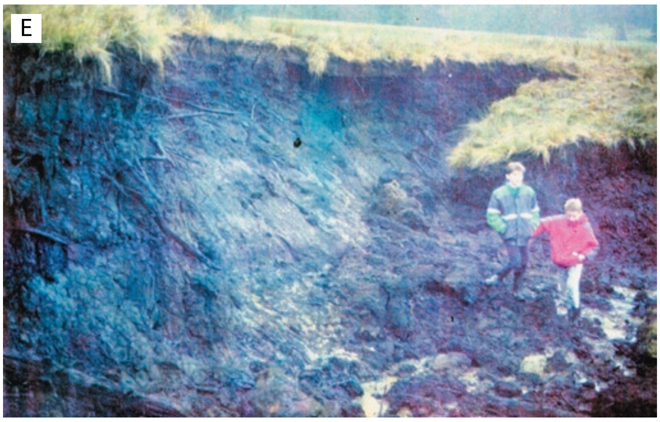
Aerial photographies from Hübscher and Gautschi

B

C

D

E



Photos Parriaux

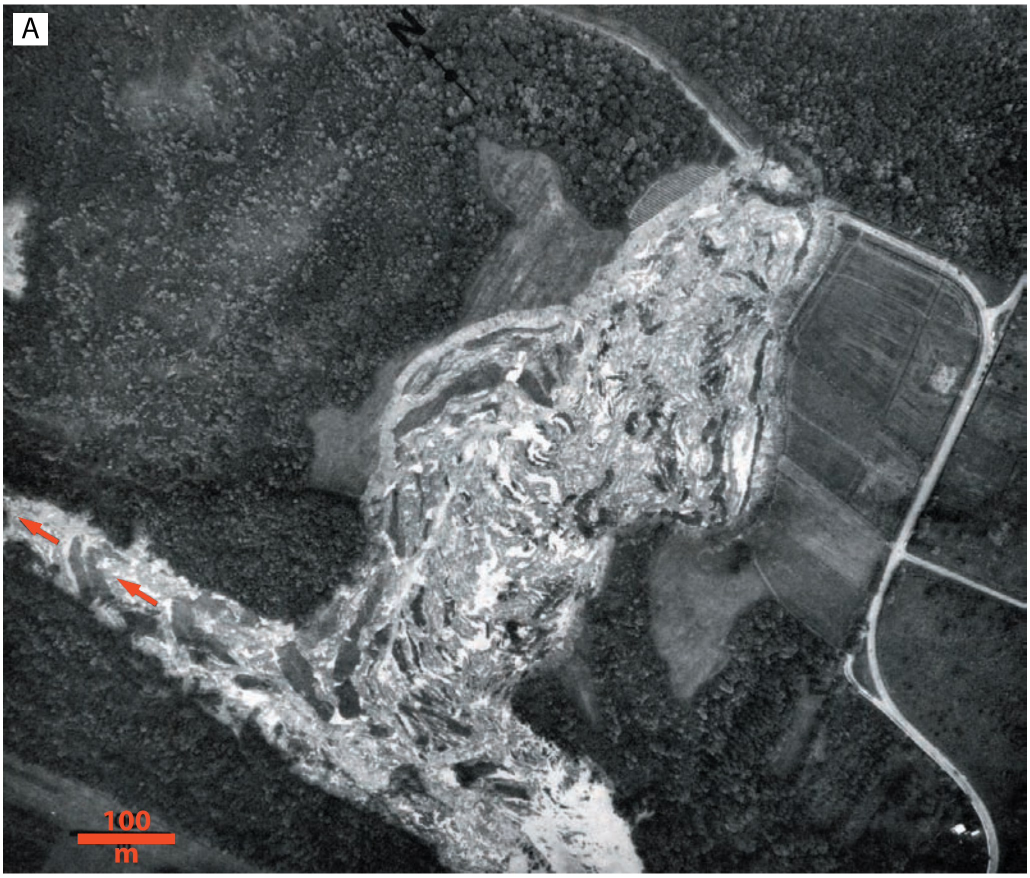
Fig. 5.5.12: Rissa landslide (Norway)

