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Analysis of landslides triggered by anthropogenic factors in Europe

Work Package 1.4 - Landslides triggered by anthropogenic factors

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SUMMARY

This deliverable studies the impact of human activities on increasing or decreasing the landslide hazard. To achieve the objectives of the study, the problem was approached from three different angles: statistical analysis of previous landslides, case studies of specific events, and expert opinion pooling.

On the basis of the results of statistical analysis of previous landslides and expert opinion pooling, an empirical model for assessing the changes in landslide frequency (hazard) as a function of changes in the demography and population density is suggested.

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CONTENTS

Appendix A: **Sample Questionnaires Submitted to Landslide Experts for Assessment of Impact of Human Activities on Landslide Hazard**

1 INTRODUCTION AND BACKGROUND

1.1 OBJECTIVES OF THE STUDY

Landslides can be triggered by both natural and human-induced changes in the environment. Human-induced landslides may result from changes in slope caused by terracing for agriculture, cut-and-fill construction for highways, construction activity, mining operations, rapid draw-down of dams, changes in land cover such as deforestation, and changes in irrigation or surface runoff.

The human-induced landslides are caused by changes of the strength or effective stresses, changes in geometry and boundary conditions, and modifications or changes of the material behaviour. These problems were underlined by Terzaghi (1950) in his landmark article: *Mechanisms of Landslides* (Figure 1.1.1).

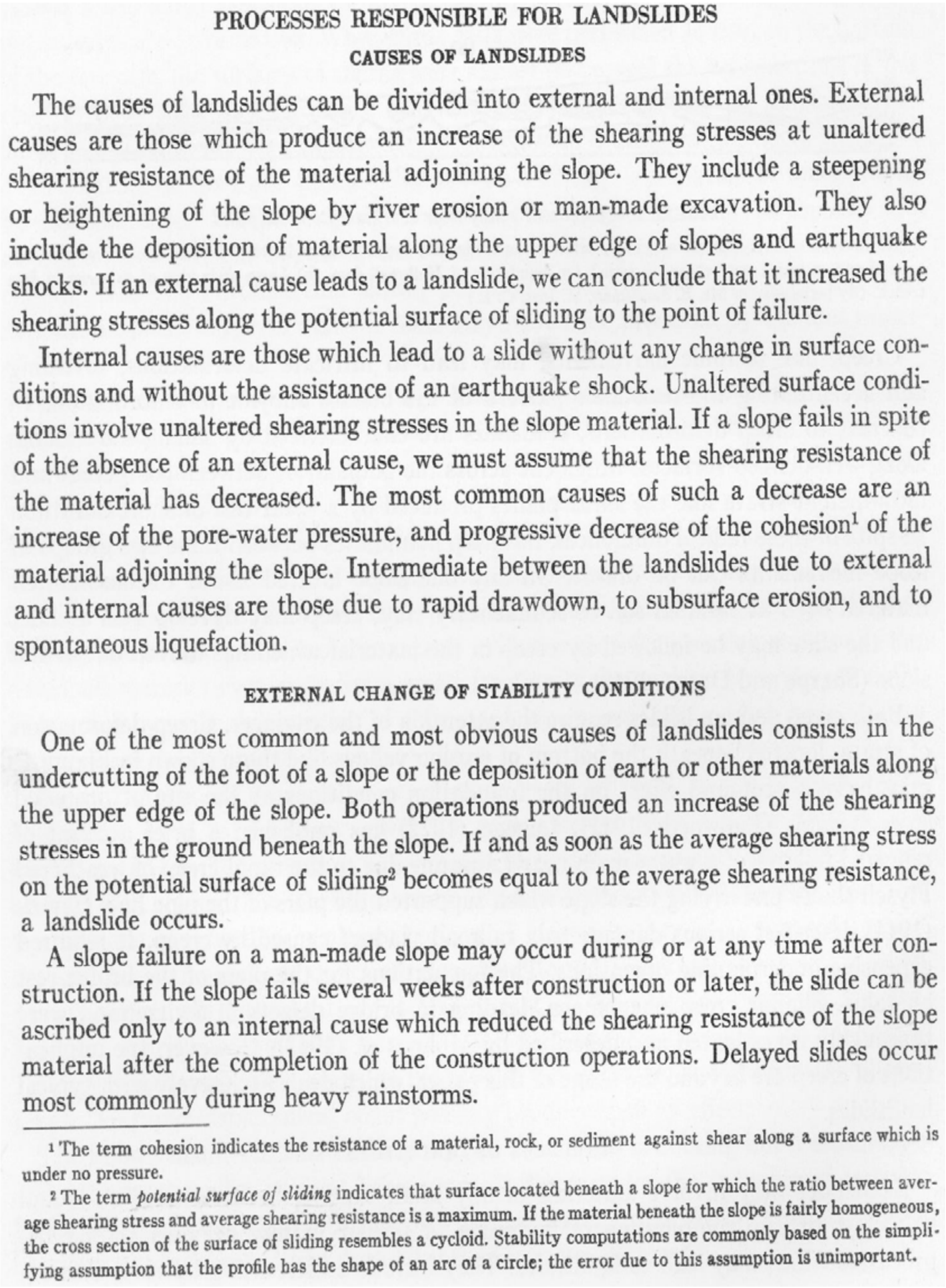
The most common anthropogenic factor leading to slope instability is the modification of slope profile, usually caused by cut-and-fills that decrease the factor of safety. The effects of changes in the pore pressure and ground water regime are several. On one hand this can simply change the behaviour of the material. For instance an artificial increase of the water flow accumulation and/or infiltration can lead to the full saturation of a material which had never been saturated in the past (and initiate a mud-flow). On the other hand the rising up of the water table caused by changes of water infiltration or reduction of permeability because of consolidation (for example by load) may produce new conditions that decrease the factor of safety.

A catastrophic event can result in a slow modification of properties and/or conditions of the stability which increase the sensitivity to triggering factors, as proposed by Terzaghi (1950). However, these modifications could also be the direct trigger for the landslide event because new conditions are encountered that did not exist before.

Construction of new infrastructures and changes in land use could also increase the susceptibility to landslides. The problems linked to road cut-and-fills are easy to understand, and uncontrolled quarrying has been a well-identified problem for a long time. Rapid draw-down of dams could lead to the destabilization of reservoir slopes. Some of the most critical issues in terms of risk are linked to the (sub-) surface water flow or the pipe leakage caused by aging that creates shallow landslides in urbanized areas.

It should be noted, however, that in many situations, the human activities have intentionally or unintentionally improved the slope stability and reduced landslide hazard. The anthropogenic factors could therefore play a positive role in reducing the landslide risk.

The main objective of the study presented in this deliverable is to improve our knowledge about the impact of human activities on increasing or decreasing the landslide hazard. The study would also contribute to the development of an empirical model for assessing the changes in landslide frequency (hazard) as a function of changes in the demography and population density.



PROCESSES RESPONSIBLE FOR LANDSLIDES

CAUSES OF LANDSLIDES

The causes of landslides can be divided into external and internal ones. External causes are those which produce an increase of the shearing stresses at unaltered shearing resistance of the material adjoining the slope. They include a steepening or heightening of the slope by river erosion or man-made excavation. They also include the deposition of material along the upper edge of slopes and earthquake shocks. If an external cause leads to a landslide, we can conclude that it increased the shearing stresses along the potential surface of sliding to the point of failure.

Internal causes are those which lead to a slide without any change in surface conditions and without the assistance of an earthquake shock. Unaltered surface conditions involve unaltered shearing stresses in the slope material. If a slope fails in spite of the absence of an external cause, we must assume that the shearing resistance of the material has decreased. The most common causes of such a decrease are an increase of the pore-water pressure, and progressive decrease of the cohesion[1] of the material adjoining the slope. Intermediate between the landslides due to external and internal causes are those due to rapid drawdown, to subsurface erosion, and to spontaneous liquefaction.

EXTERNAL CHANGE OF STABILITY CONDITIONS

One of the most common and most obvious causes of landslides consists in the undercutting of the foot of a slope or the deposition of earth or other materials along the upper edge of the slope. Both operations produced an increase of the shearing stresses in the ground beneath the slope. If and as soon as the average shearing stress on the potential surface of sliding[2] becomes equal to the average shearing resistance, a landslide occurs.

A slope failure on a man-made slope may occur during or at any time after construction. If the slope fails several weeks after construction or later, the slide can be ascribed only to an internal cause which reduced the shearing resistance of the slope material after the completion of the construction operations. Delayed slides occur most commonly during heavy rainstorms.

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[1] The term cohesion indicates the resistance of a material, rock, or sediment against shear along a surface which is under no pressure.

[2] The term *potential surface of sliding* indicates that surface located beneath a slope for which the ratio between average shearing stress and average shearing resistance is a maximum. If the material beneath the slope is fairly homogeneous, the cross section of the surface of sliding resembles a cycloid. Stability computations are commonly based on the simplifying assumption that the profile has the shape of an arc of a circle; the error due to this assumption is unimportant.

Figure 1.1.1 Terzaghi (1950; P. 88) related comments.

1.2 ANALYSIS APPROACH

To achieve the objectives of the study, the problem was approached from three different angles: statistical analysis of previous landslides, case studies of specific events, and expert opinion pooling.

- *Statistical analysis of previous landslides*: In order to make a quantitative assessment of the hazard and risk posed by landslides, one must develop a semi-empirical model based on statistical analysis of past events. An attempt was made to identify the role of anthropogenic factors in triggering different landslide types in Europe using the available databases. The statistical analyses are presented in Chapter 2.

- *Expert opinion pooling*: A simple questionnaire was sent to landslide experts in Norway, Switzerland and France to summarise their experience and expert judgement on the relative importance of human activities in triggering of landslides. The results are presented in Chapter 3.

- *Case studies of specific events*: Landslides induced by human activity can be simulated using analytical and numerical tools. Such analyses are useful for understanding the events that have happened in the past or those which can be provoked by similar changes in boundary conditions. The specific case studies are presented in Chapter 4.

As mentioned earlier, the interaction between human activities and landslide events is quite diverse and could be detrimental or positive. The different case studies cover different aspects of anthropogenic factors / landslide interactions. Table 1.1.1 provides a quick overview of the issues illustrated by the case studies described in Chapter 4. The lessons learned from case studies assist in providing guidelines for avoiding the same mistakes in the future.

Table 1.1.1 Anthropogenic factors addressed in the case studies

Case Study Category:		4.1	4.2	4.3	4.4	4.5	4.6	4.7	4.8
Topic of Case Study		Large clay slides in Norway	Landslides in pyroclastic deposits triggered by cut slopes	Rapid drawdown	Leaks in water canalizations	Mines and quarries	Cuts and fills	Activations of sensitive clays	Changes in land-use
Pore pressure changes	Water flow concentration and infiltration	X	X	X	X	X	X		X
	Permeability and porosity changes					X			
	Dam reservoir drawdown or filling			X					
	Change of micro watersheds								
Changes in geometry	Modification of slope profile	X		X	X	X		X	X
	Cut and fill					X	X	X	X
Modification of geotechnical properties	Cyclic loading							X	
	Changes in salt content	X							
	Residual strength characteristics	X	X	X	X	X	X	X	X
Triggering factor	Erosion/ unloading at toe of slope	X			X				
	Extreme precipitation			X		X	X		X
	Earthquake								
	Explosion/ blasting			X				X	
	Loading on top of slope	X			X	X		X	
	Transient loading (traffic, …)							X	

Table 1.1 (cont.) Anthropogenic factors addressed in the case studies.

Case Study Category:		**4.1**	**4.2**	**4.3**	**4.4**	**4.5**	**4.6**	**4.7**	**4.8**
Topic of Case Study		**Large clay slides in Norway**	**Landslides in pyroclastic deposits triggered by cut slopes**	**Rapid drawdown**	**Leaks in water canalizations**	**Mines and quarries**	**Cuts and fills**	**Activations of sensitive clays**	**Changes in land-use**
Negative anthropogenic (inter)action	Land-use change	X	X						X
	Roads and railways	X				X	X	X	X
	Dams			X					
	Lifelines								
	Excavation	X			X	X			
	Leakage from ageing pipeline			X	X				
	Ageing embankments								
Positive anthropogenic (inter)action	Collection of water by used-water network	X							
	Collection water by roads								
	Stabilisation works	X					X		
	Land-use change	X							
Timing (action/reaction)	Immediate slope response	X	X	X	X	X	X	X	X
	Delayed failure	X	X	X	X	X			X

2 STATISTICAL ANALYSIS OF HUMAN-INDUCED LANDSLIDES

2.1 NORWAY

2.1.1 Extent and cause of mass movements in Norway

Mass movements, like rock falls, debris slides and snow avalanches, are the most common natural disaster in Norway, and the one claiming most lives (Furseth 2006). In the last 150 years more than 1500 people have died due to catastrophic slope movements (Norwegian Geological Survey 2008, Norwegian Geotechnical Institute 2009). Statistically, 10 catastrophes caused by large slides and avalanches are expected in Norway over the next 100 years, each with the potential of killing between 20 and 200 people (Amundsen 2009).

Mass movements are often associated with mountainous regions, but history shows us that such disasters can take place in all regions of the country (Furseth 2006). Historical analyses of slide events suggest that rockslides are most frequent in the mild coastal regions of Norway, while the mountainous regions in central- and northern Norway are most exposed to snow avalanches. Eastern Norway and Trøndelag have the highest occurrences of earth, clay and flood slides, see Figure 2.1.1 (GeoExtreme 2009b).

Precipitation is the most common triggering factor for mass movements in Norway. Snow avalanches are the most connected to rainfall, followed by earth slides, while only a weak correlation is observed for rockslides. Pore pressure build-up in joints and fissures is still the most important cause for destabilisation of rock slopes. Studies of historical sliding events have shown that earth slides can be expected when more than 8 % of yearly precipitation falls within 24 hours (GeoExtreme 2009a). Earth slides are also triggered naturally by erosion and undercutting along rivers, streams, fjords and seashore, and are especially associated with floods. The same natural triggers can apply to clay slides.

Human activity is also a major trigger for clay slides, and particularly quick clay slides which have little dependence on topography and climate (Norwegian Geotechnical Institute 2009). Quick clay is extremely sensitive to changes in stress and completely loses its strength when it is remoulded and starts behaving like a fluid. Owing to these material properties quick clay slides typically display a retrogressive failure mode, and are therefore often large in extent (Lefebre 1996). This can result in very destructive slides causing much damage, for instance the large quick clay slide in Verdalen, in 1893, killed 116 people (GeoExtreme 2009a).

Human impact on ground stability plays an increasingly large role as development is expanding, and more roads and houses are built. Especially alarming is the increase in construction of cabins and roads in areas where no building development previously existed (GeoExtreme 2009a). Human interventions that can lead to destabilization of slopes include deforestation, removal of vegetation cover and concentration of water runoff. Common anthropogenic factors triggering landslides are cut-and-fill constructions, blasting and other construction activity, poor drainage and increased supply of water, changes in slope geometry, dam failure, traffic and mining (Skrednett.no 2009). Human-induced landslides are the most preventable type of sliding occurrences, therefore it is important to place focus on this topic and investigate what can be done to reduce the frequency of these events.

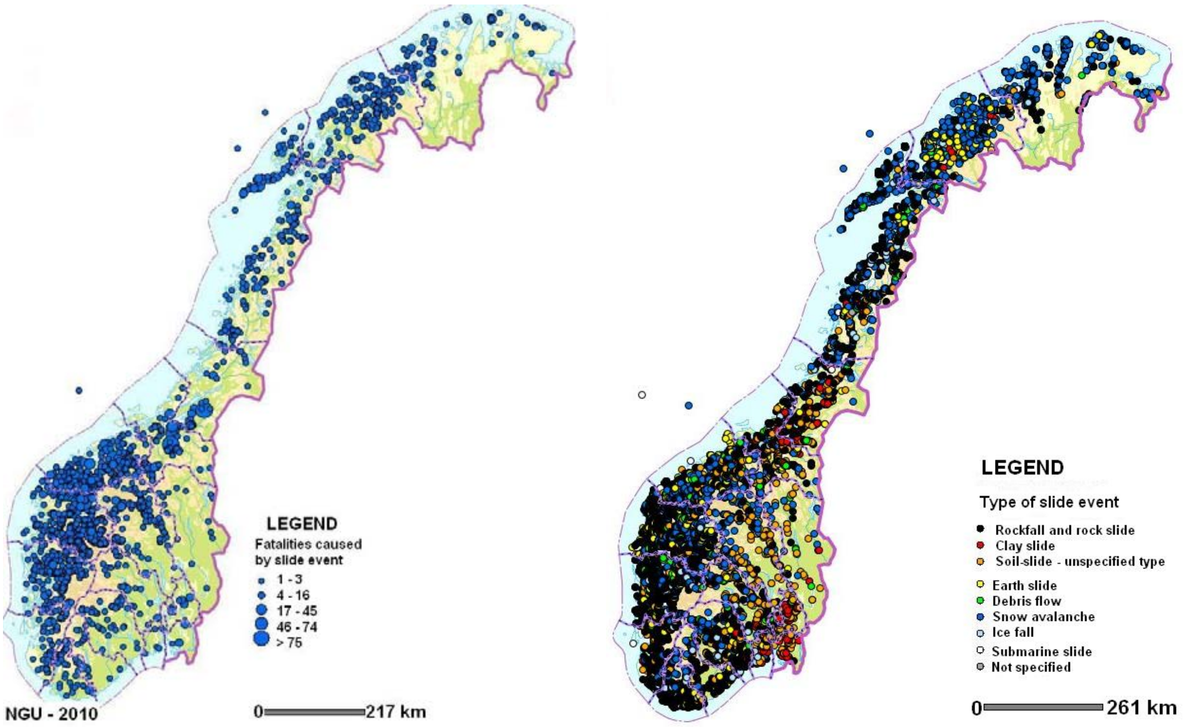

Figure 2.1.1 Maps showing all reported sliding events in Norway. The first map illustrates the number of fatalities from each slide, while the second shows the events classified by slide type (Skrednett.no 2010).

2.1.2 Analysis of historical data

The dataset used for the study of historical landslides is provided by NGU and consists of the 4000 slide disasters (snow avalanches included) collected by the local historian Astor Furseth in the national database for slides in Norway. Only slides that have resulted in loss of lives or material damage are defined as disasters and are included in the dataset. The survey reports on slides from the whole country back to the 12th century, and the amount of information that could be obtained about each slide is therefore limited (Skrednett.no 2009).

Only clay slides and earth slides were included in the analyses since these landslide types are regarded as most sensitive to human activity. Clay slides also include quick clay slides, as these two types are not separated in the database. Earth slides are debris slides consisting of various mixtures of soil, including the grain sizes cobble, gravel and sand, and typically involve glacial till deposits here in Norway. In addition, earth flows (flood slides) mobilized by excessive amounts of water are reported as earth slides in the database. Such slides are most often caused by flooding of rivers and streams which leads to increased erosion and changes in course. The database describes 380 historical clay slide disasters and 950 earth slide disasters (Norwegian Geotechnical Institute 2009, Skrednett.no 2009).

The historical data, as collected by Astor Furseth and dating back to the 12th Century, does not provide complete descriptions of the triggering mechanisms that lead to the landslides reported in this database. Therefore, when possible, the most likely cause was inferred from the descriptions of each slide event. An attempt was made to deduce the triggering factors for 380 reported clay slides and 950 reported earth slides. The results of these analyses are shown in Table 2.1.1 below.

Table 2.1.1 Results from the analysis done on triggering events of historical landslide catastrophes reported in the NGU database by Astor Furseth.

Analysis of triggering/cause of historical slides

	Human	Partly human	Natural	Unknown
Clay slide	40	3	79	253
Earth slide	28	21	546	350
Clay slide	33 %	2 %	65 %	Not included
Earth slide	5 %	4 %	91 %	Not included

Most of the clay slides are triggered by one or more of the following natural factors; intense and/or prolonged rainfalls (22), floods (13), rivers changing their course (11), water erosion from sea or rivers (7). However, almost all of the earth slides are caused by rainfall or flooding, often in connection with spring thaw. As many as 104 earth slides are reportedly caused by Ofsen; the great flood in 1789. In terms of human-induced landslides, the majority (24) are categorized as due to construction work in connection to road or railway. 19 slides have been associated with landfills or embankments that were either placed at unfavourable locations or slid out during heavy rains etc. The other major triggering events include excavations (10), dam failures (9), changes in natural runoff/drainage (8), and work in gravel/sand pits, mines etc. (8).

2.2 FRANCE

2.2.1 Inventory of historical events

The following statistical analysis is based on the mass movements recorded in the French national database of ground instabilities, « Base de données mouvements de terrains », (www.bdmvt.fr)[1].

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[1] BRGM is in charge of this database since 1994 and develops it in collaboration with:
- LCPC (French Public Works Research Laboratory),
- CETE (*Centres d'Etudes Techniques de l'Equipement*) and
- RTM (*Restauration des Terrains en Montagne*),

with the support of the French Ministries of Ecology, Energy, Sustainable development and sea, and of Secondary Education and Research.

This database lists the mass movements which have been observed and recorded in France in the past, back to the 13th century. Its initial purpose is to provide information for natural risks prevention policies on past, as well as recent, movements.

The data comes from either old databases, archives and partial inventories from partners; specific departmental inventories done since 2001 or punctual information from different origins (media, studies, individuals, collectivities, associations…) and are regularly updated by local organisms (RTM, CETE, LCPC and BRGM's regional services).

In October 2009, the 33,553 recorded mass-movements in the database were classified according to 5 different types of event, as follows:

- 6494 rocks-falls events
- 2060 mudflows events
- 12212 sinkholes events
- 2817 bank erosion events
- 9970 landslides events

Several data fields can be filled in for each event such as identification (type, date, city, department, coordinates …), quality (precision and exhaustiveness), sources, comments, consequences (casualties and damage), geology and causes (natural, human).

2.2.2 Analysis of historical disasters

In order to match the scope of the different SafeLand case studies, the analysis of historical slide disasters in France was restricted to rock falls, mudflows and landslides. Moreover, as the French overseas territories (Guyane, Martinique, Guadeloupe and La Réunion) face different climatic and anthropogenic pressures, and so do not represent typical European contexts, only events observed in metropolitan France were selected.

Furthermore, in order to be consistent with the above Norwegian analyses, only movements which have caused casualties or physical damages are considered as disasters. Another filter criterion for the selection of events used in the analyses was the existence of a known date of occurrence (with a precision of at least one decade). Indeed, this information is necessary to put the events in their context, and so to evaluate the influence of human activities on triggers of mass-movements.

As a result, the database contains 2055 rock-falls disasters, 605 mudflows disasters and 3232 landslides disasters fulfilling these criteria.

The causes are not always stated[2]. Moreover, it has not always been possible to determine which the triggering cause of the event. As a consequence, the analyses focus on causes, which is sometimes a combination of human and natural mechanisms. The results are shown in Table 2.1.2.

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[2] By default, if no further information was given in the detailed cardboards, it was assumed that if only one cause was filled out, it was the only cause, otherwise the causes were assumed unknown

Table 2.1.2 Results from the analysis done on causes of historical landslide disasters reported in the BDMvT.

Analysis of cause of historical slides in France

	Human	Partly human	Natural	Unknown
Rock falls	85	169	786	1015
Mudflows	2	92	409	102
Landlisdes	148	715	1374	995
Rock falls	8.2%	16.3%	75.6%	Not included
Mudflows	0.4%	18.3%	81.3%	Not included
Landlisdes	6.6%	32%	61.4%	Not included

The results are somehow similar to the ones presented in Table 2.1.1 from the Norwegian analyses. Most of the analyzed mass-movements are caused by natural events, mostly hydrological events such as rainfall (major cause in 3178 events), but also bank erosion (156), snow-melt (17) but also other consequence of natural phenomena, vegetation (5), drought (3) or earthquake (2) and other (182).

Like in Norway, among the mass-movement disasters recorded in France, just a small proportion (less than 10%) was caused exclusively by human activities. Between one sixth and one third of the disasters are due to a combination of human causes and natural circumstances. The human causes fall into the same categories as in Norway. The most frequent anthropogenic causes are related to change in geometry of the slopes and overloading of surfaces (in 934 events). Some (84) are the adverse consequences of change in water runoff, either due to modification of the drainage system or to leakage of pipes. The other categories are past or current works in pits and mines (81); agricultures and changes in vegetation (77); vibrations (from traffic or explosion) (29), and other (6).

2.2.3 Evolution of the landslide causes in the last century

As could be expected, causes of landslides are better known for more recent disasters (Figure 2.2.1). As a consequence, the result of the analysis presented below should be interpreted cautiously. Indeed, causes filled in might not represent the disaster conditions identically between the different decades.

Nevertheless, tendencies can be pointed out from the statistical analysis of the database. As Figure 2.2.2 shows, landslides disasters were caused more and more by human activities during the last century. This could be explained by an increase in anthropogenic pressure: a result of demographic and economic developments.

The modification of tendency in the last decades might be the result of awareness of public authorities, implementation of mitigation measures and better practices in construction and maintenance.

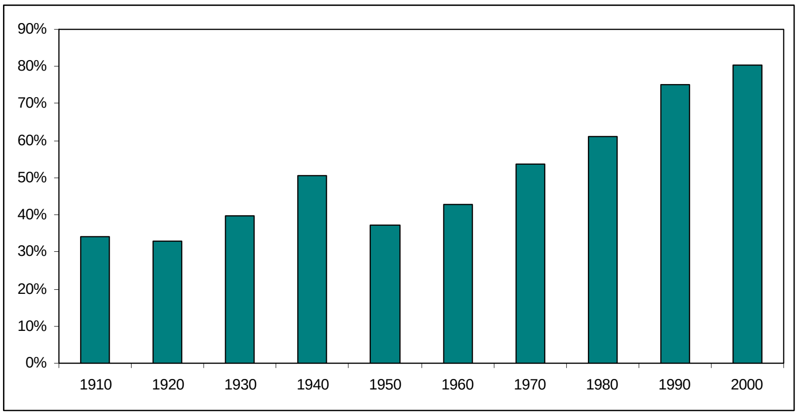

Figure 2.2.1 Evolution of the proportion of landslides disasters with at least one known cause during the 20th century

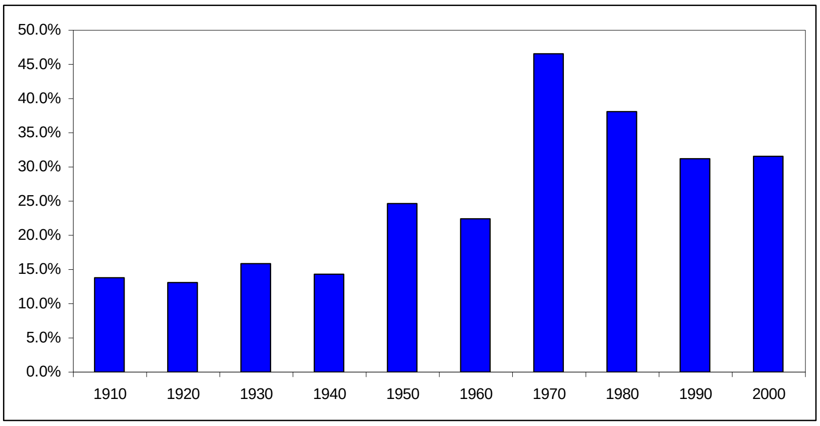

Figure 2.2.2 Evolution of the proportion of landslides disasters caused by human activities over disasters with known causes.

2.3 SWITZERLAND

2.3.1 Anthropogenic influence on the stability of Alpine slopes: A historical review

A historical perspective on the anthropogenic influence on Alpine slopes has been given by Lateltin et al. (1997). Mankind did not have any noticeable influence on the evolution of potentially unstable slopes, except in the last 300 years. The Prealpine slopes of Switzerland above 1000 amsl were not inhabited until the 12th century. The agricultural development up to the 15th century took place simultaneously with the economical developments in the villages of the plane. From then on, the craftsmanship in the villages declined more and more, while the agricultural activities, mainly related to the production of cheese, grew constantly. A progressive colonisation of Alpine regions took place and deforestation for the creation of pastures increased. Due to the high demand of wood for the industry, the forested surfaces decreased rapidly to the point where, towards the end of the 19th century, 10% of the originally forested surface remained in some regions. Over 200 years, the vegetation cover and the hydraulic regime of the Prealpine catchments have been modified substantially, leading repeatedly to catastrophic inundations, debris flows and landslides, as reported for example for the case of the Lac-Noir region in 1851, 1852 and 1897.

Major changes in land use followed after 1870 marked by an agricultural crisis. The pastures on flysch soils were often impermeable and swampy and have shown a low crop. The Confederation recommended to rapidly reforest those regions and acquired itself numerous slopes.

In the second half of the 20th century, touristic developments lead to the latest major modifications in Prealpine and Alpine land use. Most notably, the construction of infrastructure and holiday houses on potentially unstable slopes has increased the risk associated with landslides (i.e. Falli-Hölli landslide).

2.3.2 Landslide statistics in Switzerland

Landslides represent a major threat to human life, property and constructed facilities, infrastructure and natural environment in most mountainous regions of the world (Figure 2.3.1). In Switzerland, more than 6% of the territory is affected by permanently slow movements or sub-critically stable zones (Noverraz and Bonnard 1990; Bonnard 2006). An average of nine people die each year in floods, debris flows, landslides and avalanches (FSO & FOEN 2008). The economical cost of the damage amounted to a total of 8000 million Euros within the last 36 years and is constantly rising (Figure 2.3.2). Due to urban sprawl, more and more material assets are located in hazard zones, leading to an increased vulnerability of the infrastructure.

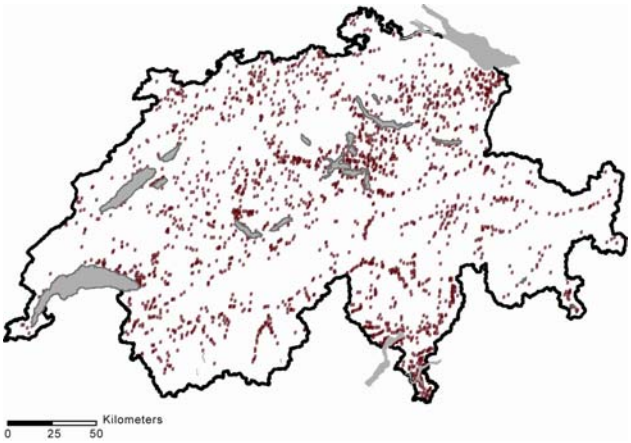

Figure 2.3.1 Distribution of landslides causing damage between 1972 and 2002 (Lateltin & Bonnard, 2006).

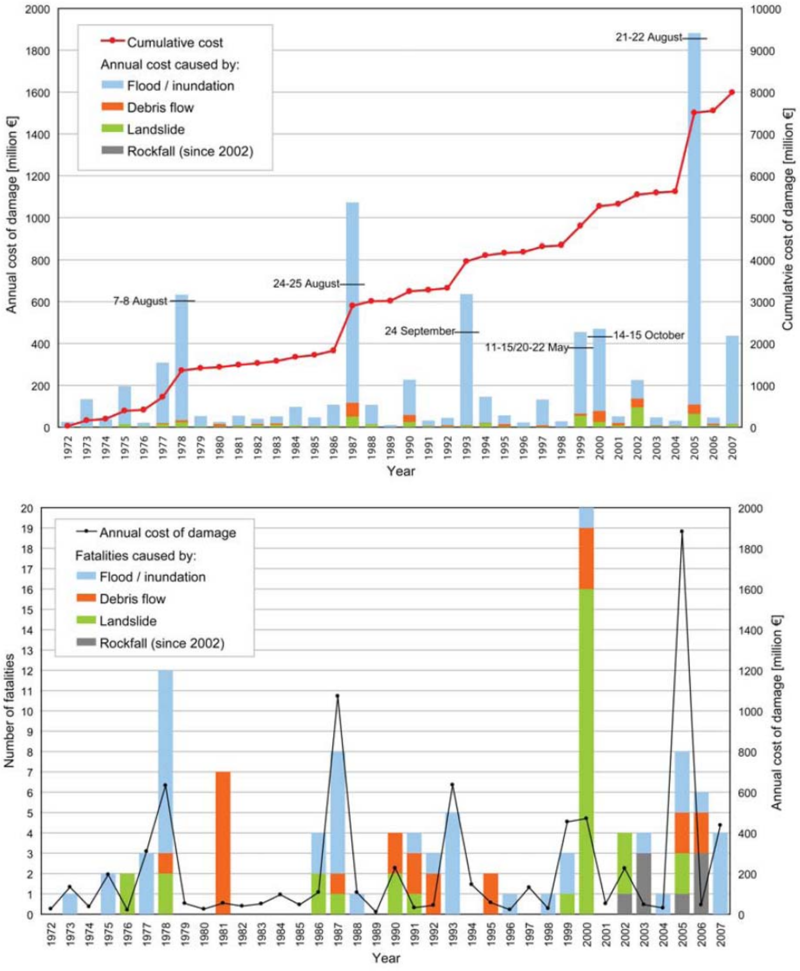

Figure 2.3.2 Economical damage and fatalities caused by floods and landslides in Switzerland from 1972 to 2007 (Hilker et al., 2009).

The Swiss Federal Research Institute WSL has been systematically collecting information on flood and mass movement damage in a database since 1972. The data is also regularly integrated in the cadastre, *StorMe*, from the Swiss Federal Office for Environment (Burren & Eyer 2000; www.bafu.admin.ch). This provides a common tool, for 26 Cantons of Switzerland, for the retrieval of information on documented events related to natural hazards. In fact, the Cantons are obliged by federal laws (WaV, 1992; see also chapter 5.2) to create hazard cadastres and maps. This documentation, as a part of a hazard information system, plays an important role in the assessment of natural hazards, the statistical evaluation of potential hazard zones and in the prediction of future events.

The database should be continuously updated, as past information becomes available and new landslide events occur. The quality of the databases differs from one Canton to another; in some cases the work has already reached an advanced stage, e.g. in the Canton of Berne 10,000 landslide events have been documented. For each event, a predefined formulary is filled out, comprising the type of movement (slide, debris flow, subsidence and collapse), associated secondary processes, climatic conditions (storm, rainfall, snow melt), triggering factors (natural, human-induced), geometry of the sliding mass and description of the run-out phase and deposition zone. The specific activities leading to each sliding event are not reported, but a short description of the damage is usually provided. Nonetheless, this allows, for numerous cases, the identification of current and/or past human actions which led to slope failures.

The focus of the geologists and local authorities is very often set on natural hazard events which cause primary damage to infrastructure and living beings, and secondary damage to forests or agricultural land. Only events causing actual damage are stored in *StorMe*. Most human triggered landslides are of small extent and are not further reported. The Cantons subsidize remedial measures if the origin of the slope movement is natural. For this reason, and also for legal issues, individuals prefer internal solutions which involve insurance companies more so than local authorities. Consequently, statistics on the occurrence of landslides need to be treated with precaution.

In particular, with respect to human-induced landslides, the databases often present a lack of information and the number of events reported is certainly not statistically representative. The Cantons are investing a lot of effort into generating detailed maps of natural hazards. For that assignment, landslides of anthropogenic origin are either not considered or not distinguished from naturally triggered landslides. For example, in the Canton of Bern 120 of 10,000 cases, respectively 1.2%, are attributed to human interaction. For comparison, in France, 5% of the reported landslides are due to direct, and 31% due to indirect, human action (see chapter 2.2.2).

Nonetheless, there are some general trends and conclusions which can be drawn from simple statistics on human-induced landslides. Figure 2.3.3 (a and b) show, for the human-induced landslides, that around 80% of the slides in the Canton of Bern mobilise volumes of up to 500m^3 (73 slides in total) and affect surface areas of up to 500m^2 (56 slides in total). Most slides are shallow with failure surfaces between 0.3 and 2m in soil depth. Out of 120 reported cases, 93 have a slip surface in less than 2 meters depth, 24 between 2 and 10 meters and 3 above 10 meters.

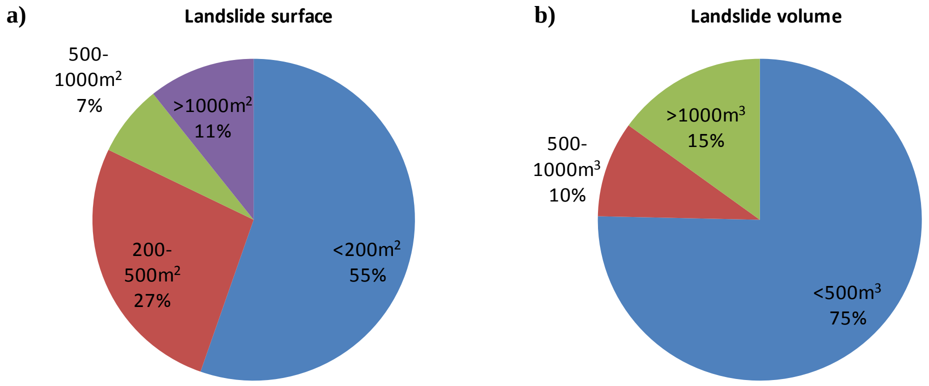

Figure 2.3.3 Percental distribution of surface area (a) and mobilised soil mass volume (b) of human-induced landslides in the Canton of Bern.

Apart from the shallow failures, some important sliding events with more than 1000m^3 are recorded as well. These cases are reported as related to either the failure of existing embankments or retaining walls in combination with high intensity or long-lasting rainfalls, failures during road construction involving the breaching of pipelines or heavy rainfall, overloading of the slope surface and the deviation of water run-off or discharge at an unsuitable location (Figure 2.3.4).

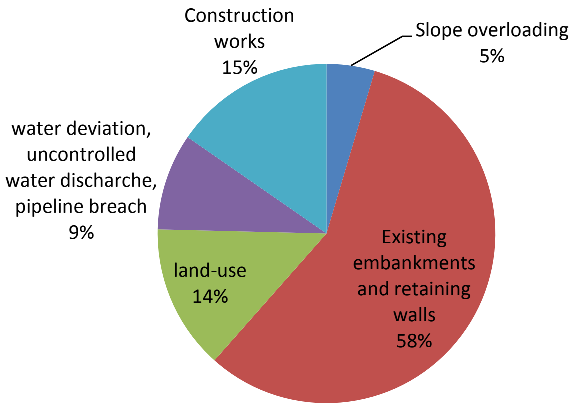

Figure 2.3.4: Human causes for landslides in the Canton of Bern.