5.5.9 A

Case study of Lemieux, Canada

Photo Parriaux

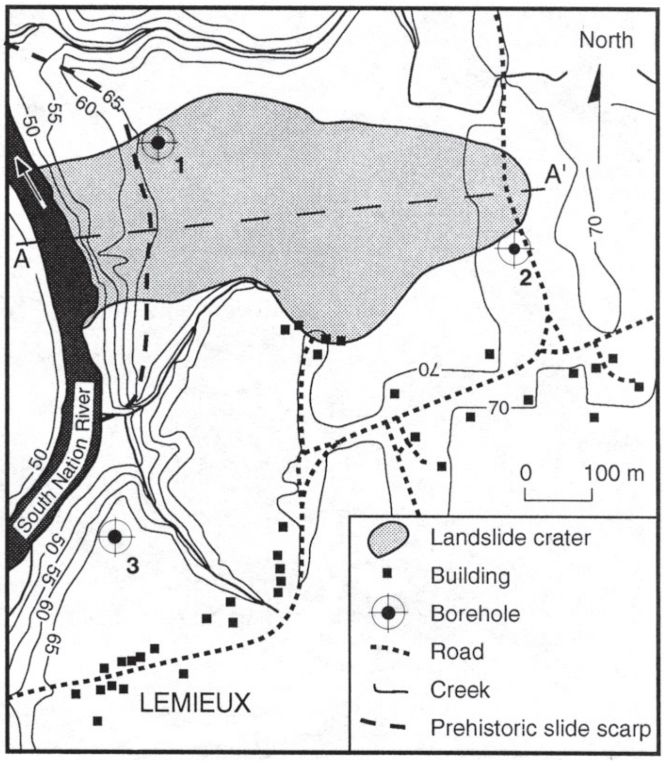
http://listingsca.com/Ontario



Evans & Brooks, 1994

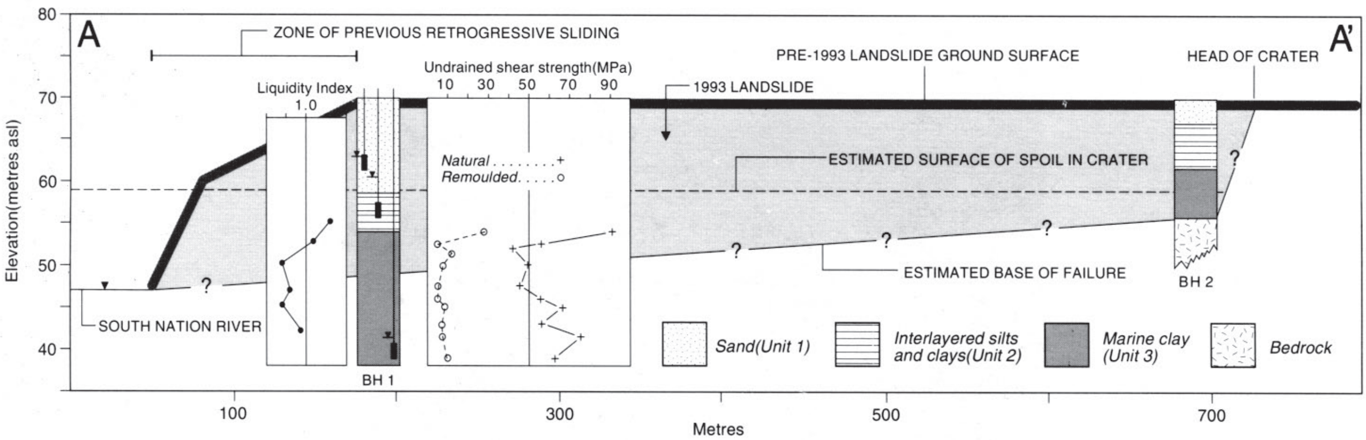
Photo Parriaux

Case study of Lemieux, Canada (continuation)



Map showing the extent of the 1993 Lemieux earth flow

Evans & Brooks, 1994



Evans & Brooks, 1994

Approximate cross section (A-A') and geotechnical profile of Lemieux

Unit	Lithology	Depth range (m)	Index properties W_p (%)	W_L (%)	W (%)	I_L	Undrained strength C_u (MPa)[a] Natural	Remoulded	Sensitivity
1	Silty fine sand	0–7	—	—	—	—	—	—	—
2	Interlayered silty clay	3–17	25	52.5	36.7	0.4	68.7–91.7	23.8–28	2.19–3.18
3	Silty clay	8–32	19.9–27.8	31.4–56.2	36.4–59	0.8–1.6	41.7–76.7	3.7–10.9	4.3–11.4