One large landslide which took place in Rueschegg in 1931, which involved 20 million m^3, was triggered by agricultural land-use change in combination with a prolonged snow melting period. The great majority of human-induced landslides occur in combination with either high intensity or long duration rainfall.

3 EXPERT OPINION – SUMMARY OF RESULTS

3.1 NORWAY

Expert opinion pooling has proven to be an efficient and inexpensive method which provides valuable information, especially in situations where data is limited (Kuhnert et al. 2009). When pooling expert opinions, it is, in general, better to perform simpler aggregation methods than more complex methods (Clemen and Winkler 1997). A questionnaire was sent out to nine landslide experts in Norway, asking for their opinion on four topics related to the occurrence of human-induced landslides in Norway.

The questionnaire addresses the following four main topics, with several subtopics, which the experts were asked to give their subjective opinions on.

1. The percentage of major landslides in Norway triggered directly by human activity, expressed by main type of sliding material.
2. The percentage of major landslides in Norway triggered by human activity combined with natural factors (not including the cases in question 1), expressed by main type of sliding material.
3. Categorization of the type of slope where landslides triggered fully or partly by human activity occur in Norway.
4. The change in landslide frequency triggered fully or partly by human activity if the population density in a landslide-prone area in Norway increases by 50 %.

The experts answered only for those slide types for which they had personal experience. Answers could be given by selecting a range of values provided as alternatives in the questionnaire, or one could simply set a single value. For topic number 3, the experts had to set the percentages so that the sum of them added up to 100%.

The method of linear opinion pooling was selected to pool the replies from the nine experts. This is a simple and popular pooling method, presented by DeGroot (1974), Lacasse and Goulois (1989) and Clemen and Winkler (1997). This method combines the individual expert probability distributions into a single probability that reflects the groups combined opinion.

Consider n experts expressing their opinion on some topic θ. For $i = 1, \ldots, n$, $p_i(\theta)$ represents the subjective probability distribution which expert, i, assigns to θ. Now, a non-negative weight, w_i, is assigned to each expert to reflect his or her relative expertise within the group. The weights, w_i, must sum to one.

Let $P(\theta)$ denote the combined probability distribution, i.e. the linear pool of the expert opinions. The distribution of the average expert opinion can then be expressed as:

$$P(\theta) = \sum_{i=1}^{n} w_i p_i(\theta)$$

In this analysis the experts are given weights according to their years of experience working with landslides. The opinions of the six experts with more than 20 years of experience are regarded as most valuable and are assigned the highest weighting. The three others are given half of their weight. The weights within each of the two groups are identical.

The expert opinions are assumed to be independent. The fact that two thirds of the experts work for the same company could give reason to doubt their independence, but the large variation in their answers suggest that their opinions are not influenced by one another.

The method of linear opinion pooling requires that the experts express their opinion in the form of a probability distribution. Since the experts have instead provided either a range of values of uniform distribution or a single value, the mean of the selected range has been used to represent the individual expert opinion, $p_i(\theta)$. Histograms have also been made to illustrate the spread in replies. Unfortunately, the dataset is too small to obtain a probability density function from the histograms.

Table 3.1.1 Average expert opinion on the percentage of slides triggered directly by human activity and by human activity in combination with other natural factors.

Triggered directly by human activity

	Quick clay	Clay	Silt and sand	Mixed debris	Rock
Unequal weights	41 %	27 %	16 %	10 %	8 %
Equal weights	43 %	30 %	15 %	11 %	8 %

Triggered by human activity and other natural factor

	Quick clay	Clay	Silt and sand	Mixed debris	Rock
Unequal weights	16 %	14 %	22 %	32 %	9 %
Equal weights	15 %	15 %	28 %	35 %	10 %

Table 3.1.2 Average expert opinion on the type of slopes in which landslides, triggered fully or partly by human activity, occur.

In what slopes do these landslides occur?

	Natural terrain altered by human activity	Engineered slopes and embankments	Cuts and fills along railways	Cuts and fills along highways	Cuts and fills along secondary roads	Other
Unequal weights	30 %	12 %	9 %	20 %	26 %	3 %
Equal weights	33 %	12 %	10 %	19 %	23 %	3 %

The questionnaire replies from the nine landslide experts are, in general, varying considerably and thus an average opinion is difficult to attain. A weighted average has been calculated based on the linear opinion pool and compared to the simple average obtained by assigning all experts equal weight. The results are shown in Tables 3.1.1-3.1.3.

Table 3.1.3 Average expert opinion on the expected change in frequency of landslides triggered fully or partly by human activity if population in a landslide-prone area in Norway increases by 50 %.

Expected change in human-induced landslide frequency if population increases by 50 %	
Unequal weights	14 %
Equal weights	18 %

A boxplot of the replies of topic 3 is presented below in Figure 3.1.1. The boxplot illustrates the minimum value, first quartile, median, third quartile and maximum values of the expert opinions. Therefore, the mean and spread of the expert opinions is nicely summarized. Since the dataset for each subtopic is very small, some of the parameters are identical, which causes the boxes to appear incomplete or lacking. The spread in subtopic 1 is greatest, followed by subtopic 5, while the best consensus relates to subtopic 6. Several of the experts have given the same answer for subtopic 2, resulting in only four values to be plotted.

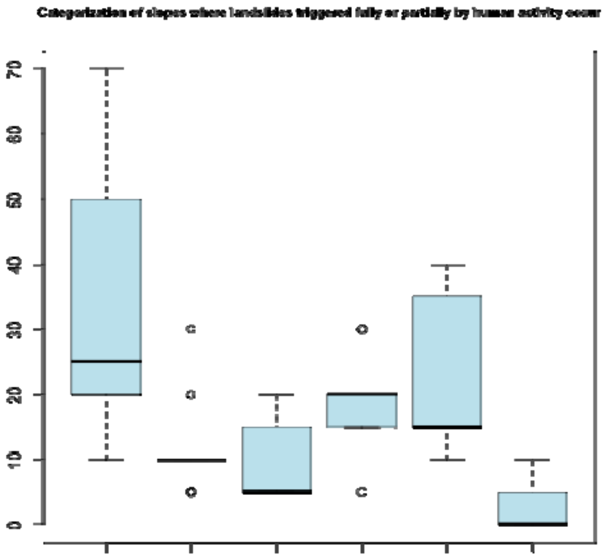

Figure 3.1.1 Boxplot of expert opinions on categorization of the type of slopes where landslides triggered fully or partly by human activity occur. Boxes represent (from left to right) "Natural terrain altered by human activity", "Engineered slopes and embankments", "Cuts and fills along railways Cuts and fills along highways", "Cuts and fills along secondary roads", "Other", respectively.

3.2 SWITZERLAND

EPFL has sent a questionnaire out to the 26 cantonal authorities that deal with natural hazards, as well as another four well-known experts. To date, one feedback form has been obtained from the experts, and seven from the Cantons. However, no one has answered the questionnaire; all of their datasets are either incomplete or lacking sufficient detail. On a cantonal level, data on landslide events not been systematically documented and saved in a common database in the past, although there are general GIS-based maps available for natural hazards, which engineering offices in the cantons filled out (Figure 3.2.1). The phenomenological maps for mass movements are, in this case, limited in the sense that they do not distinguish between human or natural causes.

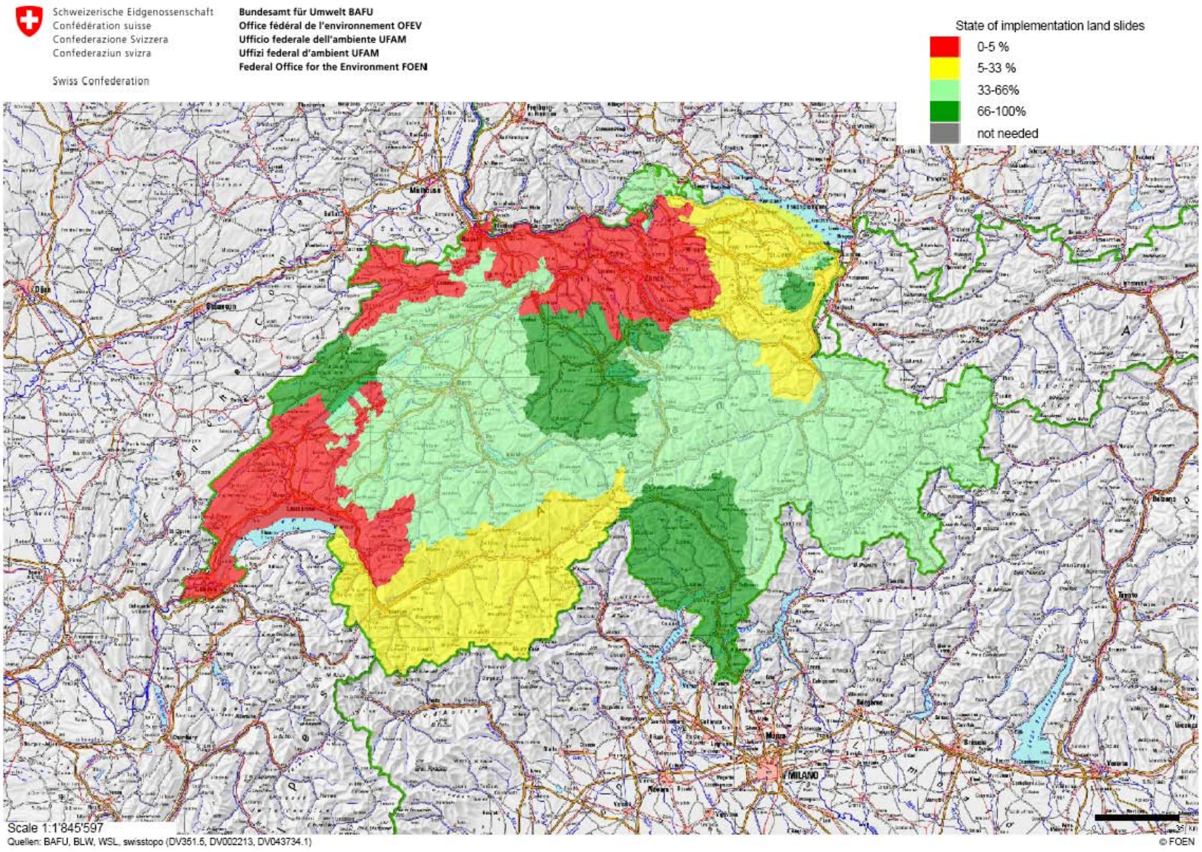

Figure 3.2.1 State of advancement of natural hazard mapping at cantonal level (Project ShowMe, source: bafu.admin.ch).

Detailed information on past events remains the property of private companies. Building insurance companies are often of more help, as many cases of human-induced landslides are reported to them rather than at the cantonal level. In fact, the Cantons subsidize remedial measures if the origin of the slope movement is natural. For many cases of human-induced damage, internal solutions are found in order to avoid costly legal processes. As a result, the will to report human-induced damage or point at a guilty party is limited and determining the cause of the accident becomes less important than dealing with the consequences.

3.4 FRANCE

A questionnaire (see Appendix A) has been sent to the experts in charge of filling out the landslide database (cf Section 0). The questionnaires dealt with 4 topics, similar to those addressed in the Norwegian and Swiss questionnaires:

1. Proportion of landslides directly triggered by human activities, according to the main types of sliding materials
2. Proportion of landslides triggered by combinations of human activities and natural factors, according to the main types of sliding materials
3. Description of the slopes (soil covers) where landslides occur
4. Influence of a demographic evolution by 50% on landslide frequency

Unfortunately very few experts responded to this questionnaire and it was not possible to do any meaningful analysis for France on the basis of the responses to questionnaire.

4 SELECTED CASE STUDIES

4.1 EXPERIENCE FROM LARGE CLAY SLIDES IN NORWAY

Larger slides in marine deposited clay areas in Norway are a serious problem. Statistically, during the past century Norway has experienced one or two larger clay slides per year. Bjerrum (1971) realized that the ravines in the clay areas were not in equilibrium, and toe erosion would be a possible triggering factor for larger slides in future. Bjerrum suggested starting a national mitigation plan including mapping of areas with soft clay followed by physical mitigation measures in critical areas. Politically this suggestion was a few years to early, but today most of those ideas are realized.

Little is known about the geotechnical properties of the materials involved in historical slides. However, when a larger slide occurs in clayey areas, highly sensitive clay is usually involved. Slides in clay with low sensitivity will not develop into retrogressive slides because the material will block and stabilize the back scar. In Norway, historical recording of slides goes back to 1349, and NGI has up to now recorded about 510 major clay slides. After the year 1928, 297 slides have been recorded and 65 of these are classified as large slides (area greater than 10,000 m^2 or volume greater than 50,000 m^3).

Figure 4.1.1 shows the decadal distribution of the 65 large clay slides from 1928 to 2009. A clear trend that can be observed is that the slide activity increased in the middle of the last century, and dropped during the last two decades. The fraction of human-induced slides has increased and has been half of the total of large slides during the past 40 years.

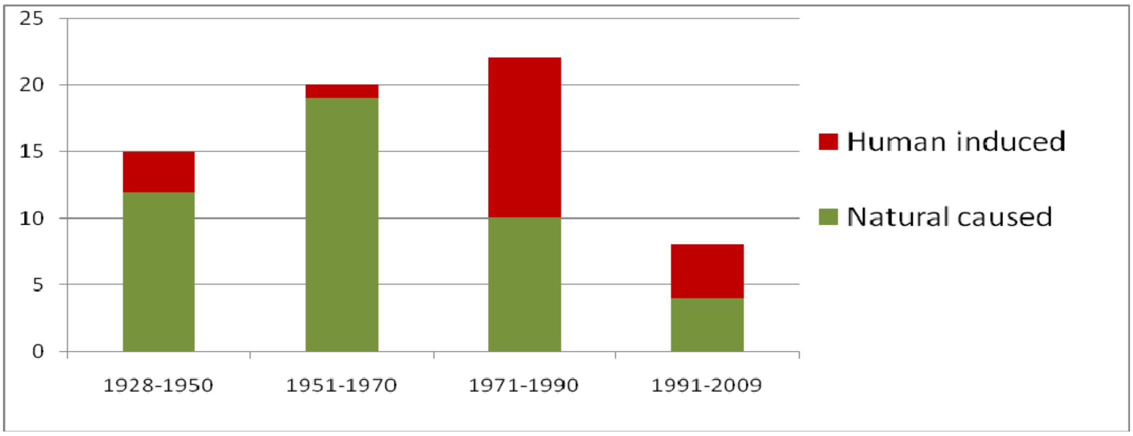

Figure 4.1.1 Decadal distribution of large soft clay slides in Norway.

Soft clay slides are usually triggered by an initial slide, caused either by toe erosion or by a load on top of the slopes. Toe erosion is believed to be the most common natural mechanism to trigger landslides, but human activity or political decision can also influence this process.

In the first column of Figure 4.1.1, most of the human-induced slides happened during the Second World War and were related to quay constructions. Later, in the middle of the 1950's, a number of larger quick slides happened along the river, Namsen, in the county of Nord

Trøndelag. These slides started a large mitigation project managed by the Norwegian Water and Energy Directorate (NVE). Most of all river protections in Norway are designed and carried out by NVE, which has its own construction service.

In 1970, the farmers received national support for agriculture landscaping. The grass areas dominated by ravines were turned into an undulating terrain more suitable for agricultural activity. This activity initially increased the frequency of human-induced slides, but after some years, guidelines for agriculture landscaping were developed with help from NGI (Landbruksdepartementet, 1974) and the number of slides was reduced significantly.

Figure 4.1.2 illustrates the seasonal distribution of large soft clay slides in Norway. Human-induced slides seem to have an even distribution through the year. Naturally-triggered slides have their highest frequency in the spring and thereafter in the autumn. Both of these periods are related to flood events and the spring season is of course a thawing period. The large number of slides in April is mainly a Trøndelag (mid-Norway) phenomenon. The slides south of Trøndelag are more evenly distributed throughout the year.

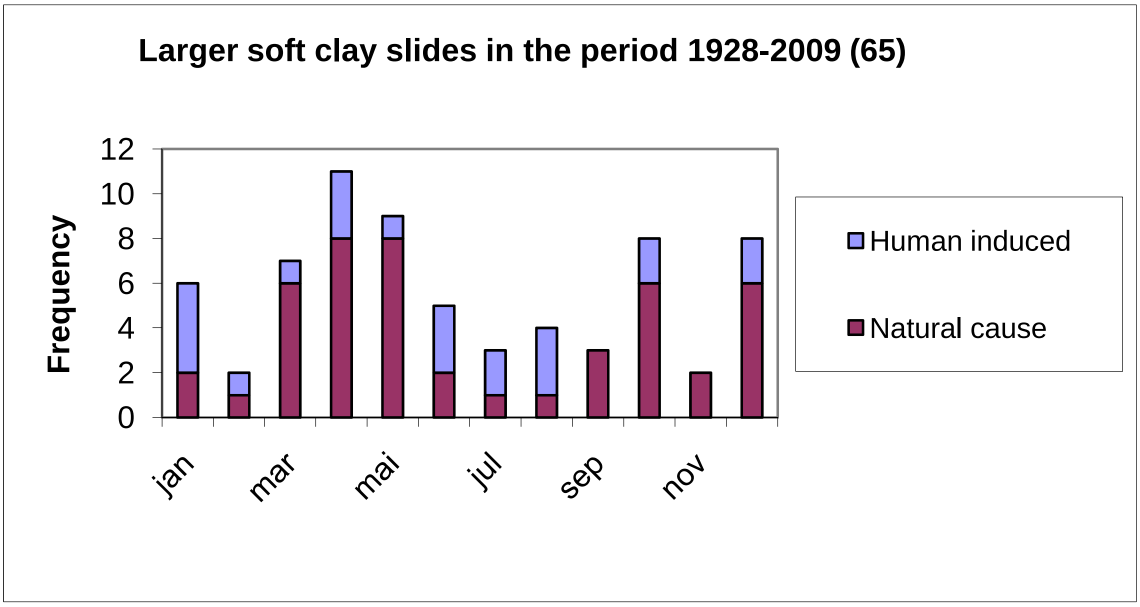

Figure 4.1.2 Seasonal distribution of large soft clay slides in Norway.

Human activities that influence clay slides in Norway can be grouped into the following categories:

- Construction work, typically road or quay construction;
- Agricultural landscaping;
- River regulation; and
- Slide mitigation.

Both the protection works by NVE and the agriculture landscaping activities should be seen in light of technological developments. The development of excavators and lorries made it possible to make rip-rap protection in a much larger scale in the 1950's than was possible earlier. Wheelbarrows and manual work were now history. Agriculture landscaping was not practical and economically possible before the bulldozers became available.

The Rissa slide in 1978 (Gregersen, 1981) led to increased focus on the political responsibility of this type of threat, and the political process ended up with a national programme in 1980 for soft clay mapping, quite similar to what was suggested by Bjerrum (1971). The soft clay mapping programme identified new critical areas that were in immediate need of stabilization.

Guidelines, mapping of soft clay, involvement of geotechnical consultants, and general knowledge are believed to be the reasons for reduced slide activity in Norway during the last decades. However the lower slide activity the past 20 years cannot only be explained by better applied knowledge of land stability. Large areas that were previously susceptible to slide activity have been stabilized by the agriculture landscaping. Landslides were triggered in the most critical areas by this activity, resulting in a more stable topography.

In the beginning of the 1990's, the regional NVE office in Mid Norway reported that the rip-rap measures carried out in Namsen in the 1950's and 1960's needed maintenance. This started an internal project at NVE, where the need for protection work in all regions was assessed and budget for the required mitigation measures was estimated. The required financial support was much greater than the funds available for stabilizing measures, and NVE had to develop a strategy for prioritizing the measures and making visible the consequences of soft clay slides. This resulted in the clay slide risk mapping project that was executed by NGI from 2000 to 2006. In this project, more than 1500 soft clay areas have been classified with respect to hazard, consequence and risk. Today the soft clay mapping programme is followed up by landslide hazard mapping along the coast and in areas outside the main clay areas.

The funding available for erosion mitigation in Norway has fluctuated with the political trends. Up to the mid-1980's, protection and development of agriculture land was politically correct. Thereafter, a "green" period followed where the rivers should follow their natural route and several rivers were "restored", removing the earlier protection works. Nowadays, river protection work should demonstrate a cost-benefit value that would have excluded many of the earlier measures motivated by agricultural priorities. In recent years, people's safety has been the governing criterion for selecting projects and protection works have turned from countryside projects into projects in cities and more densely populated areas.

Going back to the list of human activities that influence soft clay stability, the following points should be noted:

- Today, construction work is the dominating anthropogenic factor triggering large soft clay slides in Norway. If one also includes the smaller rotational slides in the analyses, the fraction of human-induced slides would be even greater. The geographical areas in Norway with most slide activity today are Nord-Trøndelag and Nordland counties. Both these counties have had challenging road construction projects.

- About 9 of the large soft clay slides have occurred in the coastal zone. Seven of those are related to human activity, either road or quay construction work. A large part of the roads along the shore in Norway are founded on hard rock. However, soft clay and soft sediment (unconsolidated sediments) are quite common just outside hard rock along the sea. When roads are widened or footpaths are constructed, embankments into the sea are common. The picture of an excavator partly below water is a common sight in Norwegian newspapers.

- During agricultural landscaping, the areas were mainly turned from hilly grassland into flatter areas suitable for grain production. The clay itself has too low permeability to drain the surface water by infiltration. The areas are therefore systematically drained by small pipes in the unsaturated zone and larger, interconnected drainage pipes. This means that the drainage system must be maintained to avoid surface erosion and a new period with developing ravines. Maintenance can be a serious problem the day the agriculture is not economically profitable.

- Norwegian rivers are regulated through reservoirs mainly for hydropower production. The regulations reduce the size of the floods. This should also reduce the river erosion, but this is not always the case. Another effect of river regulation is that sediment transport in the rivers is reduced. The sediments are trapped in smaller or larger intake basins. In a river, mass transport is a continuously ongoing process where sediments are removed and settled. Removing the sources of sediments, the river will only erode. For example in the lower part of Skiensvassdraget in southern Norway, between Skien and Porsgrunn, the sediment sources are sealed from the lower clay areas through a number of dams and locks. Lowering of the river bed was observed and together with low stability river banks, requiring large mitigation measures in recent years.

- There is a group of slides for which volume and area have not been recorded in the database; these are slides in regulated basins. Holmesen (1963) and Korbøl (1975) have reported these slides. Several of them were definitely larger slides that had impacts on roads, farm land and houses. Korbøl (1975) analyzed 47 of these slides. The size of these slides is generally small, but of 9 lakes situated below the marine limit (MG) 6 experienced clay slides while the remaining 3 had no sediments that could slide. One lake with several slides of this type was the lake Selbusjøen i Trøndelag (middle of Norway). Here a number of soft clay slides occurred during the first operating seasons when water was lowered below original water level. The slides triggered shortly after the lowest regulated water level was reached.

- Slide mitigation is generally positive for land stability. However, controlling river erosion is not easy. Many rip-rap protections are placed along the shore, but that does not prevent the erosion below the rip-rap protection. As a result, it takes a longer time before unstable areas are triggered and the size of the slides often increase. An intervention in a watercourse will always influence the river hydraulics and may cause increased erosion at other localities. For example, the Gaula watercourse in Trøndelag is strongly regulated. Mass transport in this river has been reduced strongly because of the regulations, rip-rap protection, and commercial exploitation of river gravel. The result is that clay is exposed in the river bed, and this could have serious consequences for a river running through soft clay areas.

4.2 ANALYSIS OF FLOW-TYPE LANDSLIDES IN PYROCLASTIC DEPOSITS TRIGGERED BY ANTHROPOGENIC FACTORS

4.2.1 Introduction

Rainfall is the most frequent triggering factor for shallow landslides in a variety of unsaturated soils (Alonso et al., 1995). For such landslides the failure mechanism is primarily controlled by rainfall patterns, e.g. intensity and duration (Rahardjo et al., 2001; Pirone, 2009), soil initial conditions (Tsaparas et al., 2002), and local natural factors, such as slope angle, thinning of deposits and close-ended layers. Slope failure phenomena can also be influenced by morphological conditions due to the presence of trackways and cut slopes. These anthropogenic factors cause changes in topography, discontinuities of stratigraphy and lower soil hydraulic conductivity values compared to those in neighbouring zones (Gasmo et al., 2000; Luce and Black, 2001). Along man-made cuts, rainwater can generate surface runoff, ponding conditions and erosion processes that often produce significant rills and gullies especially in granular soils subjected to nil suction, as reported in the literature concerning Thailand (Ziegler et al., 2004), Australia (Croke and Mockler, 2001), US Virgin Islands (McDonald et al., 2001) and Malaysia (Sidle et al., 2004).

The effects of anthropogenic factors on superficial and sub-superficial groundwater circulation are particularly relevant in some areas of the Campania region of Southern Italy, where unsaturated pyroclastic deposits overlie carbonate massifs. Mountain roads, constructed to allow the coppicing of woods, are usually not protected or sealed; rainwater can infiltrate in large quantities through the roadway, affecting pore pressure in the subsoil and predisposing slopes to failure. Significant examples of human-induced landslides in Campania were observed during the May 1998, namely the Sarno - Quindici events.

4.2.2 Case study in Campania (Southern Italy)

The influence of man-made cuts on triggering flow-type landslides in Campania has been pointed out by several authors (Celico & Guadagno, 1998; Brancaccio et al., 1999; Di Crescenzo & Santo, 1999; Guadagno and Perriello Zampelli, 2000; Guadagno et al., 2003). In particular, Guadagno et al. (2005), refer to the Pizzo d’Alvano area (the 1998 Sarno, Quindici, Bracigliano and Siano events), which describes an initial slide that occurred at a short distance from a cut for a trackway. In this example, the pyroclastic masses can be considered to be in kinematic freedom (Figure 4.2.1), concluding that 44% of such landslide source areas were connected to man-made cuts and tracks located at distances lower than 10 metres in most cases.

Two cases are distinguished in the literature: instability above man-made cuts and instability involving fills. In the first case, translational slides involve masses located uphill of trackway cuts (Figure 4.2.1A); in the second case, sliding failures involve fill material located just downhill from the trackways (Figure 4.2.1B) and/or at the road bends (Figure 4.2.1C). Both superficial water and groundwater circulation also play an important role in initiating landslides, especially where cuts for roads and trackways create concentrated runoff that channels surface water to specific points with a low slope gradient (Figure 4.2.1C).

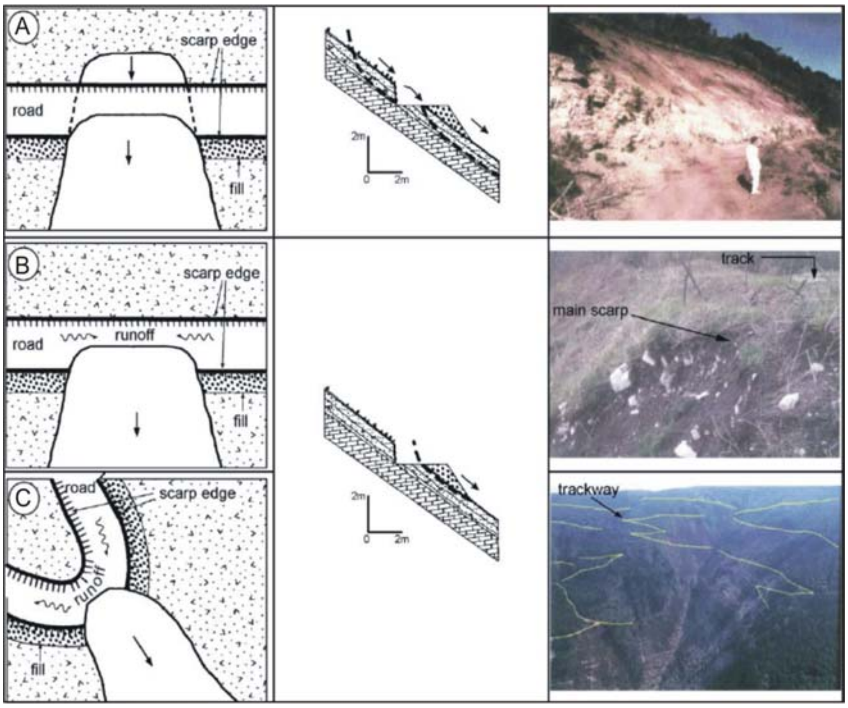

Figure 4.2.1 Schemes of mudflow triggering (from Guadagno & al., 2003)

For a large cluster of flow-type landslides distributed across a widespread sector of Campania (172 landslides), Di Crescenzo and Santo (2005) showed that most of the first movements (45%) were located near artificial tracks (Figure 4.2.2A). In particular, 41 source areas were less than 10 metres from these morphological discontinuities (Figure 4.2.2B). Clearly, the widespread past practice of using artificial cuts to break the continuity of very steep “infinite” slopes, covered by cohesionless soils, only worsened equilibrium conditions, inducing significant changes in both surface water and groundwater circulation patterns.

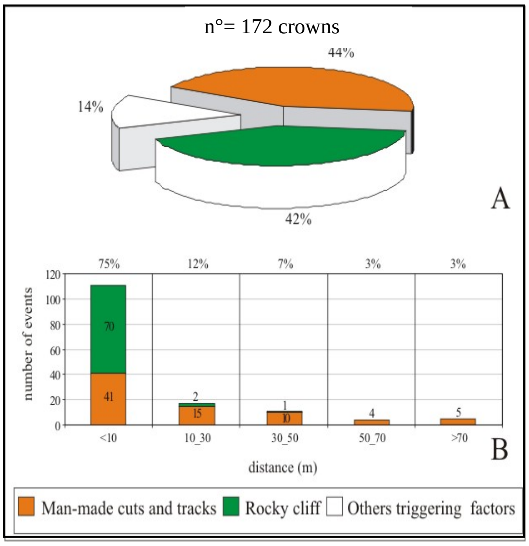

Figure 4.2.2 Statistics on sites involved in mudflow triggering (from Di Crescenzo and Santo 2005)

Cascini et al. (2008) recognised that 16% of the 133 analysed landslide source areas were related to the presence of mountain tracks along the hill slopes facing the town of Quindici (Figure 4.2.3).

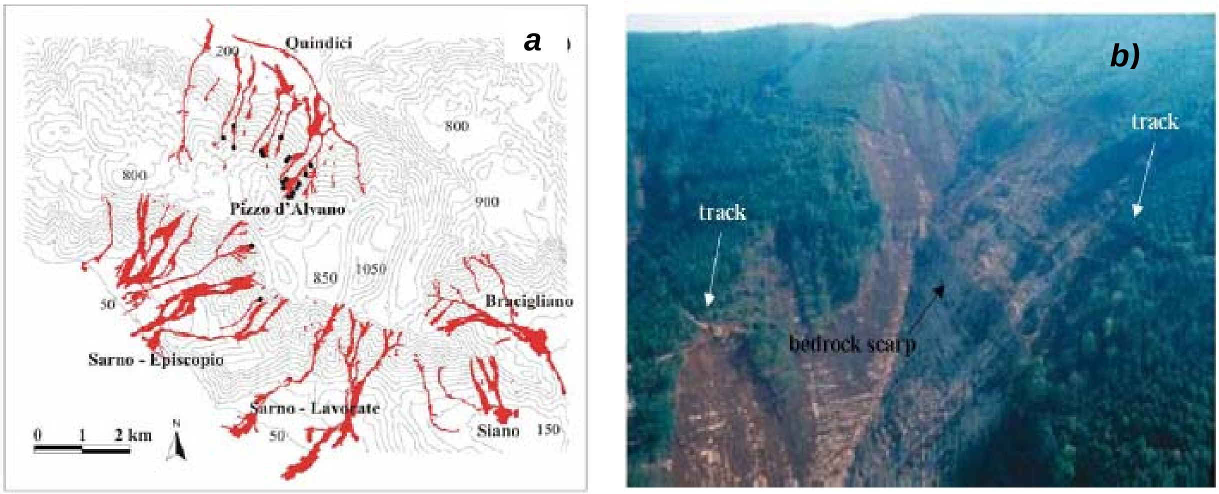

Figure 4.2.3 a) In-situ evidence for some landslides occurring along the hillslopes facing the town of Quindici (Cascini et al., 2008); b) Shallow flow-type landslides connected to mountain tracks during the May 1998 event.

The first-failure stage of landslides induced by mountain tracks in Campania region was modelled and analysed by means of numerical analyses with FEM code in particular by Guadagno et al. (2003), Crosta et al. (2003), Evangelista et al. (2005), Cascini et al. (2008). Cascini at al. (2008) modelled the landslides of Sarno and Quindici occurring in May 1998. They performed parametric analyses, referring to simplified schemes (Figure 4.2.4a) that reproduced typical stratigraphic settings observed all over the massif and adopting as hydraulic and mechanical soil properties in saturated and in unsaturated conditions those available in the literature (Sorbino and Foresta, 2002; Bilotta et al., 2005; Cascini et al., 2005) (Table 4.2.1).

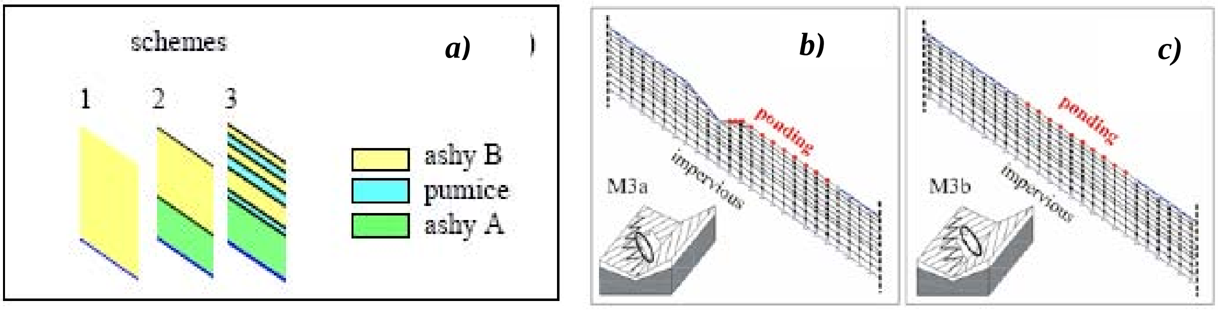

Figure 4.2.4 a) Schemes adopted in the numerical analyses performed by Cascini et al., 2008; b), c) Two geometries adopted in the numerical analyses carried out by Cascini et al., 2008.

Two cases were analysed: a 30° slope (Figure 4.2.4c) and another crossed by a steep, 14°, track (Figure 4.2.4b). Pore water pressures induced by the May 4-5, 1998 rainfall storm were computed through the Seep/W finite element code (Geoslope, 2004) using the computational schemes, shown in Figure 4.2.5. In the first case analysed, the rainfall values were assumed as boundary conditions at the ground surface, and local ponding was considered downslope of the bend. In the second case, the same ponding condition was assumed in order to simulate the possible lateral redistribution of surface runoff. For slopes with continuous pumice soil layers (scheme 3, Figure 4.2.4a), the pore water pressures were compressive in larger portions of the slope than in the previous schemes (Figure 4.2.5); similar results were also obtained for scheme M3b. These results highlight that the groundwater regime is primarily controlled by the assumed boundary conditions at the ground surface and the stratigraphy rather than by local geometrical discontinuities. Indeed, the same results are obtained for schemes M3a and M3b.

Table 4.2.1 Soil mechanical and hydraulic properties used in the numerical analyses by Cascini et al. 2008.

	γ_d (kN/m^3)	γ_{sat} (kN/m^3)	n (-)	k_{sat} (m/s)	c' (kPa)	φ' (°)	φ^b (°)	ν (-)	E (MPa)	ψ (°)
Class B ashy soil	7.30	13.1	0.58	10^{-5}	0 ÷ 5	36 ÷ 41	20	0.26	5 ÷ 7	10 ÷ 20
Pumice soil	6.20	13.1	0.69	10^{-4}	0	37	20	-	-	-
Class A ashy soil	9.10	15.7	0.66	10^{-6}	5 ÷ 15	32 ÷ 35	20	0.30	1 ÷ 3	10 ÷ 20

γ_d, (γ_{sat}): dry (saturated) unit weight of soil, n: porosity, k_{sat}: saturated soil conductivity, c': effective cohesion, φ': friction angle, φ^b: rate of increase in shear strength due to suction, ν: Poisson's ratio, E: Young's modulus, ψ: dilation angle.

Cascini et al. (2008) performed limit equilibrium analyses also with the Slope/W code (Geoslope, 2004), assuming as input the computed pore water pressures. Their results show that a local ponding condition causes failure involving zones both downslope and upslope of the cut when schemes 2 (ashy A and B soils) and 3 (A and B, pumice soil) are considered (Figure 4.2.4a). The same results are obtained if scheme M3b is undertaken (Figure 4.2.6). The results clearly point out the role played by stratigraphy on failure onset. Hence groundwater modelling definitively shows that ponding conditions strongly affect the transient pore water pressures, mostly depending on the local stratigraphical setting.

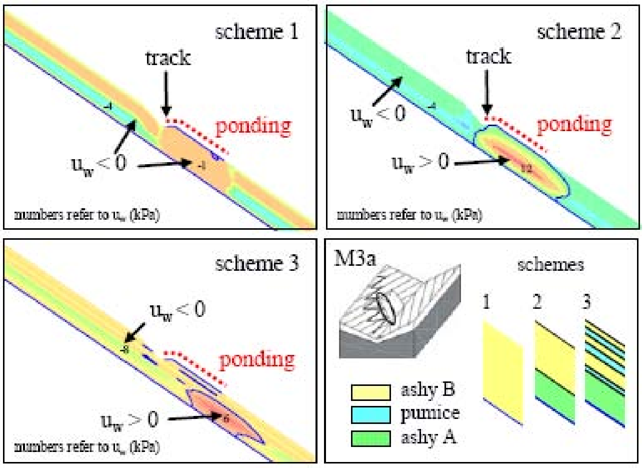

Figure 4.2.5 Results in terms of pore water pressure in three schemes analysed in the first case (Cascini et al., 2008)

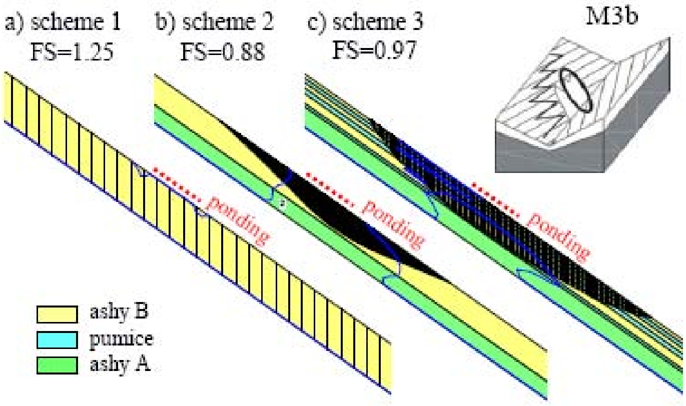

Figure 4.2.6 Limit equilibrium analyses for scheme M3b (Cascini et al., 2008)

Evangelista et al. (2005) also modelled the Sarno and Quindici events, analysing a 35° slope crossed by a road cut (Figure 4.2.7) by means of an FEM code, Plaxis Flow. The pyroclastic cover resting on the massif was modelled by three layers: a superficial pyroclastic layer, a pumice layer of the Avellino eruption (17ky BP) and a bottom cineritic layer (Di Crescenzo & Santo, 2005).