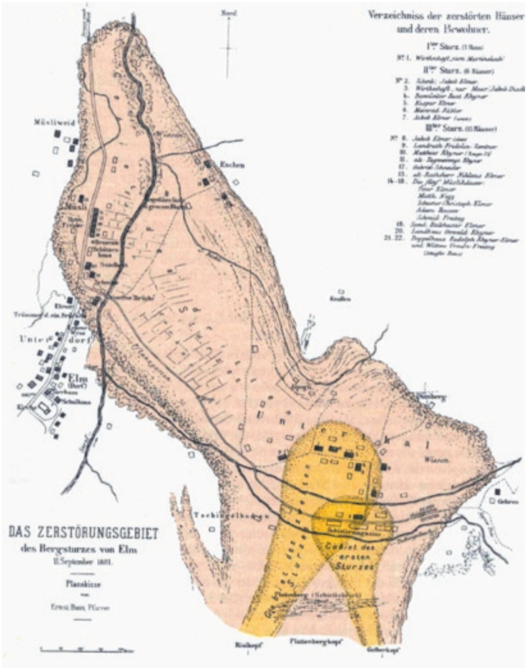
[a]Field vane tests.

Evans & Brooks, 1994

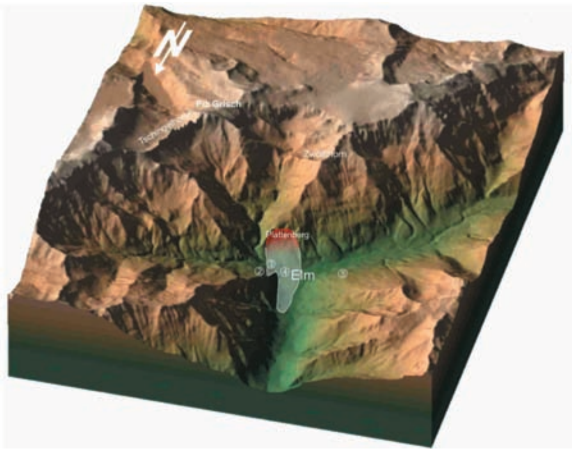
Lemieux landslide: summary of geotechnical data