The Van Genuchten model was adopted for the retention curve and the permeability curve; the hydraulic properties used for the top layer, A, and for the bottom cineritic layer, F, refer to experimental data obtained respectively by Sorbino and Foresta (2002) and Scotto di Santolo (2000) (Figure 4.2.8). The pumice layer was modelled by the Durner model for the double porosity materials; the retention curve is the linear combination of two Van Genuchten-type retention curves, and the permeability function was obtained from the Mualem model as a function of the retention curve. The parameters for the pumice were obtained by laboratory tests performed by the same authors (Figure 4.2.8).

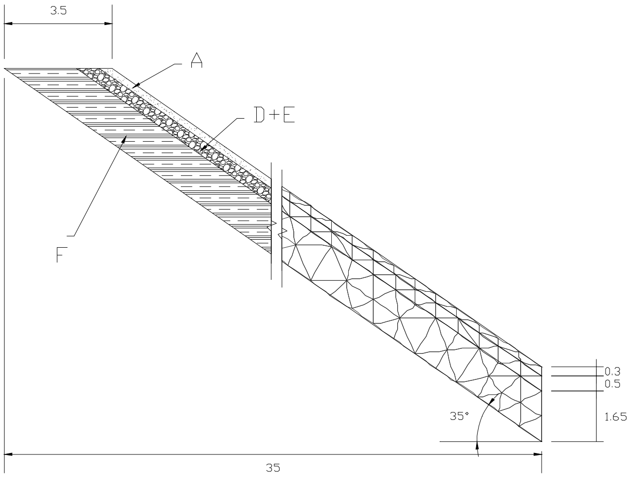

Figure 4.2.7 Model used in the numerical analyses by Evangelista et al., 2005.

Evangelista et al. (2005) performed analyses in steady-state conditions; the suction distribution resulting from steady-state analysis may represent the limit condition for the rainfall intensity equal to or less than that adopted. 52mm/day of rain, obtained as k_{sat} of superficial soil divided by 100, was applied on the ground surface; run-off was allowed. Two different lower boundary conditions were considered, draining or impermeable boundary. In Figures 4.2.9 - 4.2.11, the suction contour obtained by the same authors for the two different lower boundary conditions are shown.

The pore water pressure below the cut was compressive in both analyses, involving much of the slope in the analysis with an impermeable lower boundary (Figs. 4.11 and 4.12). The same authors performed another analysis, adding a layer of pyroclastic soil A on the surface of the road cut. The results showed that the compressive pore water pressure involved even more of the slope than in the previous analyses (Figure 4.2.11).

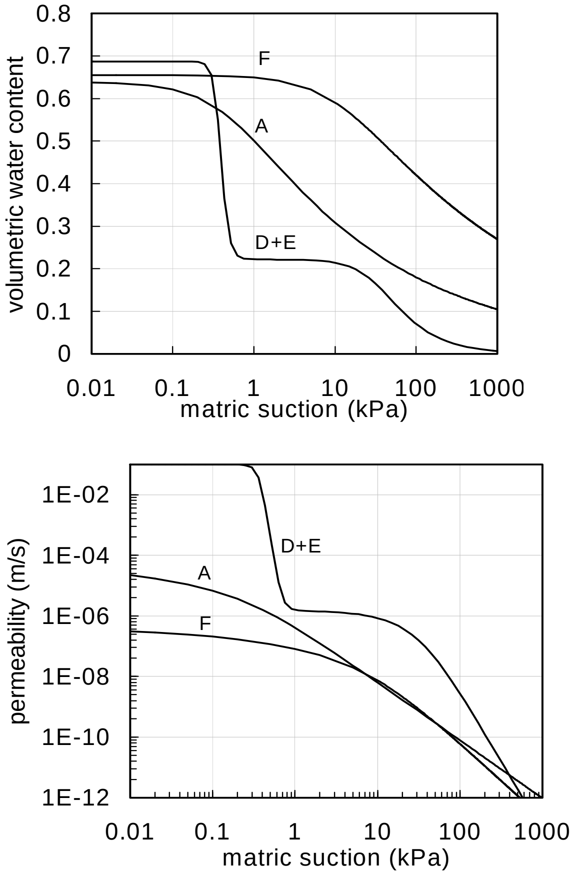

Figure 4.2.8 Retention curve and permeability function used by Evangelista et al., 2005

Evangelista et al. (2005) show that pore water pressure at the man-cut roads, especially if recovered from material with the same permeability as superficial soils, is compressive for intense rain applied on the ground surface and may worsen slope stability local conditions.

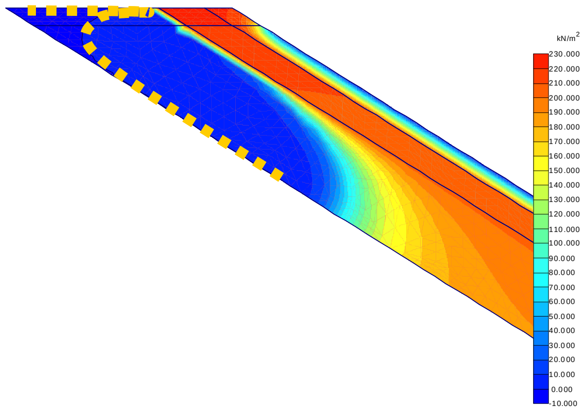

Figure 4.2.9 Suction contour resulting from the analysis with the draining lower boundary condition (Evangelista et al., 2005)

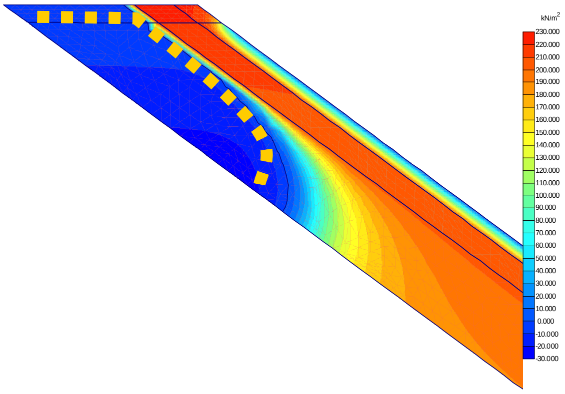

Figure 4.2.10 Suction contour resulting from analysis with the impermeable lower boundary condition (Evangelista et al., 2005)

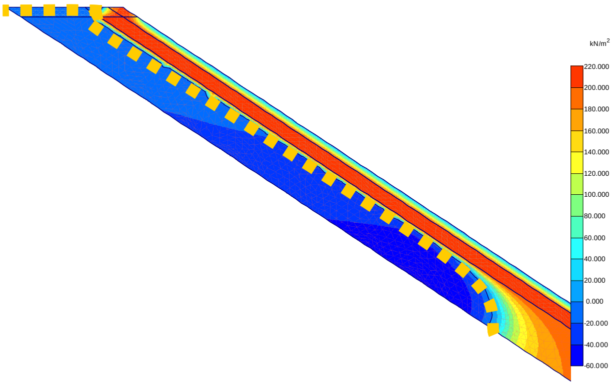

Figure 4.2.11 Suction contour resulting from analysis with the impermeable lower boundary condition and road cut surface covered by the top pyroclastic soil A (Evangelista et al., 2003)

4.2.3 Lessons from the Campania events

The events that occurred in Sarno and Quindici in 1998 were strongly influenced by morphological conditions due to the presence of trackways. A close connection between the existence of cuts and fills (made to construct mountain roads) and triggering of flow-type landslides is demonstrated by means of observation and analysis. The negative role of man-made cuts and fills is felt not only in terms of slope stability but also in terms of hydrogeologic conditions.

Regarding the areas upslope of the roads, the possible initiating mechanism is related to the decrease in support due to excavation of the soils along the road cut. Downslope of roads, the initiating mechanism is related to the increase in loads on the natural slope and to the infiltration of water in fills, from which the water infiltrates into the subsoil.

Given such considerations, the construction of mountain roads should be severely limited. As mountain roads are constructed to gain access to slopes with trucks, they are large and impacting. However, access to the mountain for coppicing could be gained with farm machinery even on very steep slopes, in the absence of mountain roads, by means of small beaten tracks.

4.3 RAPID DRAWDOWN OVERVIEW

The drawdown condition is a classical scenario in slope stability, which arises when totally or partially submerged slopes experience a reduction of the external water level. This is a common situation in riverbanks, subjected to changing river levels. Flooding conditions are critical in this case because river levels reach peak values and the velocity of decreasing water level tends to reach maximum values too.

Rapid drawdown conditions have been extensively analysed in the field of dam engineering because reservoir water levels fluctuate widely for operational reasons. Drawdown rates of 0.1 m/day are common. Drawdown velocities of 0.5 m/day are quite significant. One meter/day and higher rates are rather exceptional. However, reverse pumping storage schemes may lead to such fast water level changes in reservoir levels.

Sherard et al. (1963) in their book on earth and earth-rock dams describe several failures of the upstream slope of earth dams attributed to rapid drawdown conditions. Interestingly, in most of the reported failures the drawdown did not reach the maximum water depth but approximately half of it (from maximum reservoir elevation to approximately mid-dam level). Drawdown rates in those cases were not exceptional at all (10 to 15 cm/day).

A Report on Deterioration of Dams and Reservoirs (ICOLD, 1980) reviews causes of deterioration and failures of embankment dams. Thirty-three cases of upstream slips were collected and a third of them were attributed to an excessively rapid drawdown of the reservoir. A significant case was San Luis dam, in California (National Research Council, 1983). San Luis dam is one of the largest earthfill dams in the world (100 m high; 5500 m long; 70 million m^3 of compacted embankment). An upstream slide developed in 1981 after 14 years of successful operation of the dam because of a drawdown, which was more intense than all the previous ones. In this case, the average drawdown rate was around 0.3 m/day and the change in reservoir level reached 55 m. Lawrence Von Thun (1985) described this case.

The stability of riverbanks under drawdown conditions is also of concern. Desai (1971, 1972, 1977), in a series of papers, describe experimental and theoretical studies performed at the Waterways Experiment Station to investigate the stability conditions of the Mississippi earth banks.

When the water level is high, hydrostatic pressures help to stabilize the slope. A reduction of water level has two effects: a reduction of the stabilizing external hydrostatic pressure and a modification of the internal pore water pressures. The second effect has traditionally received considerable attention because it may lead to critical conditions of the slope. The subject has been approached from different perspectives, which have been largely dictated by current advances in Soil Mechanics. Current approaches to analyze drawdown are classified into two different groups: flow methods, which should be applied in relatively pervious slopes; and undrained methods, which find applications in impervious soil slopes.

Methods from the first group concentrate on the solution of the flow problem in a situation that involves changes in boundary conditions and a modification of the initial free surface. These methods implicitly assume that the soil skeleton is rigid and therefore they do not consider any modification of the initial water pressure because of the change in total boundary stresses imposed by the drawdown. Methods developed to handle this problem include flow net analysis (Reinius 1954, Cedergren 1967); methods based on ad-hoc hypothesis (typically Dupuit-type of assumptions) (Brahma & Harr, 1962, Stephenson 1978); finite element analysis of flow in saturated soil (Desai, 1972, 1977, Cividini & Gioda 1984) and finite element analysis for saturated-unsaturated flow (Neumann, 1973, Hromadka & Guymon, 1980, Pauls et al, 1999).

The second group considers only the change in pore pressure induced by an instantaneous drawdown. This is the undrained case in which flow is not considered. Key early references for this approach are Skempton (1954), Bishop (1954) and Morgenstern (1963) and more recent work has been published by Lowe & Karafiath (1980), Baker et al. (1993) and Lane & Griffiths (2000). In a recent contribution, Berilgen (2007) uses two commercial programs for transient/flow and deformation analysis respectively and reports a sensitivity analysis involving simple slope geometry.

In practice neither one of the two mentioned approaches can reliably approximate the field situation because soils, compacted or natural, are far from being rigid with pure undrained conditions. Even fairly impervious soils are too conservative for common drawdown rates, which fall in the range 0.1 to 1 m/day.

A recent comprehensive description of fundamentals of drawdown and the limitations of the two classical approaches is given by Pinyol et al (2009). In this contribution it is argued that accurate modelling requires coupled analysis. The term “coupled” analysis refers to the joint consideration of flow and stress deformation analysis. The paper describes in detail one of the few cases in which pore pressure records during drawdown are available (the behaviour of Shira dam, Paton and Semple, 1961) and compares the predictions of different types of analysis with actual field records of pore pressure.A recent case of a large landslide triggered by a massive drawdown is described below.

4.3.1 Canelles landslide: A failure triggered by rapid drawdown

The left margin of Canelles reservoir (Huesca, Aragón, Spain) is a sequence of subhorizontal thick units of Cretacic and Paleogene origin. Lower hard limestones are covered by levels of the Garum facies which includes claystones and limestones. The clay levels exhibit high plasticity (w_L=54-57%, PI=27-31%) and are known to be involved in slope stability problems at regional scale. The reservoir serves several purposes: irrigation, electric generation and fluvial control. Rapid drawdown conditions are associated with irrigation demands in dry climatic periods.

In the summer of 2006 a long continuous tensile crack, more than one kilometer in length, parallel to the reservoir water line created some alarm. Investigations performed immediately afterwards allowed the identification of a large landslide whose volume was estimated as $40 \cdot 10^6$ m^3 (Figure 4.3.1).

The crack was located at the foot of continuous scarp 4 to 5 m high which was identified as a limiting boundary of an ancient slide (Figure 4.3.2).

Figure 4.3.1 Aerial view of Canelles reservoir. Landslide contour indicated by the yellow line (approximate length of yellow line: 1.8 km).

Figure 4.3.2 Detail of a tension crack at the foot of an ancient scarp. The motion of the slide (on the left) looks essentially translational.

Most likely the slide was reactivated by a rapid drawdown condition on the neighbouring reservoir. Figure 4.3.3 shows a multiyear record of water levels in the reservoir. The maximum historic drawdown rate was close to 0.5 m/day and these velocities were measured on the month of July/August 2006.

This large landslide raises two major concerns:

- The possible development of a catastrophic and rapid slide which would invade the water of the reservoir.
- The restriction which should be imposed on the reservoir operation to maintain an adequate level of safety.

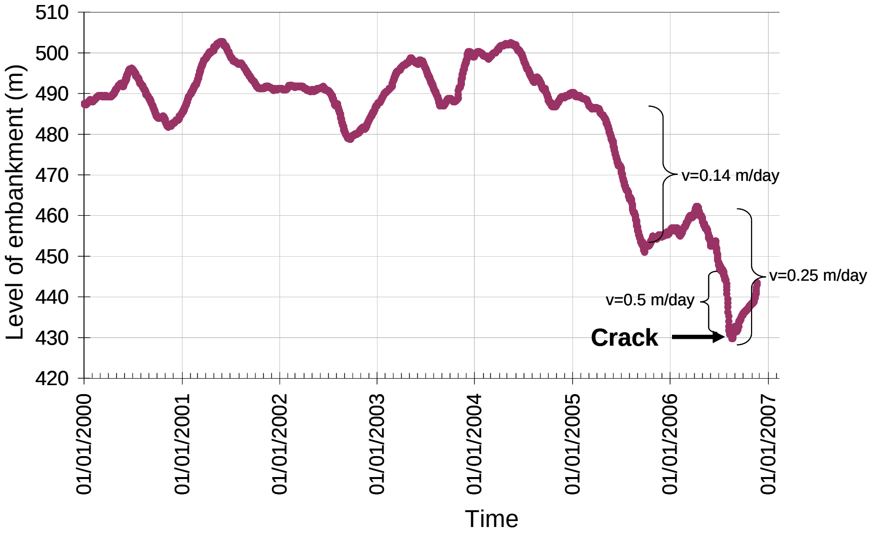

Figure 4.3.3 Reservoir level history.

As first and fundamental information, it was necessary to establish with certainty the shape of the rupture surface(s). The answer to this crucial question was provided by a detailed examination and interpretation of recovered cores. It was found that striated shearing planes were systematically located within the Garum clay facies. A representative cross section of the slide is given in Figure 4.3.4. It shows a profile located approximately on the central axis of the slide. The profile shows the sequence of main strata and the position of boreholes. Also some levels of the water in the reservoir are indicated as a general reference.

Remoulded samples from the Garum clay strata were tested in laboratory. A permeability test at constant hydraulic load provided a low value of permeability equal to $4 \cdot 10^{-10}$ m/s. Ring shear test were also carried out to determine the residual frictional angle of the material which is close to 10º.

Analysis:

A central section of the slide has been chosen for the numerical analysis of the Canelles slide during the drawdown (Figure 4.3.5). A hydro-mechanical coupled analysis was carried out by means of the finite element program, Code_Bright, in order to calculate the pore pressure distribution after the drawdown. Later, a stability analysis considering the obtained pore pressure distribution after drawdown was performed with a conventional Limit Equilibrium method.

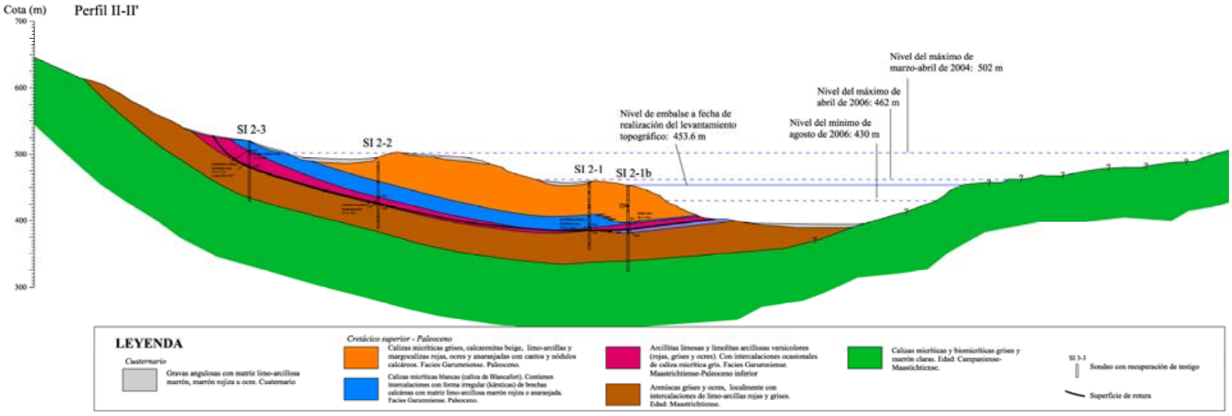

Figure 4.3.4 Representative cross-section of the landslide

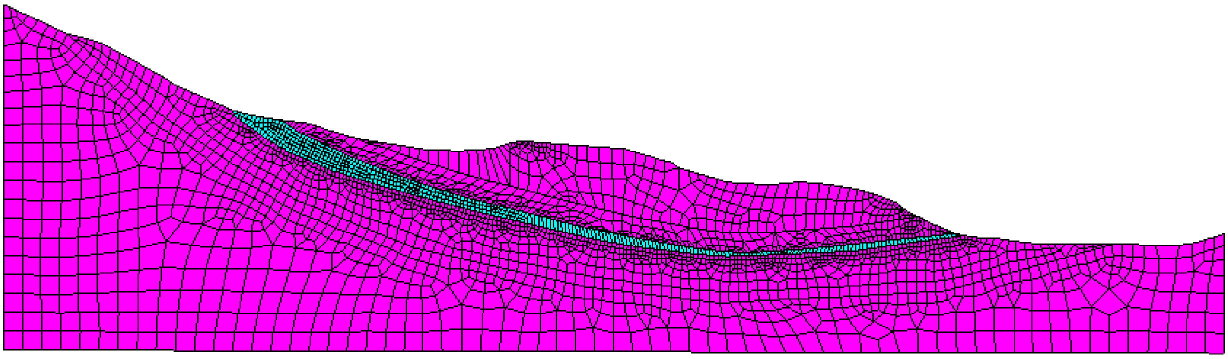

Figure 4.3.5 Cross section analyzed.

Table 4.3.1 Mechanical and hydraulic parameters for Canelles Landslide.

Parameter and unit	**Clay strata**	**Limestone/claystones**
Young modulus (MPa)	500	2500
Poisson's ratio	0.3	0.3
Saturated permeability (m/s)	$4 \cdot 10^{-10}$	10^{-6}
Van Genuchten Parameters:		
λ	0.33	0.33
P_0 (MPa)	0.3	0.01
Sr_{max}	1	1
Sr_{min}	0	0

Materials have been defined by means of a linear elastic law characterized by Young modulus and Poisson's ratio. Experience shows that the effect of including an elastoplastic law in the modelling drawdown is limited, especially for relatively stiff materials and moderate slope, as is the case here. For simplicity the claystones and limestones above and below of the clay strata have been simulated by a unique material characterized by the elastic parameters indicated in Table 4.3.1. Parameters of clay level and the expected lower stiffness of the Garum clay level are also indicated in the table.

The obtained value of saturated permeability of the clay sample in the laboratory ($4 \cdot 10^{-10}$ m/s) has been introduced in the calculation. The permeability value of the rock mass, above and below the clay strata, has been estimated equal to 10^{-6} m/s (a few orders of magnitude higher). Retention curves have been defined according to Van Genuchten model. The chosen values for parameters are indicated also in Table 4.3.1. The main difference between the more pervious limestone and marl strata and the clay formation lies in the air entry value.

Reservoir level history has been simulated. Figure 4.3.3 shows the reservoir level data measured during seven years, before the formation of the crack. Only the last four years, before the reactivation, have been modelled. The reservoir level remained between 480 and 500 m for a long period (from the beginning of 2000 to the summer of 2004). Accordingly, a stationary hydraulic condition defined by a reservoir level at elevation 480 m has been defined as initial condition. It corresponds to October 2002. The reservoir level history during the following four years has been modelled following the actual recorded reservoir elevation.

Rainfall has also been considered in the analysis performed. In this case a constant average value has been calculated from a meteorological station located near the reservoir. A constant flow equivalent to 400 l/m^2 per year has been imposed as a boundary condition on the surface of the landslide above the reservoir level.

Figure 4.3.6 shows the water pore pressure distribution in August 2006. The horizontal black line indicates the position of the reservoir level. The effect of the imposed flow simulating the rain can be observed in the upper part of the slope.

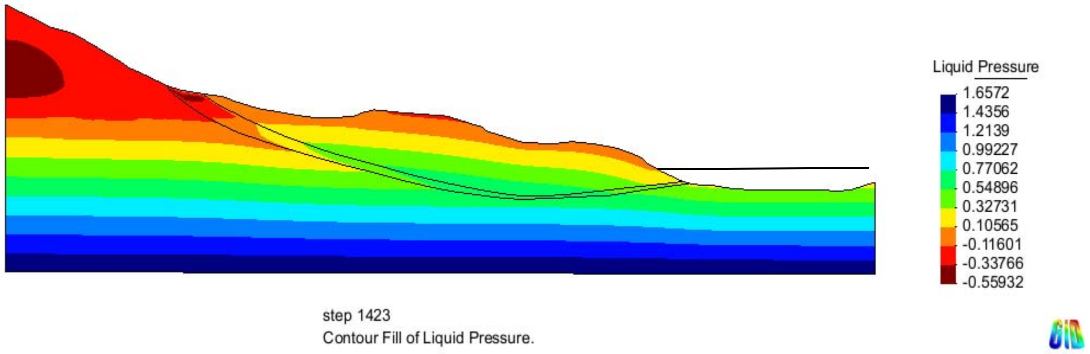

Figure 4.3.6 Calculated pore water pressure distributions in August 2006, when the crack was first observed.

It is interesting to realize the important effect of the fine impervious clay strata on the pore pressure distribution in the slope.

Stability analysis after the drawdown has been calculated taking into account the pore pressure distribution indicated in Figure 4.3.6. No effect of suction has been introduced. Therefore, only positive pore pressures have been considered in the stability analysis. However, the length of sliding surface affected by negative pressures is small compared with its overall length. The slide surface has been predefined according to field observations. The slide surface only crosses the Garum clay strata. Therefore, only the strength properties of this material are relevant in this analysis. The strength response has been defined by a Mohr Coulomb law with cohesion equal to zero (residual conditions) and frictional angle equal to 10º, as discussed before.

According to the laboratory tests the value of the density of the clay for calculation is 18 kN/m^3. The density of the unstable rock has been estimated as 20 kN/m^3. These parameters yield a safety factor of 0.98, following the Morgenstern-Price method. This is in good agreement with field observations.

The case shows the relevance of rapid drawdown conditions and their capability to trigger large landslides. Available methods for coupled flow-deformation analysis are capable of predicting drawdown conditions and their effect on stability.

4.4 LEAKS IN WATER CANALIZATIONS

4.4.1 Fourvière slide

In the city of Lyon, France, on the hill of Fourvière (quite steep for a city), a landslide destroyed several buildings (Allix, 1930; Albenque, 1931). The landslide was triggered by an increase in pore water pressure after a period of intensive rainfalls. Soils became fully saturated because, in addition to heavy rainfall, old water canalizations and drainages were leaking due to a lack of maintenance, even though the underground network of canalizations was mapped by an architect and two geologists. Together these two additional water sources created an exceptionally unstable situation which, on November 13, 1939, led to two landslides that killed 39 people.

Figure 4.4.1 View of the Fourvière slide (Ref: http://www.musee-pompiers.aso.fr/)

4.4.2 Fully slide

In the city of Fully, Switzerland, several debris flows occurred after intense rainfalls (see Figure 4.4.2). However, these landslides were actually induced by non-natural provisions of water.

After heavy rainfall events, a break in the mountain derivation water pipe brought tons of water in scree deposits and moraine debris. As a result, several debris flows carried between 350,000 and 450,000 m^3 of materials 1500 m lower. Fortunately, there were no fatalities, however, chestnut and vine farming fields were seriously affected.

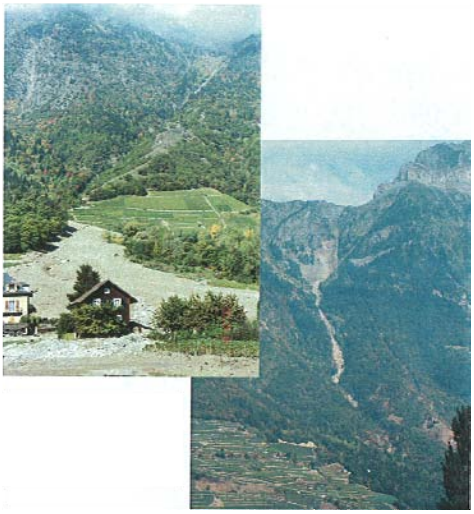

Figure 4.4.2 View of the Fully debris flow. Left: deposit area. Right: source area.

4.4.3 Lutzenberg slide

In a slope located above the village of Luztenberg, in north-eastern Switzerland, a landslide occurred in September, 2002, which damaged three houses and killed three people. The local geological settings were favorable to landslide occurrence as the water pressure was extremely high due to the confinement of a highly permeable silty-sand layer between two low permeability layers.

Although an exceptional rainfall event triggered the landslide, back analysis and numerical modeling demonstrated that a broken water pipe found near the head of the landslide was responsible for the permanent saturation of the terrain.

Figure 4.4.3 View of the Lutzenberg translational slide of 2002 (From www.planat.ch)

4.4.4 Quebec City slide

In Quebec City, 1889, part of the cliff along the Saint Laurence River collapsed, killing 40 people. Although local geological conditions, such as sub-vertical bedding and metric opened cracks, were favorable to the slope failure, human activities contributed to intensified levels of slope instability; the toe of the cliff was cut several times and a leak in the upper part of the drainage system severely increased the water pore pressure. During the 11.5 hours of rainfall preceding the 1889 landslide, the drainage canalization brought 700 m^3 of water to the unstable area, five times more than due to natural streaming (140 m^3). The undermining of the toe of the slope and the increased pore pressure levels were the conditioning and triggering factors, respectively.

Figure 4.4.4 Quebec landslide of 1889 (From Geological Survey of Canada collection)

In addition, it is important to note that Baillargé (1893) completed a report a year prior to this catastrophe, which indicated the potential issue linked to the drainage problem.

4.4.5 Conclusions and lessons water leakages

Failures of water supply networks and/or drainage canalizations often lead to landslides; these slides are fully human-induced. The issue is that these types of infrastructure are often buried and difficult to maintain. It is well known that drinking water network leak up to 30% (Giret M. and Rathieuville, 1996), which is a significant problem, and is likely worse for drainage canalizations.

In addition, there is significant potential for landslides to occur near houses as most of the pipes are located in urbanized areas. The previous example, in Quebec City, identified a relatively small landslide that, due to its location, was very dangerous, killing 40 people. Furthermore, the Quebec City example showed how intense rainfall (return period of a few years) coupled with water seepage can cause extreme levels of saturation never before experienced by the slope (corresponding to large natural return periods) and/or induce fatigue in the material, and eventually lead to a landslide.

4.4.6 Recommendations

It is possible to forecast the impact of water seepage, as demonstrated by Baillargé (1893) in the case of Quebec City. However, it not easy to detect leaks in buried pipes.

For example, a landslide occurred in Lutzenberg, Switzerland, in grasslands that were crossed by a broken water pipe. This is very difficult to forecast, even though networks locations are normally known and pipe leakages can be observed. In addition, European infrastructure is often old, and age is an important factor to consider (Jaboyedoff and Bonnard, 2008), especially for newly urbanized regions built close by older networks. Thus, the following recommendations should be noted:

- Future studies in detailed landslide risk assessment of urbanized areas (or future urbanized areas) should take into account the water pipe and canalisation network
- Potential pipe leakages and breaks should be considered when designing the methodology of the risk assessment.

4.5 MINES AND QUARRIES

4.5.1 Aberfan slide

Mining activities in the South Wales coalfield created tailings coal debris. The stability of these human constructions was precarious on many occasions, and several unstable incidents, without grave consequences, occurred in this area. However, the Aberfan soil heap dramatically slid on the October 21, 1966, destroying buildings (e.g. a local junior school and 18 houses) and killing 144 people (116 children and 28 adults) (Bishop and Penman, 1968; Siddle et al., 1996).

After this catastrophe, the potential risk of coal slag heaps was investigated by the National Coal Board in South Wales Area, leading to a revision of existing legislations on colliery and mine tips (Mine and Quarries Act, 1969).

Figure 4.5.1 View of the Aberfan slide (Ref: http://www.nuffield.ox.ac.uk)

4.5.2 Arvel slide

A large rockslide, involving 615,000 m^3 of limestone and marls, occurred on the March 14, 1922 (Choffat, 1929; Crosta et al., 2009; Jaboyedoff, 2003; Choffat, 1929; Pedrazzini et al., 2009). Although the geometry of the slope and the orientation of the discontinuity sets were favorable to a complex failure, including wedge failure associated with toppling failure, the general destabilization of the slope was disturbed and worsened by quarry activities. This failure produced significant economic damages. Fortunately, no fatalities occurred.

Figure 4.5.2 View of the Arvel slide of 1922 (From Choffat, 1929)

4.5.3 Elm slide

A huge avalanche involving 30 million m^3 of rock occurred the September 11, 1889, affecting the villages of Untertal and Elm (Switzerland) and killing 115 people. Even if geology and structural settings were favorable to the failure, the activity of the Elm quarry was identified as conditioning factor; the progressive undercutting of the toe of the cliff for slate extraction clearly worsened the stability of the slope.

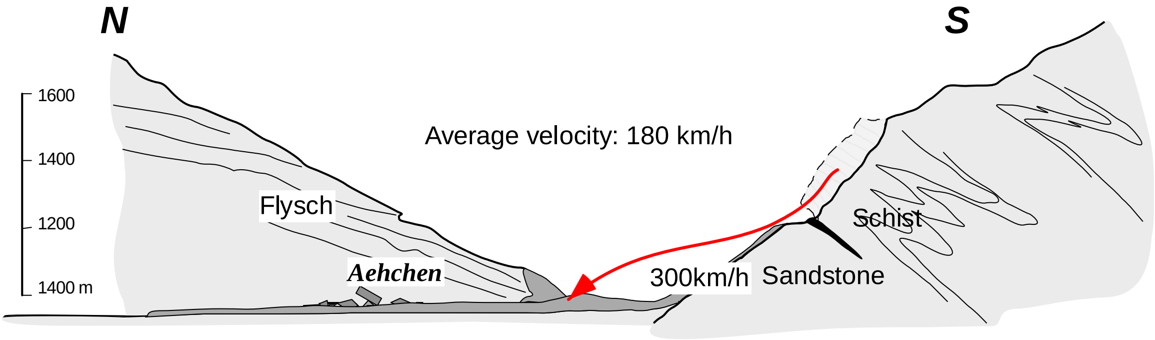

Figure 4.5.3 Cross section of the Elm rock avalanche of 1889 (Modified after Heim, 1932)

4.5.4 Frank slide

On April 19, 1903, a massive rock avalanche occurred in Turtle Mountain, located in the southern region of the Rocky Mountains in Canada (McConnel and Brock, 1903; Allan, 1933; Cruden and Krahn, 1973; Langenberg et al., 2006; Jaboyedoff et al., 2009; Pedrazzini et al., 2009, Froese et al., 2009). The disaster involved 30 million m^3 of material and killed 70 people. Even if discontinuity sets allowed complex wedges on the top and planar dip slope on the toe of Turtle Mountain, stability conditions were worsened by mining activities, which certainly accelerated the destabilization process leading to the catastrophic failure.

Figure 4.5.4 View of the Frank slide of the deposit and of the scar of Frank slide (IGAR-Pictures).

4.5.5 Conclusions and lessons on mining activities

It is well known that quarrying and mining activities create slope instabilities; this is one of the main subjects of geotechnical engineering. Nevertheless is it less common for such activities to interact directly with society. As a consequence these events must involve more than the exploited area and the volumes are important.

The excavation or accumulation of soil can destabilise the slopes. For hard rocks it is mainly undercutting and subsidence that lead to progressive failures. This happens mainly if the area is already prone to landslides, as pointed out by Cruden and Martin (2004) for the Frank slide. In the case of tailings, the pore pressure condition or their modifications is one of the main issues.

4.5.6 Recommendations

Restrictive legislations, implemented as a result of past catastrophic events, address the issues associated with tailings instability and have introduced relatively good practices. Nevertheless, the operators are often pressed by economic conditions which can produce undesirable effects on exploitations. However, it is essential that in all cases, tailings and excavations must abide by the following geotechnical recommendations:

- If a slope is above an excavation, which is located near an inhabited or industrial region, the exploitation must follow careful geotechnical analyses.
- Monitor the activity of small.

4.6 CUT-AND-FILLS

4.6.1 Aalesund

During the night of March 26, 2008 a 1400 m^3 block slid and hit the base of a six story building in the city of Aalesund (western Norway) (Ref: Skredulykka I Aalesund, Rapport fra Aalesundutvalget, 2008). The two lower floors collapsed, causing five fatalities. In addition, a gas tank located in the basement began to leak, leading to the evacuation of approximately 500 people in the surrounding area. In order to build this two year old house, the natural rock slope was cut, creating a 20 m high vertical wall. A serious underestimation of the size of potential sliding blocks led to inadequate slope stabilization measures (anchors were too short).

Figure 4.6.1 View of the Aalesund slide (ref: Skredulykka I Aalesund, 2008)

4.6.2 Road cut in Eterpas (Valais, Switzerland)

On January 9, 2001 a 2,000 m^3 rockfall cut a secondary road in Eterpas. This event was the result of a road created along a 30 m high rock wall in shaly sandstones. After several years this rock wall collapsed. It was triggered by important antecedent precipitations as well as freeze and thaw cycles. Direct observations indicated that water was running throughout the unstable mass only tens of minutes before the collapse. In addition, it has been shown that this location was initially a spur, located near a regional fault and previous activity of rock fall was demonstrated by a scree slope below the rockfall predating the road-cut.

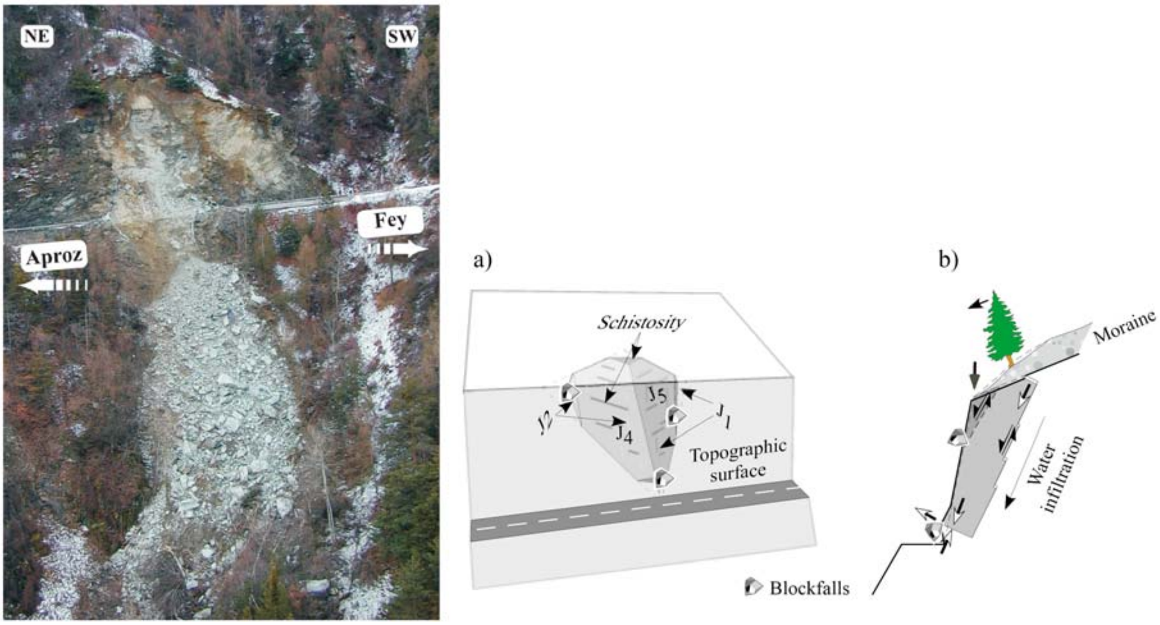

Figure 4.6.2 (Left) Picture of the scar cutting the road. Sketch of the failure mechanism. (Right (a) unstable rock wedge; b) The mechanism was a wedge going with a buckling at the bottom of the slope (From Baillifard et al., 2003).