5.5.10 A

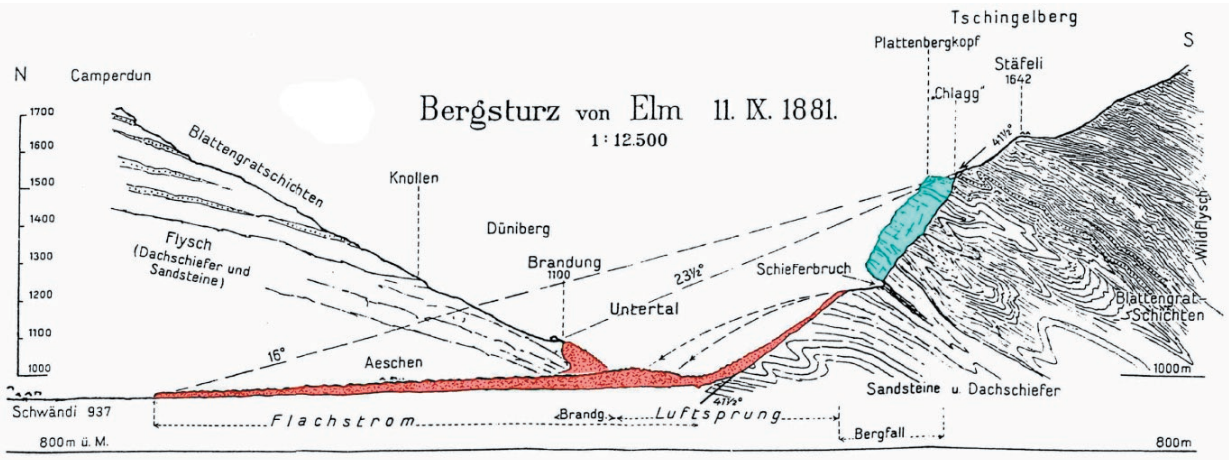
Case study of Elm, Glarus Canton



Thuro & Valley 2003



Interactiv Atlas of Switzerland, Swisstopo; in Thuro & Valley 2003

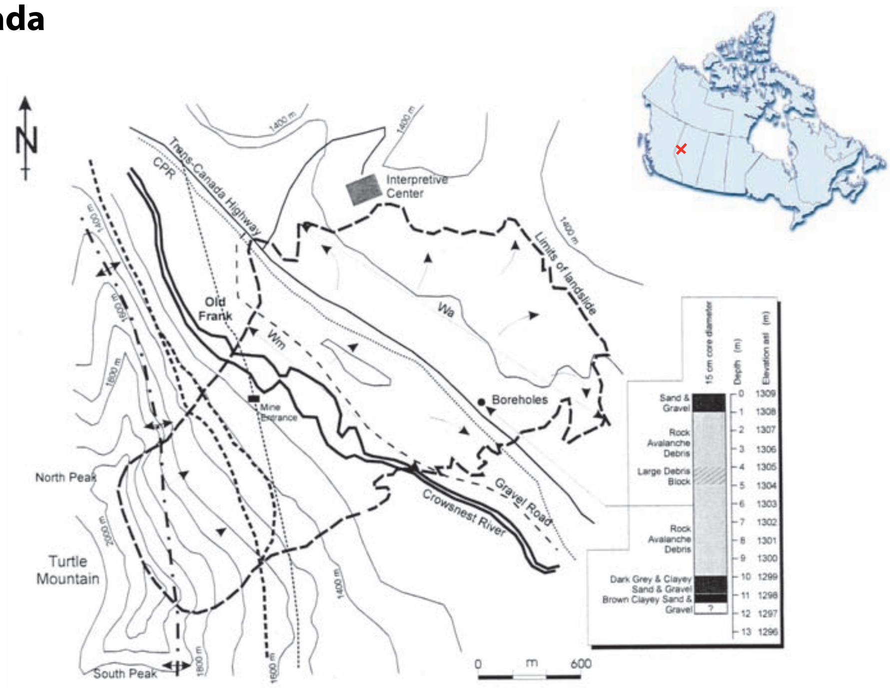


Buss & Heim 1881 in Thuro & Valley 2003

Burger in Thuro & Valley 2003

5.5.10 B
Case study of Frank slide, Canada

A)



Couture, 2001

Photo Parriaux

Photo Parriaux

5.6 A

Case study of Bex, Vaud

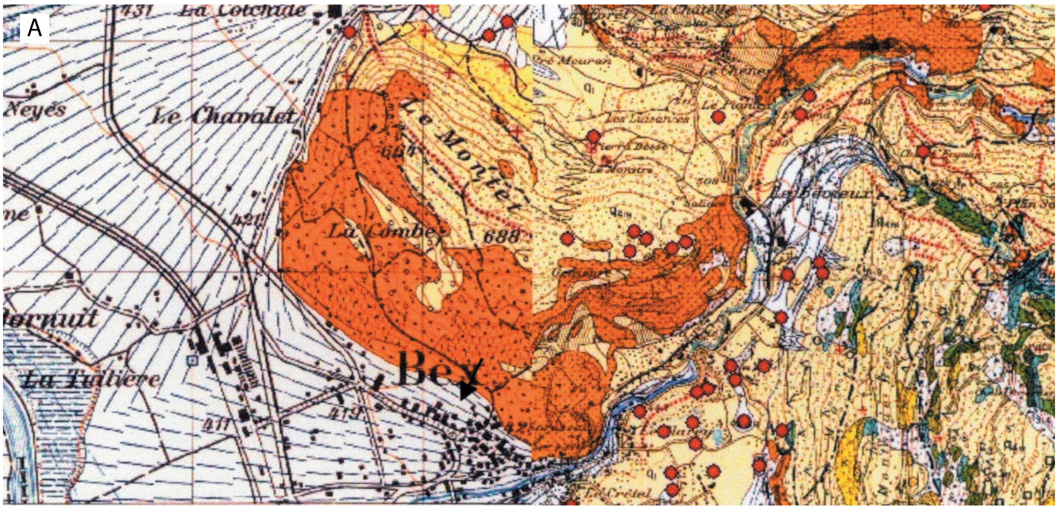


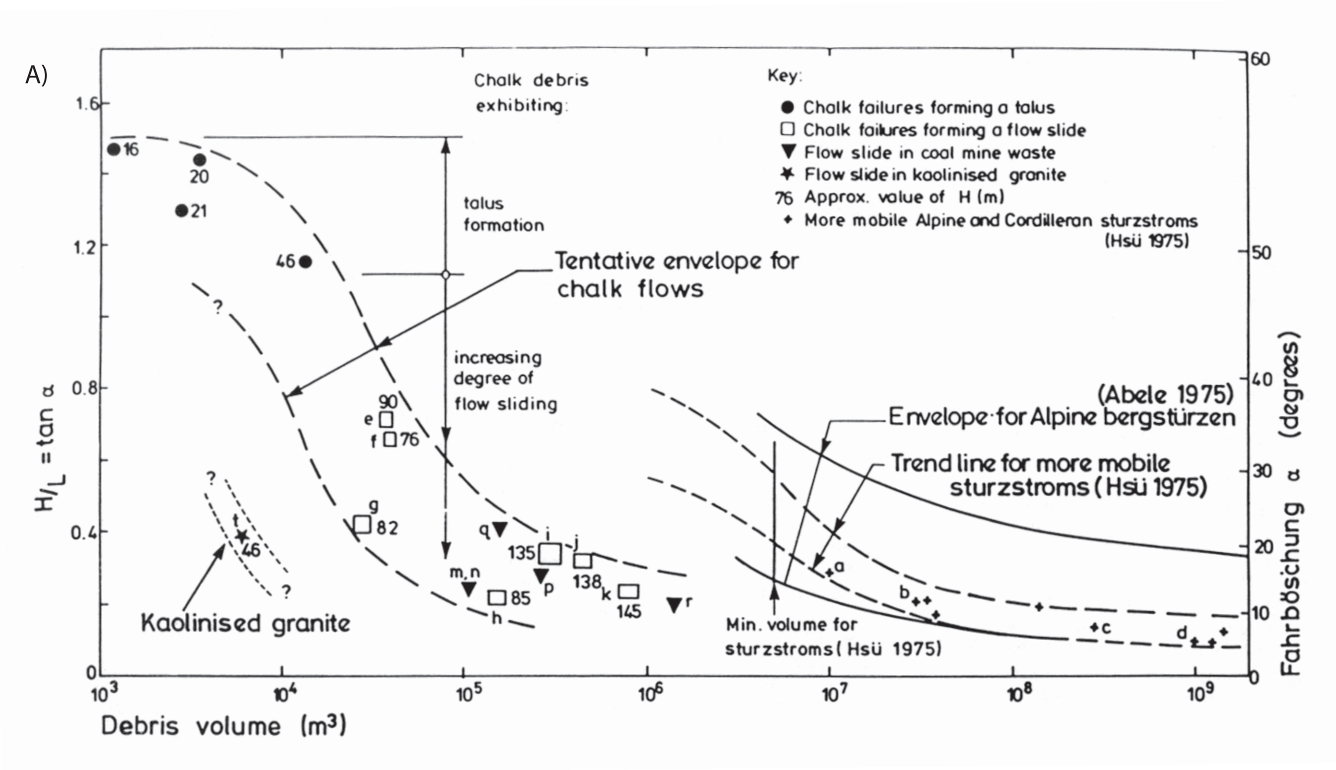
Photo Barras

Photo Parriaux

Photo Parriaux

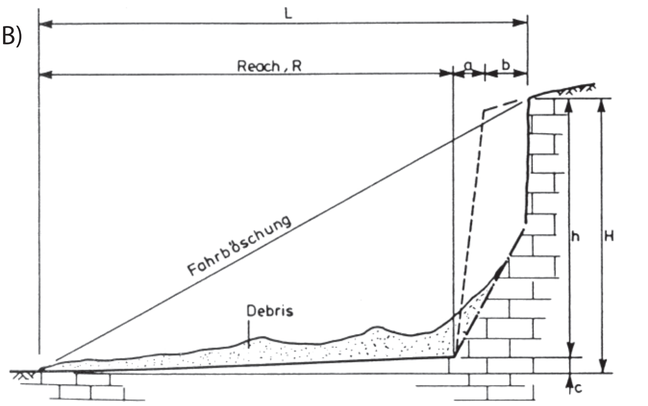
Photo Parriaux

A)



Hutchitson, 1988

B)



Hutchitson, 1988

Fig. 5.5.13