4.6.3 Fill slopes

Filled slopes frequently lead to landslides. They usually only affect a small part of the slopes, however, they can have a large impact on traffic by cutting through roads or railways (Figure 4.6.3). It can result in failure embankments for buildings. Incremental failure can be observed all over the world on roads (Collins, 2008). USGS (2004) pointed out that the fills are one of the major causes of landslides.

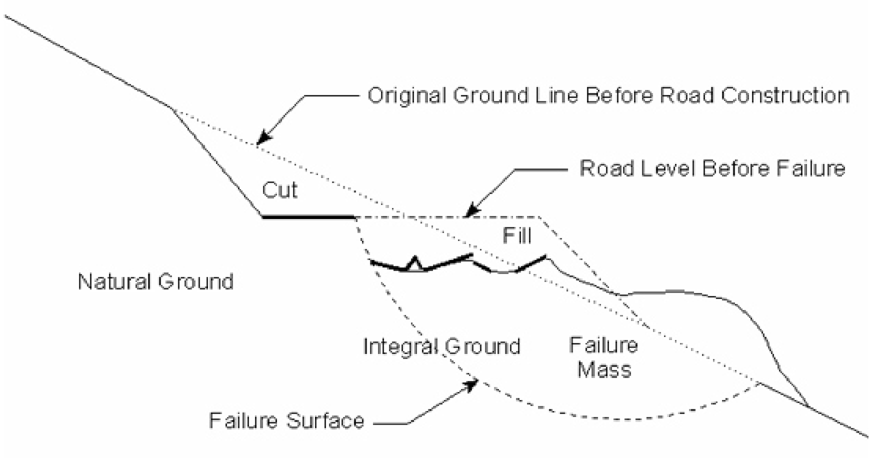

Figure 4.6.3 Typical cut-and-fill slope failure (from FEMA, 2006).

Figure 4.6.4 Example of road fill in North Carolina (USA) that initiated a debris-flow. This occurred during heavy rainfall (From Collins, 2008).

4.6.4 Conclusions and lessons on cut-and-fill

Landslides caused by cut-and-fills are usually small in size, however, they occur frequently. Although cut-and-fill slopes are usually designed by engineers and preventively stabilized, failures can still occur. It must be pointed out that failures can occur weeks, or even several years, after slope re-profiling. Cut-and-fill failures are mainly caused by:

- Preexisting weaknesses in rocks, such as faults, large preexisting dormant landslides, etc.; and/or
- Triggering factors linked to extreme events such as earthquakes and heavy rainfall.

Pre-failure can often be observed from rockfall activity or cracks within the slope or on the road. A careful survey of preexisting weakness or pre-failure signs is recommended to forecast such events. Even small cut-and-fill failures have a relatively high impact because these engineering works generally occur in areas near people and infrastructure. Therefore, the risk represented by this type of landslide is often high.

4.7 ACTIVATION OF SENSITIVE CLAYS

4.7.1 Namsos (blasting)

On March 13, 2009, a 400,000 m^3 quick clay slide was triggered by rock blasting in the vicinity of the town of Namsos (Trondelag, Norway) and ten houses were destroyed. Fortunately there were no fatalities (Ref: Skredet i Kattmarkvegen i Namsos 13 Mars 2009. Rapport fra undersøkelsesgruppe, 2009). The blasting was part of a road construction project and it took place in the bedrock very close to the limit with the sensitive clays.

Figure 4.7.1 View of the Namsos slide (Photo by Leif Arne Holme)

4.7.2 Rissa (head loading)

On April 29, 1978, a 5 to 6 million m^3 quick clay slide took place at Rissa (Trondelag, Norway) (Gregersen, 1981). Seven farms and five houses were destroyed and one person died. The landslide was initiated by dumping of earth on the shore of a lake, in an area of sensitive clays. The slide then progressed retrogressively and eventually covered over 300,000 m^2. A relatively small volume of earth (700 m^3) was enough to trigger one the largest quick clay slides of the twentieth century.

Figure 4.7.2 View of the Rissa slide

4.7.3 Conclusions and lessons on sensitive clays

Quick clays are such a particular phenomenon that they deserve their own category. The evolution of some marine sediments towards sensitive clays is, of course, due to natural processes, and is not human induced. However, once the clayey material has reached this state of sensitivity, many apparently benign human activities may trigger disasters (cuts, head loading, blasting, livestock grazing, etc.). Moreover, in many regions, the areas covered by potentially sensitive marine sediments represent the best flat areas for farming and/or habitation settlements. Some important towns, such as Trondheim in Norway, are even built mostly on sensitive clays.

4.7.4 Recommendations

The first step is to be aware of the presence of sensitive clays. Firstly, this requires a systematic mapping of marine sediments, although all the marine sediments are not sensitive. Next, sampling and testing the properties of the sediments is required in order to assess the level of sensitivity. Then, depending on the sensitivity, prevention measures such as the type of land occupation and engineering works can be defined (if necessary). Countries such as

Norway, Canada and Sweden have much experience with this specific phenomenon and have developed very valuable methods to deal with it.

4.8 CHANGES IN LAND-USE

4.8.1 Menton (Alpes-Maritimes, France)

The rainfall event of November, 2000, caused more than 400 superficial landslides on the whole territory of Menton. These induced damages on buildings and created ruptures on networks and roads, but fortunately, without any injuries or fatalities. These types of rainfall events are not exceptional on the commune, but it showed the brittleness of the territory which is experiencing the consequences of fast urbanization without the organization of superficial water management.

Figure 4.8.1 Menton, French Riviera – France

Figure 4.8.2 View of shallow landslides and mudflows

4.8.2 Conclusions and lessons on land-use changes

The evolution of the territories during the past decade has introduced a lot of changes in land-use. At one time, people managed the territory and controlled the water flow through agriculture, and collected water to use in its natural form; today, land-planners and decision-makers have urbanized the regions and water sources are often over-exploited.

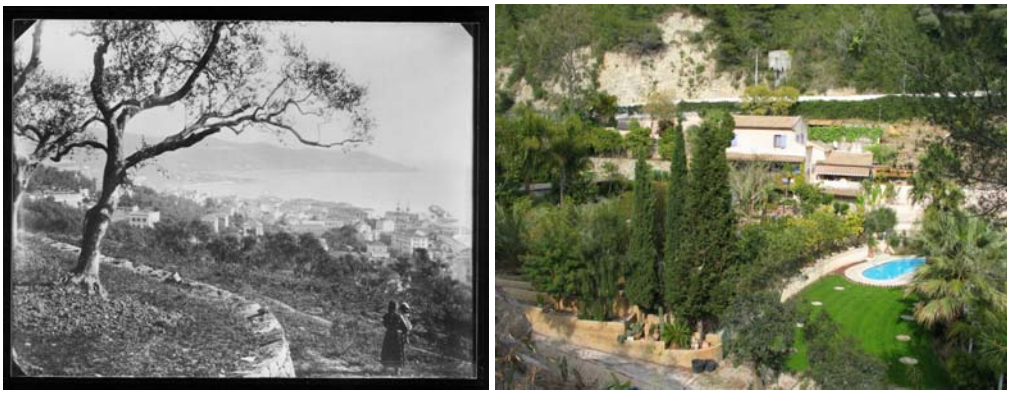

Figure 4.8.3 Menton a few decades ago (left) and Menton today (right).

4.8.3 Lesson and recommendations

A territory is a global system in which all components are continuously interacting with one another. Therefore, when an action is applied to one component, a reaction can be expected from the other components within the system. Increasing levels of urbanization puts additional stresses on the environment and induces changes in the hydrological cycle. Due to the nature of the system, these changes in water flow, in terms of quantity and velocity, in one region can induce changes in other nearby regions as well.

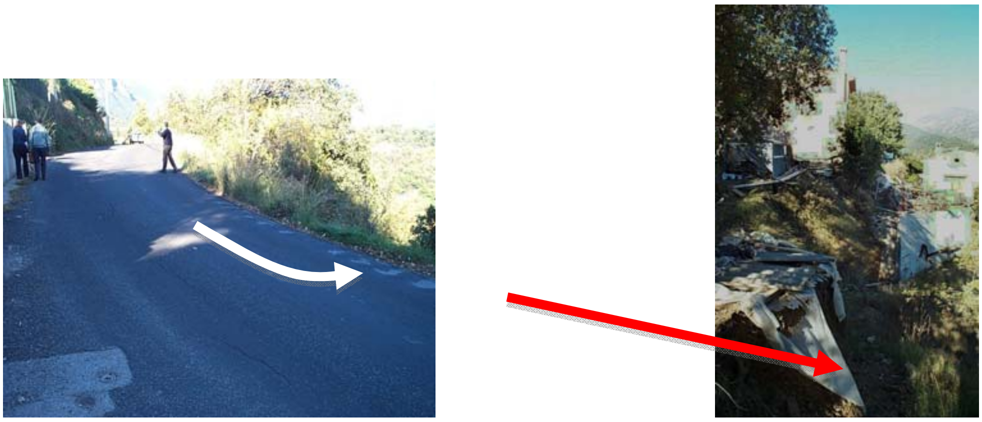

Figure 4.8.4 Lack of water flow control on the road induces landslides nearby.

Understanding the evolution of the territory may help to explain the development of landslide hazards and risk. A systemic analysis of the territory is required in order to understand the consequences of land-use changes.

4.9 SUMMARY OF LESSONS FROM HUMAN-INDUCED LANDSLIDE CASE STUDIES

As part of the work in SafeLand, several major human-induced landslides were studied in detail to identify why they happened and what lessons could be learned. These case studies, introduced in Sections 4.4 – 4.8 above, are summarized in Table 4.9.1. More detailed information about them is provided in SafeLand Deliverable D6.1.

Table 4.9.1 Case studies of human-induced landslides in Europe and other significant cases that were assessed in detail.

Case Study	Location	Date	Material type	Main cause	Consequences
4.4.1 Fourvière	Lyon, France	13 Nov. 1930	Marly sand & backfill layers	Lack of maintenance of the old water canalization network, which led to increased pore water pressure in the superficial layers.	39 deaths (23 rescuers buried by the 2nd event) and 15 mill. old French francs
4.4.2 Fully	Switzerland	15 Oct. 2000	Karsts, scree deposits and moraines	Breaking of water canalization that created several debris flows.	No fatality, but significant farming damages.
4.4.3 Lutzenberg	Switzerland	1 Sept. 2002	Moraine, sandstone and marls	Permanent water saturation caused instability due to broken pipe.	3 houses destroyed killing 3 people.
4.4.4 Quebec	Quebec city, Canada	19 Sept. 1889	Sedimentary rocks (Utica slate formation)	Unfavourable geometry of discontinuities + slope cutting + water infiltration due to leak in drainage pipe.	40 people died in their destroyed houses.
4.5.1 Aberfan	Wales, United Kingdom	21 Oct. 1966	Coal mining debris	Spoil heap destabilized by modification of the geometry.	School and 18 houses destroyed killing 116 children and 28 adults.
4.5.2 Arvel	Switzerland	14 March 1922	Rock	Geometry of slopes and discontinuity sets were favourable for toppling. The general stability of the slope was disturbed and worsened by the quarry.	No fatality, but significant material damage.
4.5.3 Elm	Switzerland	11 Sept. 1889	Slate	Unfavourable geometry of discontinuities + critical slope cutting.	115 fatalities.
4.5.4 Frank	South West Alberta, Canada	29 April 1903	Rock	Unfavourable geometry of discontinuities + mining activities.	70 deaths and significant material damage.
4.6.1 Ålesund	Møre and Romsdal, Norway	26 March 2008	Rock	Bad slope design and inadequate slope stabilization.	5 fatalities and significant material damage.
4.6.2 Eterpas	Switzerland	9 Jan. 2001	Shaly sandstones	Road cut.	Significant damages of the infrastructure.
4.7.1 Namsos	Trøndelag,	13	Quick clay	Blasting during road	No casualty, but significant

	Norway	March 2009		construction.	economic damage.
4.7.2 Rissa	Trøndelag, Norway	29 April 1978	Quick clay	Building works (head charge with excavation material) leading to retrogressive sliding.	One casualty and significant economic damage.
4.8.1 Menton	Menton, France	Winter 2000	Superficial soils	Heavy rainfall event on a territory where land-use has changed. Bad management of water flows.	400 shallow landslides and mudflows within few days ; no fatalities ; 10 M€ of urgent work.

5 POLICIES, LEGISLATION & ADMINISTRATIVE PROCEDURES

5.1 LEGISLATION AND ADMINISTRATIVE PROCEDURES IN NORWAY

The Building and Planning Act in Norway has been under development since 1924, and the act went into force for the whole country in 1966. The latest revision dates to 1987. The Building Act applies when a detailed hazard plan is prepared with corresponding detailed maps. The on-going hazard mapping effort on survey maps at 1:50,000 scale has been operative since 1979, and approximately 110 maps have been completed to date. However, another 100 maps still need to be prepared, and an estimated 15 more years will be required to finish the task. So far the maps are not legally binding, but are used to help land-use planning in communities. The building council of the counties must comply with the rules stated in the Act. Advice on hazard zones and protective measures are given by geo-consultants. For avalanche-endangered houses older than 1966, the National Fund for Natural Disaster Assistance can finance rebuilding with protective measures or moving the houses. In 1980, a new Act stated that all property with Fire Insurance must also have Natural Hazard Insurance coverage. Damage caused by natural hazards will normally be compensated in full unless the owner has displayed gross negligence. Insurance companies do not initiate hazard assessment or recommend safety measures. They may, on the other hand, increase the insurance premium or refuse permission to rebuild.

Today, risk and vulnerability analyses must be performed before regulation plans and building requests are approved by the county authorities. At the county level, the project proponent needs to establish whether the area is susceptible to landslide. For the regulation plan to be approved, the proponent needs to determine whether a hazard exists and what its potential consequences would be. In the building plans, the proponent needs to document safety or prepare mitigation measures.

There is on-going work in Norway at the ministerial level to improve the coordination of risk mitigation for all types of slides (clay slides, rockslide, debris flows, avalanches and underwater slides). Both organization and responsibilities will be re-examined, factoring in increased hazard and risk due to climate and demography changes. Responsibility for coordination was assigned to the Norwegian Water Resources and Energy Directorate (NVE). The Directorate will be in charge of preparing guidelines and ensuring efficient operation for the following aspects:

- National strategy for landslide management
- Hazard assessment, preparedness and emergency response in acute situations
- Landslide warning
- Detailed mapping of hazard, vulnerability and risk
- Quantifying landslide hazard and risk
- Safety measures, mitigation and early warning systems
- Compensation in case of damage
- Increased awareness and educational programs on landslides

5.2 LEGISLATION AND ADMINISTRATIVE PROCEDURES IN ITALY

In Italy, Law 183/89 established the River Basin Authorities, assigning them the tasks of soil conservation, the use and management of water resources management, environmental protection and town-and-country planning inside the basin, with respect to hydrogeological hazards. The boundaries of river basins were fixed according to geomorphologic and environmental criteria. Moreover, the law defined "Basin Plans" as planning tools to adopt sound land use and water management.

After the tragic events of Sarno (May 1998) in Campania (Southern Italy), Laws 267/98 and 365/2000 were adopted concerning identification of hazard conditions, aiming to minimize the impact of events. According to these laws, the Basin Authorities had to define the boundariess of "areas exposed to high risk of landslides and floods" in order to limit land use, by drafting special plans that were to anticipate ordinary Basin Plans. The civil protection plan to safeguard human lives was also envisaged. The Ministerial Decrees DPCM 2004 and 2005 further laid down the guidelines for managing the national and regional early warning system.

An important initiative in Europe is represented by the EU Directive 2007/60/EC. It proposes to introduce specific legislation on protection from hydrogeological risk. According to the European community, the approach to be implemented consists of three phases: preliminary risk assessment, drafting of hazard maps and developing a risk management plan. The hazard maps should be drafted by June 2013 and the risk management plan by June 2015. In our opinion Italy is well ahead of schedule, as the maps of the River Basin Authorities in Italy are already available. Such maps answer most of the points laid down in EU Directive 2007/60/EC.

5.3 LEGISLATION AND ADMINISTRATIVE PROCEDURES IN SWITZERLAND

In Switzerland and other European countries, disasters from natural hazards have led since the 1980's to a growing awareness of the vulnerability of human life and infrastructure amongst populations and authorities. In fact, the potential of damage has increased steadily over time as a consequence of growing population density and economical value of infrastructure and property. From a historical point of view, the developments have been promoted to some extent by safety measure constructions against natural hazards (i.e. river corrections in the 19th century). A change in perspective has taken place and today's focus is set on land use management schemes which are adapted to the natural conditions rather than the other way around.

At federal, constitutional level, there are no general regulations concerning natural hazards, but the confederation is legitimated to formulate according to Art. 75 (land use planning), Art. 76 (hydraulic constructions) and Art. 77 (forestry) basic principles and prescriptions to be followed by the Cantons which represent the legal entities in Switzerland. In the context of mass movements, the following prescriptions can be mentioned explicitly which are based on the federal laws for land use planning (RPG, SR 700) and forestry (WaG, SR 921.0):

- The Cantons are obliged to ascertain the regions endangered by natural hazards according to Art. 6 of the land use planning law (RPG). Art. 15 of the RPG states that endangered zones are not, or in a very restricted manner, suitable for construction.
- The Cantons are the entities responsible for developing the basics of protection against natural hazard events. This includes especially the hazard cadastre and hazard maps (Art. 15 of the forestry act, WaV; Art. 27 of the hydraulic construction act, WbV).
- The Cantons consider the basics of protection against natural hazards for all practice in land use (Art. 15, WaV; Art. 21 WbV).
- The Cantons consider for the compilation of the basics against natural hazards the technical directives established by the Confederation (Art. 15, WaV).
- If asked by the Confederation, the Cantons make the developments available for federal authorities and the public in a suitable form (Art. 15, WaV).
- The Swiss Confederation ensures subsidies to the Cantons for the protection against natural hazards. These include not only constructional protective measures, but also the development of hazard maps and cadastres, monitoring and early-warning services (Art. 6 WbG; Art. 36 WaG).

In order to implement concretely the prescriptions, the Confederation formulated in 1997 a catalogue of recommendations dealing with mass movements (BRP et al., 1997). As a consequence, the Cantons began with the hazard assessment of mass movements. Later, a work group for natural hazards and geology addressed in 2004 supplementary recommendations to the Confederation (AGN, 2004). On the cantonal level, natural hazard commissions composed of experts from the disciplines of forestry, water engineering, building insurance, geoinformation and land use planning are active.

According to the Federal Office for Environment, the Swiss Confederation works together with the Cantons on middle- and long-term preventive measures against natural hazards (FOEN 2010). The strategy for risk assessment and mitigation follows the general principles of integral risk management. Three components are distinguished: risk prevention, risk coping and regeneration (see Fig. 5.3.1).

With the legislations for forestry and hydraulic constructions, the Swiss Confederation gave the Cantons the assignment to create hazard maps and to consider them in all land use planning activities. Hence, the most important tool for protection against natural hazards is land use planning.

Figure 5.3.1 Cycle of integral risk management for mitigation of natural hazards (modified after Federal Office for Civil Protection 2010).

6 EMPIRICAL MODEL FOR USE IN SAFELAND

6.1 EFFECTS OF A CHANGING POPULATION

When the population of a region increases, several consequences are obvious and may subsequently occur; depending on the action, the reaction (consequence) on the territory can occur immediately or over several years, or even decades. To begin with, an increase in population often leads to an increase in occupied land space. As a result more natural landscape is modified – regions may be deforested, rural areas abandoned or urbanized, vegetation species changed, and so on. Similarly, existing developments and facilities are often expanded and more roads, railways and buildings constructed. These activities influence slope geometries, soil moisture levels and the hydrological cycle which could lead to increased levels of slope instability. However, there are many other aspects that need to be considered before a relationship can be realized between changing population and landslide frequency.

This situation has been illustrated for Norway in Figure 4.1.1 of section 4 of this report. The population of Norway has steadily increased since 1928, yet the figure indicates that the number of landslides grew from 1928 until 1990 and then declined dramatically, contrary to the growing population. This drop in landslide activity can be attributed to the introduction of guidelines for agricultural landscaping as well as increased funding and interest for geotechnical research. This introduces an important point, with more people comes more knowledge and applied skills.

In general, the level of planning and organization supported by a region is proportional to its level of development. For instance, in an underdeveloped community an increase in population generally leads to more land conversion without following the proper guidelines, thus more landslides occur. This is also often the case in more developed regions, but to a lesser degree.

6.2 HUMAN-INDUCED LANDSLIDE HAZARD MODEL

In order to develop a model that estimates the change in frequency, and thus hazard level, of human-induced landslides as a function of increasing population, the following parameters were considered:

- types of slopes that fail;
- portion of landslides caused by human activity;
- specific activities that lead to human-induced landslides;
- population density (based on the Global Rural-Urban Mapping Project, GRUMP (CIESIN, 2007) in this study); and
- level of development based on Gross Domestic Product (GDP) per capita as determined by the International Monetary Fund (IMF, 2010).

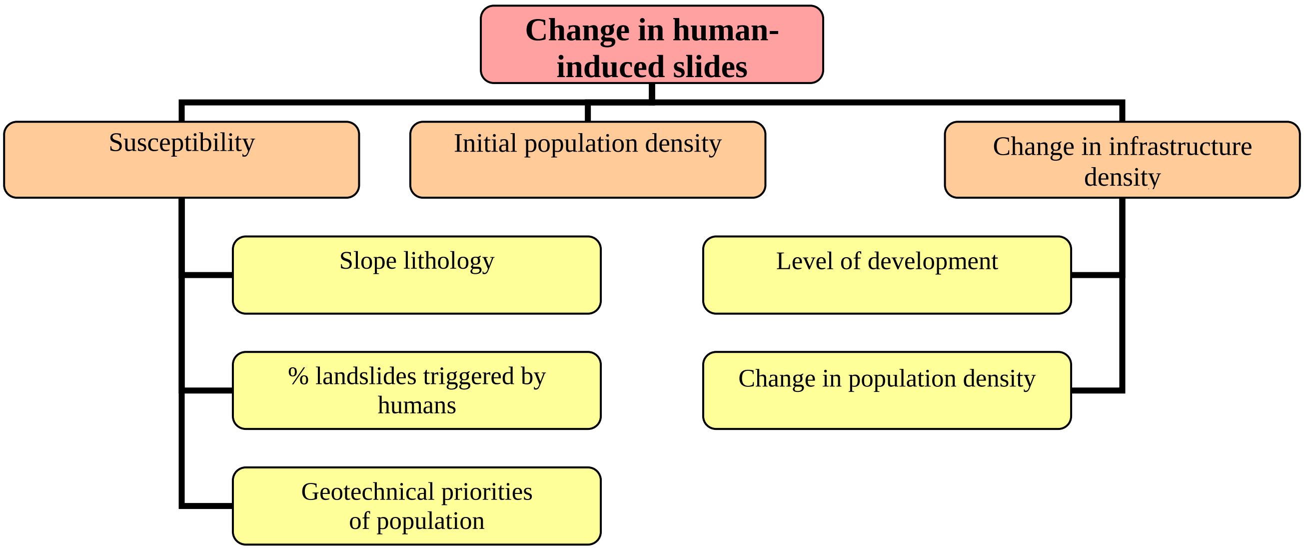

Figure 6.2.1 Parameters for SafeLand Model

The various parameters and indices used in the empirical model are shown on Fig. 6.2.1.

6.3 LANDSLIDE CHARACTERISTICS

Using whatever databases are available for the region under analysis, historical records of past landslides need to be collected to identify the most common types of slope failures. The slides are broken down into the following four categories:

- clay (comprises both sensitive and non-sensitive clay slides);
- earth;
- debris/mud; and
- rock.

These data provide an estimate for the percentage of slides that are clay, the percentage that are earth, and so on. However, this model also requires a breakdown of triggering factors for each slide type. For example, it may be found that 50% of the past slides have been clay, but what percentage were human-induced? This step is best completed through expert judgment, as historical records rarely identify the precise landslide trigger. Leading natural scientists and engineers can provide relatively reliable estimations of the percentage of clay (for example) slides induced by humans versus natural causes such as heavy rainfall. The results are however very region-specific. For instance, the majority of quick clay slides in Norway are human-induced whereas in Sweden, most are the result of toe erosion caused by changing water levels. Therefore, professionals with expertise in the specific region being analyzed should be consulted.

These data is sufficient to estimate the number of historical *human-induced* (i.e. anthropogenic) landslides,

$$a_{L\%} = F_C C + F_E E + F_D D + F_R R$$

where C is fraction of all slides that are clay, E fraction of all slides that are earth, D debris and R rock, and F_C (F_E, F_D, F_R) is the percentage of clay (earth, debris, rock) slides estimated to be triggered by anthropogenic activity.

- *Maintenance factor, M*

The introduction of improved geotechnical guidelines requires a significant amount of work (considered as *maintenance*) – soil testing, stability analyses, implementation of new mitigation procedures, and so on, therefore such situations have a high *M*-value. Referring back to Figure 4.1.1 in section 4 of this report, where a significant drop in the number of human-induced landslides was illustrated for Norway between the time periods 1971-1990 to 1990-2009, it is clear that many geotechnical advancements were made in order to reduce the human-induced landslide frequency so dramatically – thus its *M*-value would have been very high. However, it is important to note that this situation is not representative of the current circumstances, and therefore is not applicable to the proposed model, because geotechnical procedures, to some degree, are now standard throughout most of Europe, i.e. even if the population of Norway were to increase by the same number of people as it did from 1990-2009 over the next 20 years, it is highly unlikely that the number of human-induced landslides would decrease in a similar manner, even if further guidelines were introduced. Furthermore, it is more likely that given such a population change the frequency of human-induced landslides would instead increase as a consequence of the extensive landscape modifications. Therefore, the following maintenance factors have been developed for the corresponding changes in population.

Table 6.3.1 Maintenance Factor

Characteristics of change in population	***M***
increase in population; no specific geotechnical focus	0.10
increase in population; includes a notable increase in geotechnical researchers	0.35
increase in population; introduction of more extensive slope stability mitigation techniques	0.50
increase in population; introduction of more extensive slope stability mitigation techniques and new geotechnical guidelines	0.75

Note: The values selected for the maintenance factor (and all subsequent factors) are semi-quantitative and used to *relative* differences; they cannot be taken as purely quantitative.

6.4 INITIAL POPULATION DENSITY

The impact that a future population has on a region (in terms of changing landslide probability) is related to the current population density because a region can only support a finite number of people without overexploiting it natural resources. The area of the region under analysis is assumed constant thus the population density is directly proportional to the population.

- *Population factor,* F_{pop}

Table 6.4.1 Population Factor[3]

Population density (per km^2)	Classification	F_{pop}
≤ 1	Very low	1.00
[1 – 25]	Low	1.10
[25 – 50]	Moderate	1.20
[50 – 100]	Medium	1.30
[100 – 200]	High	1.40
> 200	Very high	1.50

6.5 CHANGE IN INFRASTRUCTURE DENSITY

The infrastructure density is accounted for in this model using data available for the population density and level of development of a country. These factors have been selected for several reasons. First of all, as population increases, the amount of infrastructure generally increases as well in order to accommodate the additional people. Therefore the change in population density is a good indicator of the infrastructure capacity in a region and is accounted for in the model as ΔP. Secondly, the type and quality of infrastructure in a region is vitally important because it affects water flow systems, and water is the primary trigger for slope instability. For instance, new buildings constructed to accommodate 1000 people could vary from one skyscraper to a large number of individual family dwellings. Although one skyscraper hardly increases the landslide frequency, 300 or so houses take up much more physical space and could have a drastic effect on the hydrological cycle. Furthermore, if any of these building are poorly constructed they are more susceptible to damage and can also cause even more slope instability, i.e. poor drainage systems can significantly decrease the shear strength of soil and increase levels of erosion. The development level is used to estimate the type and quality of infrastructure and is introduced into the model with the factor, F_{dev}.

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[3] The exposed population density within Europe ranges from 0.04 in Finland to 212 in Belgium to 4050 in Malta (due to minimal exposed land) with an average value of 67.

- *Development factor*

A high GDP per capita indicates that a country or region has the resources required to employ professionals and ensure that proper guidelines are followed when altering natural landscapes and creating or expanding developments. Similarly, wealthier regions are more likely to have large buildings and skyscrapers than poorer regions. However, this trend is not linear, as a country's GDP per capita decreases the likelihood of it neglecting regulations increases at a faster rate because poor countries simply cannot afford to take all necessary precautions and often lack professional expertise, whereas moderate – medium countries can usually manage, and rich – very rich countries have minimal financial limitations. This logic was used as the basis for the following F_{dev} categorization.

Table 6.5.1 GDP Classification and Corresponding Development Factor

GDP (thousands of USD)	**Category**	**F_{dev}**
> 50	Very rich	1.00
(30 – 50]	Rich	1.05
(20 – 30]	Medium	1.15
(10 – 20]	Moderate	1.30
≤ 10	Poor	1.50

6.6 PROPOSED MODEL

The recommended model for estimating the change in frequency of human-induced landslides, based on a changing population, is:

$$\Delta f = F_{dev} \cdot F_{pop} \cdot a_{L\%} \cdot (\Delta P - M\Delta P)$$

or

$$\boxed{\Delta f = F_{dev} \cdot F_{pop} \cdot a_{L\%} \cdot (1 - M) \cdot \Delta P}$$

where $a_{L\%}$ was defined in section 6.3, F_{dev}, F_{pd} and M are the factors described in Tables 6.3.1, 6.4.1 and 6.5.1, and ΔP represents the change in population density, as a percentage[4].

The change in hazard level is directly proportional to the frequency change and can be classified qualitatively as indicated in Table 6.6.1.

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[4] Since the area of the region is considered unchanging, the change in population density (as a percentage) is equivalent to the change in population (as a percentage).

Table 6.6.1 Change in hazard level of human-induced landslides

Frequency change in human-induced landslides	Increase in hazard level
≤ 0.0	None – hazard level reduced
(0.0 – 0.01]	Very low
(0.01 – 0.05]	Low
(0.05 – 0.10]	Moderate
> 0.10	Significant

6.7 APPLICATION OF METHODOLOGY, NORWAY

- *Landslide characteristics*

According to the Geological Survey of Norway (NGU, 2008) database 380 clay and 950 earth slides dating back to the 12th Century have been reported in Norway by Astor Furseth. When possible, the cause of the slides have been deduced according to the descriptions of the events, otherwise they were labeled as 'unknown' (see section 2.1 of this report). However, 603 of the 1330 slides were categorized as 'unknown', which is over 45% of the events in the database. Therefore, in an effort to determine the total fraction of human-induced slides, it is preferable to consult regional experts.

In Section 3.1 of this report, questionnaires concerning human-induced landslides were created and sent out to leading geoscientists and geotechnical engineers across Norway. The questionnaires defined slide-inducing human intervention as:

- cut-and-fills along railways, highways and secondary roads;
- engineered slopes and embankments; and
- large portions of natural terrain altered by human activity (e.g. forested areas removed for new developments).

The combined and averaged results indicated that approximately 73% of the clay (including quick clay) slides that occur in Norway are thought to be triggered by these human activities, as well as 16% of earth slides, 11% of debris slides and 8% of rock slides. Thus, $F_C = 0.73$, $F_E = 0.16$, $F_D = 0.11$, and $F_R = 0.08$. From the NGU data, the percentage of slides categorized as clay is computed as 380 over 1330, i.e. $C = 0.29$, similarly $E = 950/1330 = 0.71$, $D = 0$ and $R = 0$.

Furthermore, the experts questioned estimated that a 50% increase in the exposed Norwegian population, with no major changes in geotechnical regulations, would increase the frequency of human-induced landslides by 18%. Although this prediction will not be input into the model, the results will be compared with it.

- *Population and development factors*

Norway has a population of approximately 4,635,000 spread over an area of 324,220km^2, thus its population density is just over 14 people/km^2 and the resulting value of F_{pop} is 1.10. Its GDP per capita is approximately 79 000 USD (IMF, 2010), hence F_{dev} = 1.00.

- *Final model*

Imagine that over the next *x* years the population of Norway is expected to increase by 50%[5]. If the incoming population does not include a substantial number of geotechnical researchers (i.e. M = 0.10), this situation would result in the following increase in human-induced landslide frequency:

$$\Delta f = F_{dev} \cdot F_{pop} \cdot a_{L\%} \cdot \left[(1-M)\Delta P\right]$$

$$\Delta f = F_{dev} \cdot F_{pop} \cdot (F_C C + F_E E + F_D D + F_R R) \cdot \left[(1-M)\Delta P\right]$$

$$\Delta f = 1.00 \cdot 1.10 \cdot \left(0.73(0.29) + 0.16(0.71) + 0.11(0) + 0.08(0)\right) \cdot \left[(1-0.10) \cdot 0.50\right]$$

$$\Delta f = 0.16 = 16\%$$

However, if the incoming population does include a notable number of geotechnical researchers (i.e. M = 0.35) the increase in landslide frequency would be reduced to:

$$\Delta f = 1.00 \cdot 1.10 \cdot \left(0.73(0.29) + 0.16(0.71) + 0.11(0) + 0.08(0)\right) \cdot \left[(1-0.35) \cdot 0.50\right]$$

$$\Delta f = 0.12 = 12\%$$

This model estimates that the landslide frequency will increase by between 12 and 16% if the exposed Norwegian population increases by 50%, again with no major changes in geotechnical regulations. This corresponds very well to the Norwegian expert predictions of 18%.

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[5] By assuming that the population increases uniformly, a 50% increase in the total population also implies a 50% increase in the exposed population, which is the parameter addressed by the experts.

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Appendix A – Sample questionnaires submitted to landslide experts for assessment of impact of human activities on landslide hazard

CONTENTS

A1. QUESTIONNAIRE IN NORWAY

Your name:

Your position:

Number of years experience with landslides:

Question 1: What percentage of major landslides in your country are triggered directly because human activity? (Please only fill in the rows for which you have personal experience. You could either check the appropriate box, or write a number in the appropriate box)

Main material type involved in sliding event	Range based on your experience / expert judgment			
	0 - 10%	10 - 25%	25 - 50%	> 50%
Quick clay				
Clay (other than quick clay)				
Silt and sand				
Mixed debris				
Rock				

Question 2: What percentage of major landslides in your country are triggered by human activity combined with natural factors (like heavy rainfall)? (The cases here do NOT include the cases in Question 1. The same instructions as in Question 1 also apply to this question)

Main material type involved in sliding event	Range based on your experience / expert judgment			
	0 - 10%	10 - 25%	25 - 50%	> 50%
Quick clay				
Clay (other than quick clay)				
Silt and sand				
Mixed debris				
Rock				

Question 3: How would you categorise the slopes where landslides triggered (fully or partially) by human activity occur in your country? (The sum of all percentages in column 2 should add up to 100%)

Type of slope	**Percent**	**Type of human interference (e.g. change in geometry, change in runoff/drainage, change in vegetation cover, etc.)**
Natural terrain, altered by human activity		
Engineered slopes and embankments		
Cuts and fills along railways		
Cuts and fills along highways		
Cuts and fills along secondary roads		
Other (specify)		

Question 4: If the population density in a landslide-prone area of your country increases by 50%, what change do you expect in the frequency of landslides triggered (fully or partially) by human activity?

Please check one box only.

☐ No increase or reduction because of more attention and better engineering
☐ 0 – 10%
☐ 10 – 25%
☐ 25 – 50%
☐ 50 – 100%
☐ > 100%

Comments:

A2. QUESTIONNAIRE IN SWITZERLAND

Your name:

Your position:

Number of years experience with landslides:

Question 1: What percentage of major landslides in your country are triggered directly because human activity? (Please only fill in the rows for which you have personal experience. You could either check the appropriate box, or write a number in the appropriate box)

Main material type involved in sliding event	**Range based on your experience / expert judgment**			
	0 - 10%	**10 - 25%**	**25 - 50%**	**> 50%**
Organic soils				
Flysch (marly limestone)				
Moraine				
Colluvium				
Fluviatile deposit				
Lacustrine deposit				
Gypsum and Anhydryite				
Hard Rock				

Question 2: What percentage of major landslides in your country are triggered by human activity combined with natural factors (like heavy rainfall)? (The cases here do NOT include the cases in Question 1. The same instructions as in Question 1 also apply to this question)

Main material type involved in sliding event	**Range based on your experience / expert judgment**			
	0 - 10%	**10 - 25%**	**25 - 50%**	**> 50%**
Organic soils				
Flysch (marly limestone)				
Moraine				
Colluvium				
Fluviatile deposit				
Lacustrine deposit				
Gypsum and Anhydryite				
Hard Rock				

Question 3: How would you categorise the slopes where landslides triggered (fully or partially) by human activity occur in your country? (The sum of all percentages in column 2 should add up to 100%)

Type of slope	Percent	Type of human interference (e.g. change in geometry, change in runoff/drainage, change in vegetation cover, etc.)
Engineered slopes and embankments		
Cuts and fills along railways		
Cuts and fills along highways		
Cuts and fills along secondary roads		
Modification of pore pressure		
Other (specify)		

Question 4: If the population density in a landslide-prone area of your country increases by 50%, what change do you expect in the frequency of landslides triggered (fully or partially) by human activity?

Please check one box only.

- ☐ No increase or reduction because of more attention and better engineering
- ☐ 0 – 10%
- ☐ 10 – 25%
- ☐ 25 – 50%
- ☐ 50 – 100%
- ☐ > 100%

Comments: