GISSIZ

Geographic Information Systems in Slope Instability Zonation

Part 1: Theory. Version 2

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INTRODUCTION

The occurrence of Natural Hazards is a serious constraint on economic development, particularly in developing countries, where the economic loss due to the impact of natural hazards often makes the difference between economic growth and stagnation (Fournier d'Albe,1976; Swiss Reinsurance Company, 1990). On the other hand practice has shown that adequate hazard mitigation is possible. The successful earthquake mitigation in the western United States in comparison to the earthquake in Armenia (1988), which had a comparable magnitude, is a striking example. Also successful examples of mitigation exist for other types of natural hazards (hurricane Andrew, Pinatubo volcano, etc.).

Slope instability hazard zonation is defined as the mapping of areas with an equal probability of occurrence of landslides within a specified period of time (Varnes, 1984). A landslide hazard zonation consists of two different aspects:

- the assessment of the susceptibility of the terrain for a slope failure, in which the susceptibility of the terrain for a hazardous process expresses the likelihood that such a phenomenon occurs under the given terrain conditions or parameters.
- the determination of the probability that a triggering event occurs.

The probability for the occurrence of a landslide is mostly evaluated by calculating the probability of triggering events, as based on rainfall intensity / duration frequency data or the recurrence of major earthquakes. It is important to mention here that the calculation of landslide probability is more difficult than for some other natural disasters (such as floods or earthquakes) since there is no simple relation between the magnitude of a landslide event and a return period. Another complicating factor is that mostly there are no reliable historic records of landslides that allow for the modelling of the relation between landslide and rainfall or earthquakes.

An area is declared to be susceptible for landslides, when the terrain conditions at that site are comparable to those in an area where a slide has occurred. The instability of a slope is governed by a complex of normally interrelated terrain parameters, such as: lithology and the structural conditions of the rocks, the weathering and the contact with overlying soils, the physical properties of these soils, slope gradient and form, hydrological conditions, vegetation, land use and land use practice and finally human activities acting on the slope conditions.

The joint analysis of all these terrain variables in relation to the spatial distribution of landslides, has gained enormously by the introduction of **Geographic Information Systems** (GIS), the ideal tool for the analysis of parameters with a high degree of spatial variability.

Considering that for a slope instability hazard assessment the assumption is made that conditions which led in the past to slope failures, will also result in potential unstable conditions in the present, defines automatically the essential steps to be followed in a landslide susceptibility zoning. These essential steps in a slope instability hazard zoning are:

- a **landslide distribution mapping**, differentiating according type, activity, dimensions, etc. and based on information covering when possible a time span as large as possible,
- a **parameter mapping**, giving the spatial distribution of the most relevant terrain parameters related to the occurrence of landslides,
- the **determination of the causative factors** based on the analysis of the terrain conditions in relation to the occurrence of the different types of landslides, and
- the **assignment of weights to the individual causative factors** to enable the formulation of decision rules and the designation of slope instability susceptibility classes.

The first chapter deals with some methodological aspects of slope instability hazard zonation. Attention is paid to the essential role of the earth scientist in modelling the spatial distribution of the terrain conditions leading to instability. A scheme is given for a hierarchical approach in slope instability zonation, similar to the phases recognized in engineering projects. In a system analysis the necessary steps to come to a hazard assessment are defined, considering direct and indirect mapping techniques. An overview of current practices is given.

The second chapter gives the guidelines for a landslide classification. After a review of the most used existing classifications, a detailed description for a landslide classification is given, which is followed in this text.

The third chapter emphasizes the application of remote sensing techniques to landslide studies and hazard zonation. An evaluation is made on the applicability of different remote sensing data, considering spatial, spectral and temporal resolution.

The fourth chapter deals with the interpretation of landslides mainly from aerial photographs. Following the used classification system, a systematic guide for the recognition and interpretation of slope movements is given.

The capabilities of geographical information systems in the analysis of the terrain factors leading to slope instability are the leading topic of the second part of these notes. In chapter 5 an introduction is given to terrain classification, a methodology used in GIS supported landslide hazard zoning at reconnaissance as the spatial unit for terrain attributes.

The next chapter highlights field data collection and use of systemized field observation that are necessary to enable the data analysis in GIS. Chapter seven deals with the entering of data in GIS and the data structuring.

The last chapter emphasizes the methodologies used for data analysis in GIS at different scale levels of landslide hazard zonation. Qualitative and expert based methodologies are reviewed, as well as bivariate and multivariate statistical data analysis methodologies. Deterministic approaches in GIS, used in large scale surveys, are treated as well. Finally due attention is paid to errors and certainty in the GIS data analysis.

CHAPTER 1

Principles of landslide hazard zonation

Slope instability processes are the product of the local geomorphological, hydrological and geological conditions, the modification of these conditions induced by geodynamic processes and human activity, the vegetation and land use practices and the frequency and intensity of the precipitation and seismicity.

The **engineering approach** in landslide studies focused the attention on the analysis of individual slopes. Deterministic modelling of the physical slope parameters (c, φ, α, u, etc.) lead to a stability analysis and the necessary or adequate remedial measures. The techniques in these studies were in accordance with the required large study scale. The high degree of spatial variability of the physical slope parameters and the difficulty to estimate their value makes that these methods not appropriate for the slope instability assessment of extensive areas. The need for this type of zonation increased with the understanding that a proper planning would decrease considerably the costs of the construction and maintenance of engineering structures. This has lead to the developments of a **geomorphological approach** in landslide hazard studies, whereby judgements on the stability of slopes are based on a heuristic or statistical supported analysis of the geological and geomorphological terrain factors, which are governing the occurrence of landslides.

Considering the many terrain factors involved in slope instability, the practice of landslide hazard zonation asks for:

- a detailed *inventory of slope instability processes*
- the study of these processes in relation to their *environmental setting*
- the analysis of the *conditioning and triggering factors*, and
- the representation of the *spatial distribution* of these factors.

Hazard, vulnerability and risk

In relation to the terminology used, reference is made to Varnes (1984), who gives in his UNESCO publication on landslide hazard zonation the following definitions:

– *natural hazard* means the probability of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon

– *risk* means the expected number of lives lost, persons injured, damage to property or disruption of economic activity due to a particular natural phenomenon

Figure 1: Schematic indication of hazard, vulnerability of the elements at risk, and risk.

To enable the determination of the risk, Varnes gives also the following definitions:

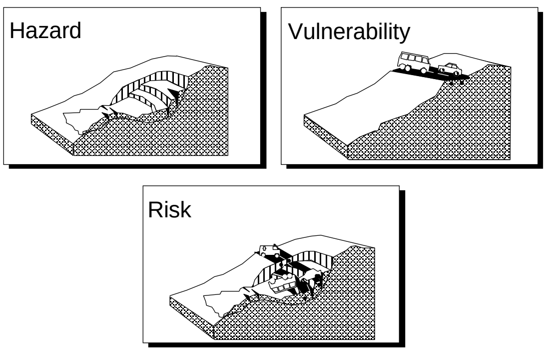
– *vulnerability* means the degree of loss to a given element (or set of elements) at risk, resulting from the occurrence of a natural phenomenon of a given magnitude

– *element at risk* means the population, properties, economic activities, etc. at risk in a given area

specific risk means the expected degree of loss due to a particular natural phenomenon.

Landslide hazard is commonly shown on maps, which display the spatial distribution of hazard classes (landslide hazard zonation). *Zonation* refers to "the division of the land in 'homogeneous' areas or domains and their ranking according to degrees of actual/potential hazard caused by mass movement" (Varnes, 1984). Landslide hazard zonation requires a detailed knowledge of the processes that are or have been active in an area, and on the factors leading to the occurrence of the potentially damaging phenomenon. This is considered the task of earth scientists. Vulnerability analysis requires detailed knowledge of the population density, infrastructure, and economic activities and the effects of a specific damaging phenomenon on these elements at risk. Therefore, this part of the analysis is done mainly by persons from other disciplines, such as specialists in urban planning, social geography, economics and engineers.

Fully worked out examples of risk analysis on a quantitative basis are still scarce in the literature (Einstein, 1988; Kienholz, 1992; Innocenti, 1992), because of the difficulties in defining quantitatively both hazard and vulnerability. Hazard analysis is seldom executed in accordance with the definition given above, since the probability of occurrence of potentially damaging phenomena is extremely difficult to determine for larger areas. The determination of actual probabilities requires analysis of triggering factors, such as earthquakes or rainfall, or the application of complex models. In most cases, however, there is no clear relationship between these factors and the occurrence of landslides. Therefore, the legend classes used in most hazard maps do not give more information than the susceptibility that a landslide will occur or relative indications on the degree of hazard, such as high, medium, and low hazard. It is considered that susceptibility is expressing the likelihood of a phenomenon to occur in an area on the bases of the local terrain conditions and not considering the probability of occurrence, which depends also on the recurrence of triggering factors (rainfall, seismicity). However, it has to be observed, that the terms hazard and susceptibility are frequently used as synonymous.



In this text only the techniques for the recognition and the analysis of landslides and methods for the *hazard assessment* are treated.

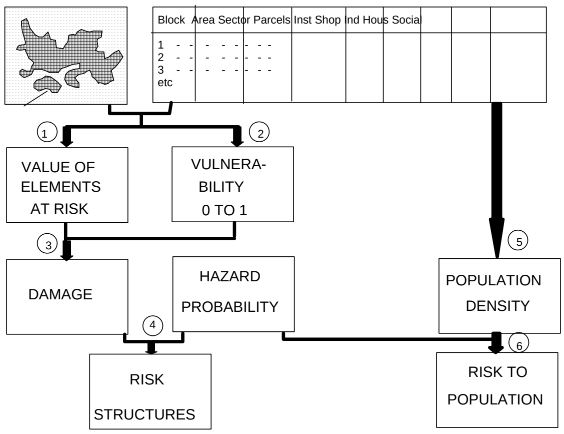


Figure 2: Schematic drawing of landslide risk analysis with GIS. Basis is a map with information per city block. 1: elements at risk, derived from the cadastral data base. 2: vulnerability analysis of the elements at risk. 3: Combination of the elements at risk , their vulnerability and the price gives us the potential damage. 4: Combination of potential damage and hazard probability gives the risk to structures. 5. Population density can be calculated also from the cadastral database. 6: this will give us the risk to population.

Hazard zonation, general considerations

An ideal map of slope instability hazard should provide information on the spatial probability, temporal probability, type, magnitude, velocity, runout distance, and retrogression limit of the mass movements predicted in a certain area (Hartlen and Viberg, 1988). The availability of a reliable landslide inventory giving the type, the activity, as well as the spatial distribution of mass movement, is essential to come to an analysis of the occurrence of landslides in relation to the environmental conditions. The differentiation of the slope instability according to the type of movement is important, not only because under different terrain conditions also different types of mass movement will occur, but also because the impact of slope failures on the environment has to be evaluated according to the type of failure.

Prediction of hazard in areas presently free of landslides is based on the assumption that hazardous phenomena that have occurred in the past can provide useful information for the prediction of occurrences in the future. Therefore, *mapping* these phenomena and the factors thought to be of influence is very important in hazard zonation. In relation to the analysis of the terrain conditions leading to slope instability, basically two philosophies can be recognised:

(1) The first mapping methodology is the experience driven applied geomorphological approach, where the earth scientist evaluates the direct relationship between the landslides and the geomorphological and geological setting during the survey at the site of the failure. This type of working is also known as the *direct mapping methodology*.

(2) The opponent of this experience based or heuristic approach, is the *indirect mapping methodology*, which consists of the mapping of a large amount of parameters and the (statistical) analysis of all these possible contributing factors in relation to the occurrence of slope instability phenomena, determining in this way the relation between the terrain conditions and the occurrence of landslides. Based on the results of this analysis statements are made regarding the conditions under which slope failures occur.

Another useful division in techniques for assessment of slope instability hazard is given by Hartlen and Viberg (1988), who differentiate between *relative hazard* and *absolute hazard assessment techniques*. The relative hazard assessment techniques differentiate the likelihood of occurrence of mass movements for different areas on the map, without giving exact values. Absolute hazard maps display an absolute value for the hazard, such as a factor of safety or a probability of occurrence.

Hazard assessment techniques can be divided into three main groups (Carrara, 1983; Hartle n and Viberg, 1988):

(1) *White box models*, based on physical models (slope stability and hydrological models), also referred to as *deterministic models*;

(2) *Black box models*, not based on physical models but on statistical analysis;

(3) *Grey box models*, based partly on physical models and partly on statistics.

Scale related objectives

The development of a clear hierarchical methodology in hazard zonation is a necessary condition to obtain an acceptable cost/benefit ratio and to ensure its practical applicability. The working scale for a slope instability analysis is determined by the requirements of the user for whom the survey is executed. Considering that planners and engineers are forming the most important users community, the following scales of analysis, which were presented to the International Association of Engineering Geologists (IAEG; 1976) have been differentiated for landslide hazard zonation:

– National scale (< 1:1.000.000)
– Regional scale (1:100,000 - 1:500.000)
– Medium scale (1:25,000 - 1:50,000)
– Large scale (1:5,000 - 1:15,000)

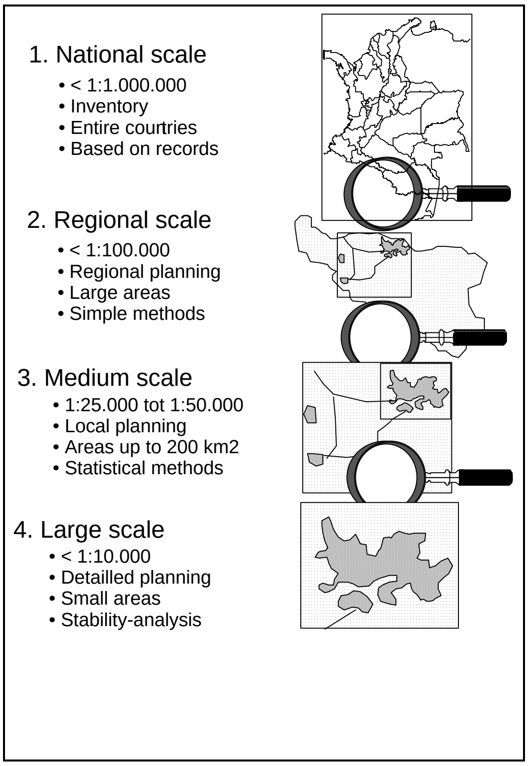


Figure 3: Scale of landslide hazard zonation, oibjectives and general approaches.

The national scale intends to give a general inventory of problem areas for an entire country, which can be used to inform national policy makers and the general public. The detail will be low, as the assessment is mostly done on the basis of general applicable rules.

The regional mapping scale is meant for planners in the early phases of regional development projects or engineers, when evaluating possible constraints, due to instability, in the development of large engineering projects and regional development plans. The areas to be investigated are large, in the order of 1000 square kilometres or more, and the required detail of the map is low. The map indicates areas where mass movements can be a constraint on the development of rural, urban or infrastructural projects. Terrain units with an areal extent of several tenth of hectares are outlined and classified according to their susceptibility for occurrence of mass movements.

Medium scale hazard maps can be used for the determination of hazard zones in areas affected by large engineering structures, roads and urbanization plans. The areas to be investigated will have an extend of a few hundreds of square kilometres and a considerable higher detail is required at this scale. The detail should be such that adjacent slopes in the same lithology are evaluated separately and may obtain different hazard scores, depending on characteristics, such as slope angle or form and type of land use. Within the same terrain unit distinctions should be made between different slope segments. For example a concave slope should receive a different rating than an adjacent straight or convex slope, when appropriate.

Large scale hazard zonation can be used at the level of site investigations previous to the design phase of engineering works. This scale is also meant to evaluate the variability of a safety factor as function of variable slope conditions or under influence of triggering factors, such as rainfall and seismicity. The size of area under study is in the order of several tenths of square kilometres and the hazard classes on such maps should be absolute, indicating the probability of failure for each grid cell or mapping unit, with areas down to one hectare or less.

Although the selection of the scale of analysis is usually determined by the intended application of the mapping results, the choice of a mapping technique remains open. This choice depends on the type of problem, the availability of data, the availability of financial resources, the time available for the investigation, as well as the professional experience of the experts involved in the survey.

Input data for landslide hazard zonation

Slope instability phenomena are related to a large variety of factors, involving both the physical environment as well as human interaction. Assessment of landslide hazard therefore requires knowledge about a large series of factors, ranging from geological structure to land use. For this reason, projects to assess landslide hazard must be multidisciplinary.

A list of the various input data needed to assess landslide hazard at the regional, medium, and large scale is given in table 1. The list is extensive, and only in an ideal case all types of data will be available. However, as will be explained in section 8.2.4, the amount and type of data that can be collected determine the type of hazard analysis that can be applied, ranging from qualitative assessment to complex statistical methods.

The input data needed to analyze landslide hazard can be subdivided into five main groups: geomorphological, topographic, engineering geological or geotechnical, land use, and hydrological data. For each group a subdivision is made into so-called *data layers*, an individual map, containing one type of data, composed of one type of element (point, lines, areas/polygons), and having one or more accompanying tables. Of course, the layers that have to be taken into account vary for different environments.

The second column in table 1 indicates the various parameters, stored in tables connected to each map. The third column of table 1 gives a summary of the method by which each data layer is collected, referring to the three phases of data collection (image interpretation, fieldwork, and laboratory analysis). A number of data layers, such as the material sequences, the seismic acceleration maps, and the watertable maps, require the use of specific models in addition to the conventional data collection techniques. Also for the various topographic maps, specific algorithms within a Geographic Information System (GIS) are required (see section 8.4).

The last three columns in table 1 give an indication of the relative feasibility that a certain data type can be collected at each of the three scales under consideration. The feasibility for collecting data at a certain scale does not imply that the specific type of data is also useful at that particular scale. A map of Terrain Mapping Units, for example, can be prepared at a 1:10.000 scale, but will be of very limited use, due to its generalized content.

Due to the large areas to be studied at the regional scale and because of the objectives of a hazard assessment at this scale (see 8.2.2), detailed data collection for individual factors (geomorphology, lithology, soils, etc.) is not a cost effective approach. Data gathered at this scale is limited to the delineation of homogeneous terrain mapping units, with the use of stereoscopic satellite imagery, and the collection of regional tectonic or seismic data.

At the medium scale almost all data layers given in table 1 can be gathered, with the exception of detailed groundwater and geotechnical information. The data collection at this scale is focused on the detailed multitemporal landslide distribution maps and the various parameters required in statistical analysis.

At the large scale, working in relative small areas, all of the proposed data layers can be collected. Data collection at this scale is related to the parameters (material sequences, seismic accelerations, watertable data) needed for slope stability modelling.

	Data layers for slope instability hazard zonation	Accompanying data in tables	Made by the use of	Scale of analysis		
				Regional	Medium	Large
GEOMOR PHOLOGY	1. Terrain Mapping Units	Terrain Mapping Units	SII + walk over survey	3	3	3
	2. Geomorphological (sub)units	Geomorphological description	API + fieldwork	2	3	3
	3. Landslides (recent)	Type, activity, depth, dimension etc.	API + API-checklist + fieldwork + field checklist	1	3	3
	4. Landslides (older period)	Type, activity, depth, dimension, date, etc.	API + API-checklist + landslide archives	1	3	3
TOPOGRAPHY	5. Digital Terrain Model	Altitude classes	With GIS from topographic map	2	3	3
	6. Slope map	Slope angle classes	With GIS from DTM	2	3	3
	7. Slope direction map	Slope direction classes	With GIS from DTM	2	3	3
	8. Slope length	Slope length classes	With GIS from DTM	2	3	3
	9. Concavities/convexities	Concavity/convexity	With GIS from DTM	1	1	3
ENGINEERING	10. Lithologies	Lithology, rockstrength, discontinuity spacing	Existing maps + API + fieldwork, field & laboratory testing	2	3	3
GEOLOGY	11. Material sequences	Material types, depth, USCS-classification, grainsize distribution, bulkdensity, c and φ	Modelling from lithological map + geomorphological map + slope map, field descriptions, field & laboratory testing	1	2	3
	12. Structural geological map	Fault type, length, dip, dip direction, fold axis etc.	SII + API + fieldwork	3	3	3
	13. Seismic accelerations	Maximum seismic acceleration	Seismic data + engineering geological data + modelling	3	3	3
LANDUSE	14. Infrastructure (recent)	Road types, railway lines, urban extension etc.	API + topographical map + fieldwork + classification of satellite imagery	3	3	3
	15. Infrastructure (older)	Road types, railway lines, urban extension etc.	API + topographical map	3	3	3
	16. Landuse map (recent)	Landuse types, tree density, root depth	API + classification of satellite imagery + fieldwork	2	3	3
	17. Landuse map (older)	Landuse types	API	2	3	3
HYDROLOGY	18. Drainage	Type, order, length	API + topographical maps	3	3	3
	19. Catchment areas	Order, size	API + topomaps	2	3	3
	20. Rainfall	Rainfall in time	From meteorological stations	2	3	3
	21. Temperature	Temperature in time	From meteorological stations	2	3	3
	22. Evapotranspiration	Evapotranspiration in time	From meteorological stations and modelling	2	3	3
	23. Watertable maps	Depth of watertable in time	Field measurements of K_{sat} + hydrological model	1	1	2

Table 1: Overview of input maps for landslide hazard analysis. The last three columns give the possibility for data collection at three scales of analysis: 3 = good, 2 = moderate and 1 = poor. Abbreviations used: SII = satellite image interpretation, API = Aerial photo-interpretation, DTM = Digital Terrain Model, GIS = Geographic Information System, K_{sat} = saturated conductivity testing.

General trends in landslide hazard zonation

A large amount of research on slope instability hazard has been done over the last thirty years. Initially the investigations were mainly oriented to the solving of instability problems on the site and techniques were developed by the engineers to come to an appropriate design of a planned structure, preventing a slope failure. Research emphasized therefore site investigation techniques and the development of deterministic and probabilistic models. However, the large variability in the geotechnical properties such as c and φ, the heterogeneity of the natural environment at regional scale in comparison to the homogeneity required in deterministic models and the costly and time consuming site investigation techniques, makes the engineering approach unsuitable to be applied with an acceptable cost/benefit ratio over larger areas, in early phases of planning and decision taking in engineering projects.

In order to solve this problem and considering that a hazard assessment has to be based on a careful study of the natural conditions of an area and the analysis of all the possible parameters involved in slope instability processes, several other types of landslide hazard analysis techniques have been developed over the last decades.

In the following sections the various methodological approaches, reviewed in excellent publications as those of Hansen (1984) and Varnes (1984), are summarized and illustrated with some examples.

Landslide inventory

The most straightforward approach to landslide hazard zonation is a *landslide inventory*, based on aerial photo interpretation, ground survey, and/or a data base of historical occurrences of landslides in an area. The final product gives the spatial distribution of mass movements, represented either at scale or as points (Wieczorek, 1984). Mass movement inventory maps are the basis for most of the other landslide hazard zonation techniques. They can, however, also be used as an elementary form of hazard map, because they display where in an area a particular type of slope movement has occurred. They provide information only for the period shortly preceding the date the aerial photos were taken or the fieldwork was conducted. They provide no insight into the temporal changes in mass movement distribution. Many landslides that occurred some time before the photographs were taken may have become undetectable. Therefore a refinement is the construction of *landslide activity maps*, based on multi-temporal aerial photo interpretation (Canutti et al., 1979). To study the effects of the temporal variation of a factor such as land use, landslide activity maps are indispensable.

Landslide distribution can also be shown in the form of a *density map*. Wright et al. (1974) presented a method to calculate landslide densities using counting circles. The resulting density values are interpolated and presented by means of *landslide isopleths*. Although the method does not investigate the relationship between mass movements and causal factors, it is useful in presenting landslide densities quantitatively.

Heuristic approach

In *heuristic methods* the expert opinion of the geomorphologist, making the survey, is used to classify the hazard. The mapping of mass movements and their geomorphological setting is the main input factor for hazard determination. Two types of heuristic analysis can be distinguished:

(1) *Geomorphological analysis*. The basis for this approach was outlined by Kienholz (1977), who developed a method to produce a combined hazard map based on the mapping of "silent witnesses (Stumme Zeugen)". The geomorphological method is also known as the direct mapping method. The hazard is determined directly in the field by the geomorphologist. The process is based on his experience and he is using a reasoning of analogy. The decision rules are therefore difficult to formulate, as they vary from place to place. Examples of this methodology for the appraisal of the susceptibility of the terrain for slope instability are coming especially from Europe, where ample experience exists in geomorphological and engineering geological mapping (Carrara and Merenda,1974; Malgot and Mahr, 1979; Kienholz, 1977, 1978; Kienholz et al., 1983, 1988; Ives and Messerli, 1981; Rupke et al., 1988 and many others, see also Varnes, 1984 and Hansen, 1984). The French programme of the 1:25.000 ZERMOS maps (Meneroud and Calvino, 1976) is in this respect the best example, but the reproducibility of the maps is much debated (Antoine, 1977). The same is true for the method used by Brunsden and his collaborators (Brunsden et al, 1975), who are even not giving a hazard zonation in a project related with a road alignment. They are projecting directly the alignment for the best possible road according their assessment for the stability of the slopes.

(2) To overcome the problem of the "hidden rules" in geomorphological mapping, other qualitative methods have been developed based on *qualitative map combination*. In a qualitative map combination, the earth scientist uses his expert knowledge to assign weight values to series of parameter maps. The terrain conditions are summated according to these weights, leading to hazard values, which can be grouped into hazard classes. Stevenson (1977) developed an empirical hazard rating system for an area in Tasmania. On the basis of his expert knowledge on the causal factors of slope instability, he assigned weighting values to different classes in a number of parameter maps. This method of qualitative map combination has become very popular in slope instability zonation. The problem with this method is that the exact weighting of the various parameter maps is often based on insufficient field knowledge of the important factors, which will lead to unacceptable generalizations.

Statistical approach

In statistical landslide hazard analysis, the combinations of factors that have led to landslides in the past, are determined statistically and quantitative predictions are made for landslide free areas with similar conditions. Two different statistical approaches are used in landslide hazard analysis:

(1) *Bivariate statistical analysis.* In this method, each factor map (slope, geology, land use etc.) is combined with the landslide distribution map, and weight values, based on landslide densities, are calculated for each parameter class (slope class, lithological unit, land use type, etc). The first example of such an analysis was given by Brabb et al. (1972), who performed a simple combination of a landslide distribution map with a lithological map and a slope map. Several statistical methods can be applied to calculate weight values, such as *landslide susceptibility* (Brabb, 1984; Van Westen, 1993), the *information value method* (Yin and Yan, 1988; Kobashi and Suzuki, 1988), *weights of evidence modelling* (Spiegelhalter, 1986), *Bayesian combination rules, certainty factors, Dempster-Shafer method* and *fuzzy logic* (Chung and Fabbri, 1993).

(2) The use of *multivariate statistical* models for landslide hazard zonation has mainly been developed in Italy by Carrara (1983, 1988) and his colleagues (Carrara et al, 1990, 1991, 1992). In their applications, all relevant factors are sampled either on a large grid basis, or in morphometric units. For each of the sampling units also the presence or absence of landslides is determined. The resulting matrix is then analyzed using multiple regression or discriminant analysis. With these techniques, good results can be expected in homogeneous zones or areas with a small variation in typology of slope instability processes, as shown in the work of Jones et al. (1961) on mass movements in terrace deposits. When applying complex statistics, as done by Carrara and his collaborators, Neuland (1976) or Kobashi and Suzuki (1988), a subdivision according to the type of landslide should be made as well, and therefore, large data sets are needed to obtain reliable results. This implies that the use of complex statistics asks for a laborious effort in collecting large amounts of data, without making use of selective criteria based on professional experience.

Deterministic approach

Despite problems related to collection of sufficient and reliable input data, deterministic models are increasingly used in hazard analysis over larger areas, especially with the aid of geographic information systems, which can handle the large amount of calculations involved when calculating safety factors over large areas. The methods are applicable only when the geomorphological and geological conditions are fairly homogeneous over the entire study area and the landslide types are simple. The advantage of these "white box models" is that they are based on slope stability models, allowing the calculation of quantitative values of stability (safety factors). The main problem with these method is the high degree of oversimplification. This method is usually applied for translational landslides using the infinite slope model (Ward et al., 1982). The methods generally require the use of groundwater simulation models (Okimura and Kawatani, 1986). Stochastic methods are sometimes used for selection of input parameters (Mulder and van Asch, 1988; Mulder, 1991; Hammond et al., 1992).

Not all methods for landslide hazard zonation are equally applicable at each scale of analysis, given in 8.2.2. Some require very detailed input data, which can only be collected for small areas at the expense of a lot of efforts and costs (see 8.2.3). Therefore a selection has to be made of the most useful types of analysis for each of the mapping scales, maintaining an adequate cost / benefit ratio. Table 2 gives an overview of the methods for landslide hazard analysis and recommendations for their use at the three most relevant scales.

Evaluating the methodological approaches (table 2) and the literature on slope instability hazard zonation practices, it appears that the applied geomorphological or direct mapping methods intends to establish, based on a scientific and professional oriented reasoning, the real causes for slope instability. However, considering the scale of slope failures and the complexity of the causes which are leading to slope instability, the direct mapping methods have to be executed on large scales and therefore a practical hierarchical set up is difficult to implement. The combination of a geomorphological analysis and the application of weights to the contributing parameters, as used for example by Kienholz (1977, 1978), improves the objectivity and reproducibility. This is particularly the case when the weights are based on the degree of contribution of the parameter to slope instability, established by simple statistics.

Type of analysis	Techniques	Characteristics	Required data from table 1	Regional 1:100,000	Medium 25.000	Large 10.000
Inventory	Landslide distribution analysis	Analyze distribution and classification of landslides	3	Yes, but... **(*)**	Yes	Yes
	Landslide activity analysis	Analyze temporal changes in landslide pattern	4,5,14,15,16,17	No	Yes	Yes
	Landslide density analysis	Calculate landslide density in terrain units or as isopleth map	1,2,3	Yes, but... **(*)**	No	No
Heuristic analysis	Geomorphological analysis	Use in-field expert opinion in zonation	2,3,4	Yes	Yes, but... **(**)**	Yes, but... **(**)**
	Qualitative map combination	Use expert-based weight values of parameter maps	2,3,5,6,7,8,9,1012,14,16,18	Yes, but... **(***)**	Yes, but... **(**)**	No
Statistical analysis	Bivariate statistical analysis	Calculate importance of contributing factor combination	2,3,5,6,7,8,9,1012,14,16,18	No	Yes	No
	Multivariate statistical analysis	Calculate prediction formula from data matrix	2,3,5,6,7,8,9,1012,14,16,18	No	Yes	No
Deterministic analysis	Safety factor analysis	Apply hydrological and slope stability models	6,11,12,13,16, 20,21,22,23	NO	No	Yes, but... **(****)**

Table 2: Analysis techniques in relation to mapping scales. The numbers in the fourth column refer to the input data, given in table 1. Meaning of the symbols: ***(*)*** *only with reliable data on landslide distribution, as mapping will be out of an acceptable cost/benefit ratio,* ***(**)*** *strongly supported by other more quantitative techniques, to obtain an acceptable level of objectivity,* ***(***)*** *only if sufficient reliable data exist on the spatial distribution of the landslide controlling factors,* ***(****)*** *only under homogeneous terrain conditions, considering the variability of the geotechnical parameters.*

Actual developments are looking for a combination of the indirect mapping methods with more analytical approaches. Working at small scales (1:50.000 - 100.000) a terrain classification may be made using stereo satellite imagery, defining homogeneous lithomorphological zones. The terrain mapping units are submitted to a general analysis based on photo-interpretation and a walk-over survey. Selected relevant parameters, based on an analysis of the slope instability in the area, are then used in the definition of the hazardness and extrapolated to the terrain mapping units according to the presence or absence of contributing factors in the attribute data base. The amount of analytical studies are increased at larger scales, when more time and money becomes available. The use of factor maps, displaying the spatial distribution of the most important factors, together with an increase of the analysis of possible contributing parameters, based on statistics, increases the accuracy of the prediction of susceptibility for instability. An adjustment or refinement of the decision rules for the hazard assessment is obtained by a verification of the results of the assessment with the real situation in the field. If necessary weights assigned to parameters are adjusted and a new hazard assessment is produced. This iterative way of working becomes necessary when the decision rules for the hazard assessment are extrapolated over areas with a similar geological/geomorphological setting, but where little ground truth is available, as studies have shown that in areas with apparent equal conditions resulting weight values may vary considerably. In detailed studies, when large amounts of data become available, the use of simple deterministic or probabilistic models to approximate the variability of safety factor for slope failure, are more and more introduced for hazard zonation.

Accuracy and objectivity

The most important question to be asked for each landslide hazard study is related to the degree of accuracy. The terms accuracy and reliability are used to indicate whether the hazard map makes a correct distinction between landslide free and landslide prone areas.

The evaluation of the accuracy of a landslide hazard map is generally very difficult. In reality a hazard prediction can only be verified by observing if failure takes (or has taken) place in time ("wait and see"), but this is not a very useful method, for obvious reasons. One of the most frequently used methods for checking the accuracy of hazard maps is the combination of the final hazard map with the pattern of existing landslides. A frequency distribution is made of the hazard scores of present landslide areas, and non-landslide areas. From the frequency distribution of the hazard scores for the landslide areas the percentage of landslides predicted as stable areas can be calculated. This error is then assumed to be equal for the prediction of the presently landslide-free areas. This method can be refined if multitemporal landslide distribution maps are available. The landslide prediction, based on an older landslide distribution map, can then be checked with a younger landslide distribution (Chung et al, in press). Also the comparison of landslide hazard maps, made by different methods (for example statistical and deterministic methods) may give a good idea of the accuracy of the prediction.

The accuracy of a landslide prediction is depending on a large number of factors, among which the most important ones are:

(1) The accuracy of the models that were used;

(2) The accuracy of the input data;

(3) The experience of the earth scientists involved;

(4) The size of the study area;

Many of these factors are interrelated. The size of the study area determines to a large degree what kind of data can be collected (table 1) at which density, and what kind of analysis technique can be applied (table 2).

Related to the problem of assessing the accuracy of hazard maps is the question of objectivity. The terms objective and subjective are used to indicate whether the various steps taken in the determination of the degree of hazard are verifiable and reproducible by other researchers, or whether they depend upon the personal judgement of the earth scientist in charge of the hazard study.

Objectivity in the assessment of landslide hazard does not necessarily result in an accurate hazard map, for example if a very simple, but verifiable, model was used, or if only a few parameters are taken into account. On the other hand, subjective studies, such as detailed geomorphological slope stability analysis, may result in very accurate hazard maps, when made by experienced geomorphologists. However, such a good, but subjective assessment has a relative value, as the reproducibility will be low. This means that the same evaluation made by another expert will probably yield other results, which can have clearly undesirable legal effects.

The degree of objectivity of a hazard study depends on the techniques used in data collection and the methods used in data analysis. The use of objective analysis techniques, such as statistical analysis or deterministic analysis, may still lead to subjective results, depending on the amount of subjectivity which is required for creating the parameter maps. Studies on the degree of subjectivity, considering the interpretation of large scale photographs (1:10.000) by a group of twelve photo-interpreters, several of them with considerable experience and some with local knowledge, have shown that the differences between interpretations can be large (Dunoyer and van Westen, in press). These findings coincide with similar investigations on the subjectivity of photo-interpretation in slope instability mapping (Fookes et al., 1991; Carrara et al., 1992).

Many of the input maps used in landslide hazard analysis are based on aerial photo-interpretation and will therefore contain a large degree of subjectivity. Also for factors which are obtained by means of precise measurements (such as soil strength) the degree of subjectivity of the resulting parameter maps may be high, as the point-wise data has to be linked with a material map, made by photo-interpretation and fieldwork.

According to the type of data collection and analysis, different levels of objectivity and also of accuracy are corresponding with the hierarchical levels determined for the various scales of hazard analysis. As a result of the demand for a high level of objectivity, several researchers have been replacing the subjective expert's opinion on the causative factors related to slope failure, by the statistical analysis of all the terrain conditions observed in areas with slope failures (Carrara et al.,1978; Neuland, 1976). Although the objectivity of such an approach is guaranteed, doubts may exist on the accuracy of the assessment, certainly considering the experience and skill required in the data collection, when filling in extensive data sheets (figure 1).

In view of the limitations inherent to the data collection and analysis techniques and the restrictions imposed by the scale of mapping, a hazard survey will always retain a certain degree of subjectivity. This does not necessarily imply an inaccuracy. The objectivity and certainly the reproducibility of the assessment can considerably be improved by the interpretation of sequential imagery, the use of clear, if possible, quantitative description of the factors considered, as well as well defined analytical procedures and decision rules, which are applied to come to the hazard assessment. The most important aspect however remains the experience of the interpreter, both with regard to various factors involved in slope instability hazard surveys, as well as in the specific conditions of the study area.

CHAPTER 2

An approach to the classification of slope movements

Introduction

In literature a wide variety of names have been used for the denudational process whereby soil or rock is displaced along the slope by mainly gravitational forces. The most frequent are "mass movement" indicating that a mass of soil or rock is moved or the more neutral term "slope movement", giving an indication where the process is mostly concentrated (liquefaction also can occur in complete flat terrain). However the generic term "**landslide**" is the most used and recent manuals are using it synonymous to all other terms used for slope movements, although landslides in narrow sense of the word (sensu strictu) indicates only a specific type of slope movement.

The term landslide denotes "the movement of a mass of rock, debris or earth down the slope" (Cruden, 1991). In addition to this definition it can be stated that the movement occurs when the shear stress exceeds the shear strength of the material, indicating the mechanism which is inducing the slope movement and therefore differentiating landslide from other mass wasting processes on the interfluves (soil erosion). Although it can be argued that this is a superfluous addition to the definition, it makes clear that the occurrence of slope movements is the consequence of a complex field of forces (stress is a force per unit area) which is active on a mass of rock or soil on the slope. The consequence of these forces in conjunction to the slope morphology and the geotechnical parameters of the material define together the specific type of landslide which might occur. In view of all this and with the objective to adhere as much as possible to existing nomenclature the following definition will be used:

Landslide is defined as the movement of a mass of rock, debris or earth down the slope, when the shear stress exceeds the shear strength of the material.

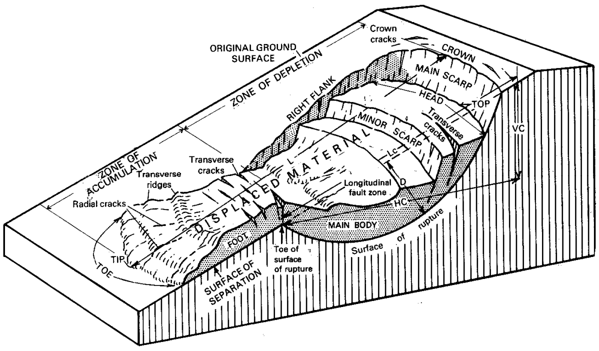


Figure 2.1: Block diagram of idealized complex earth slide-earth flow (Varnes, 1978)

Considering that changes in the (natural) field of forces leads to the occurrence of landslides indicates that the analysis of a possible increase of the shear stress and/or decrease of the shear strength of the material is the clue for the understanding of landslides and the most appropriate remedial.

The factors contributing to an increase of the shear stress are:

- removal of lateral and underlying support (erosion, previous slides, road cuts and quarries)
- increase of load (weight of rain/snow, fills, vegetation)
- increase of lateral pressures (hydraulic pressures, roots, crystallisation, swelling of clay)
- transitory stresses (earthquakes, vibrations of trucks, machinery, blasting)
- regional tilting (geological movements).

Factors related to the decrease of the material strength are:

- decrease of material strength (weathering, change in state of consistency)
- changes in intergranular forces (pore water pressure, solution)
- changes in structure (decrease strength in failure plane, fracturing due to unloading)

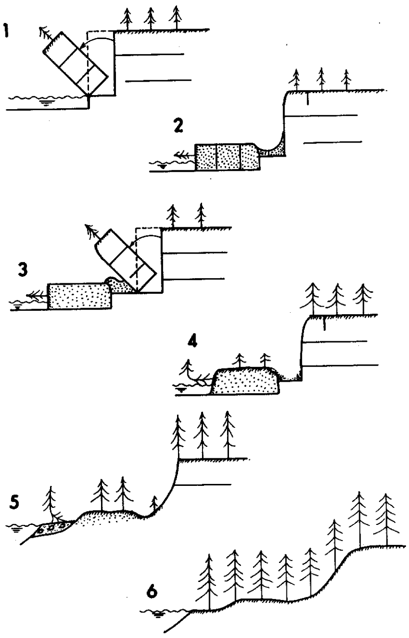


Figure 2.2: Landslide activity classes: 1: active, 2: suspended, 3: reactivated, 4: dormant, 5: stabilized, 6: relict.

Evaluating the factors which can lead to slope movements, it is understandable that the amount of diagnostic parameters, which can be used for classification purposes, is enormous and creating the possibility for a large variety of different approaches to the classification of slope movements. Existing classifications are considering parameters such as: type of movement, material, velocity, morphometric parameters, amount of water involved, velocity, climate, etc. Based on this list it is logical that there have been many classification systems in use. However, the list of really widely used classifications is rapidly decreasing, leaving a few such as the classification of Varnes (1958, 1978) which has also been used in a slightly modified form in the publication of Schuster and Turner (1996). This classification takes type of movement primarily and types of material secondarily. Factors as the velocity, depth, or state of the material (dry or wet) can be added as an adjective to the classification name. Another well known classification is the one presented by Hutchinson (1968, 1988), which heavily lends on type of movement and the morphology, enabling for a classification based only on field observation or the evaluation of landslides on aerial photography. This classification makes also a practical use of the general morphometric criteria as defined by Crozier (1986) and used by this author as primary element in his classification, where threshold values for the relations between width, depth, length, dilatation, etc. are used to define different types of slope movements.

Although it will become clear that a watertight classification system for landslides is an almost impossible task, the use of a consistent framework for a classification is extremely important to create an order in an endless variety of individual landslides for their scientific analysis. Furthermore a classification system offers scientist a common base for discussion which is strongly needed considering the amount of different names in use for similar types of slope movements. Therefore a certain unification in the classifications is highly desirable. In this respect the mentioned classifications of Varnes and Hutchinson are the most indicated ones. Nevertheless it has to be observed that it is also recommended to apply critically any classification and to adapt it to local circumstances when desired, always with the clear observations on how and why the “normal” classification has been adapted.

Review of existing classifications

In “Landslides and related phenomena” by Sharpe (1938), the author presents a classification using type of movement (slip and flow), kind of material (earth or rock) and the role of water/ice as main factors, while the speed of the movement is secondary parameter. The continuum of slope movements towards the transportation of solids mainly by water (fluvial transportation) or by ice (glacial transportation) is clearly shown in the set up of the classification. In practice the differentiation between slope movements and fluvial transportation will always be arbitrary as shown also by the graph given by Hutchinson (1988) where the difference between streamflow, hyper-concentrated flow and debris flow is based on the water content and/or the unit weight of the moving mass (>25 % water and/or a unit weight >1.8).

The original classification by Varnes defines five different types of movement (fall, topple, slides-translational and rotational, lateral spreads and flows). Besides this the type of material, bedrock versus engineering soils differentiated into coarse debris and predominantly fine earth, is a main factor. This opens the possibility to describe a landslide by two nouns: the first describes the material and the second the type of movement (rock fall, debris flow). Within such a policy no place exist anymore for mud flow or soil creep, as the terms mud and soil are not defined as types of material. Furthermore Varnes uses the speed of movement and the amount of water as further differentiating factors (rapid earth flow, dry sand flow). Care should be taken with the use of the term solifluction, which in most of the Anglo-Saxon literature is defined as a periglacial slope movement of saturated soil (debris or earth in Varnes terminology) over a permanent frozen subsurface. Equivalent movements under other climatic conditions are not clearly classified and therefore it is recommended to use the term solifluction under all climatic circumstances. The classification includes a complex form in which the movement is a combination of the five principal described types of movement. Varnes himself observes that most of the landslides are complex, although one type of movement general dominates over the others at certain areas within a slide or at a particular time. This has as consequence that in practice most slope failures are classified complex.

Useful has been the introduction and the standardization of a terminology for the speed of movement in landslides (table 1).

The classification presented by Hutchinson (1988) is almost only based on type of movement, the material is a secondary parameter. The types of movement differentiated are rebound, creep, sagging, slides, debris movement of flow-like form, topples and falls. Hutchinson also includes a group of complex slope movements, but here the complex forms are clearly defined to a limited number of typical complex forms. A certain similarity with the Varnes classification is clearly observed when considering the fact that Varnes includes creep within flows and sagging is considered by Varnes as rock flows. The term “debris movements of flow-like form” might be confusing, but Hutchinson wants to indicate that most of these movements are triggered off in different ways (often as a type of slide) and that due to the initial movement the material changes in state of consistency and continues its way down in a flow-like form. The change towards a flow is generally due to (1) the coherence of the material and (2) the amount of water within the mass. Only movements such as those in sensitive clays, quick sands or collapsible soils (e.g. loess and chalk) initiate as flow. Typical features associated with movements of flow-like form are the dilatation (spreading out) of the moved material after the run-out over a larger surface often with a lobular form, as well as the clear separation of the source of the material and the depositional area by a transportation path. Crozier observes that length / depth ratio in flow-like failures is normally much smaller than 1/10, while slides are generally in the order of 1/3 for rotational and up to 1/10 for translational slides.

Classes of landslide velocity	mm / sec	m / hour	m / year
extremely rapid			
	$5 . 10^{3}$	10^{4}	
very rapid			
	50	10^{2}	
rapid			
	0.5	1	$16 . 10^{3}$
moderate			
	$5 . 10^{-3}$	10^{-2}	160
slow			
	$50 . 10^{-6}$	10^{-4}	1.6
very slow			
	$0.5 . 10^{-6}$	10^{-6}	$16 . 10^{-3}$
extremely slow			

table 1: velocity classes for landslides. The values in the columns give the lower boundary of every class.

Landslide classification

The classification used in this text is basically following the modified classification of Varnes as presented in the book Landslides, investigation and mitigation (Turner and Schuster, 1996), using furthermore elements from the classification of Hutchinson and with additions based on own experiences. The classification uses type of movement as the primary differentiating parameter, other differentiation are based on material and morphological aspects. The class of complex movements is limited to failures showing two equivalent types of movement or to landslides where one type of slope failure depends of the occurrence of another slope movement. The scale for the rate of movement as presented in table 1 is used without any change.

In this section six distinct types of landslide movements are described in the sequence **fall**, **topple**, **slide**, **sagging**, **spread**, and **flow-like forms**. Each group of landslides has a number of typical different forms which are described separately. Finally some examples of complex forms of landslides will be shown.

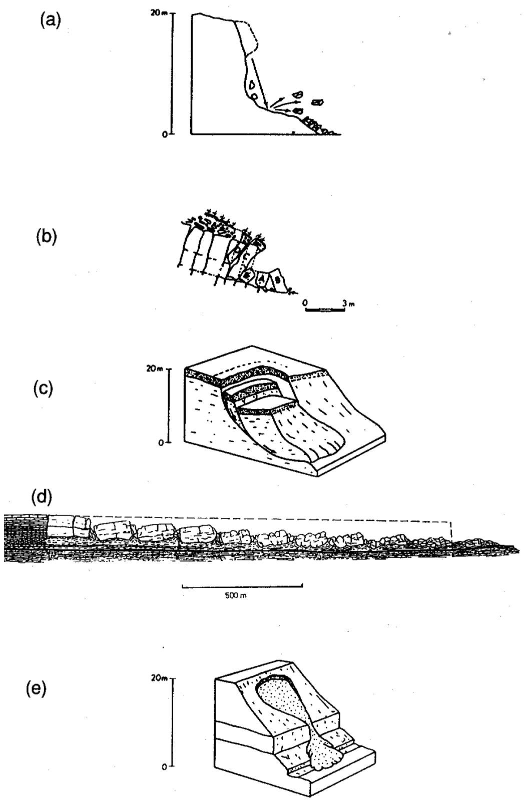


Figure 2.3: Landslide types: a: fall, b: topple, c: slide, d: spread,e: flow. (sagging is not indicated) (Varnes, 1978)

Fall

Falls comprise a detachment of soil or rock from a steep slope and the more or less free and extremely rapid descent of the material. Following this definition, the movement is largely through the air, alternated with the bouncing or rolling on the slope. Although falls can be triggered spontaneously by lateral pressures (roots, crystallisation pressures, ice wedging, etc.) or by lost of underlying support (erosion on cliffs), falling will be preceded by small sliding or toppling movements that separate the material subject to fall from the undisturbed rock mass.

Hutchinson differentiates between (1) primary rock and soil falls, involving fresh or undisturbed material, from (2) secondary stone and boulder falls, where material which has been displaced already is pushed out of the slope. In primary falls, the process of separation is generally progressive and normally initiated by the very slow aperture of tension cracks (joints).

Topple

A topple is a forward rotation out of the slope of a mass of soil or rock about a point below the centre of gravity of the displaced mass. The process is, identically to fall, associated with very steep slopes. Topples may lead to the sliding of the displaced mass, but toppling is mostly occurring in combination with fall. The process in rock slopes is generally controlled by steep inclined discontinuities more or less parallel to the free toppling face. The rotational movement of the toppling mass can be initiated in similar ways as falls or the movement is triggered by a very slow plastic deformation outside the slope of the underlying rocks. The topples controlled by a steep dipping discontinuity behind the rock face are the most common and Hutchinson describes single and multiple topples of this type. The flexural toppling as described by Varnes and Cruden (in Turner and Schuster; 1996) is a very slow plastic / brittle deformational process in rock masses which leads to unstable rock slope and toppling can be the result of this process. However this flexural rock deformation is more close to sagging and will be dealt with under that heading.

Slide

A landslide in the restricted sense of the word is a generally rapid to very rapid downslope movement of soil or rock bounded by a more or less discrete failure surface which define the sliding mass. An essential element of sliding is that the movement takes place as a unit portion of land, which implies that there are no movements within the slipped block (the internal movements). From the point of view of kinematics this is one of the characteristic differences with slope movements of flow-like forms.

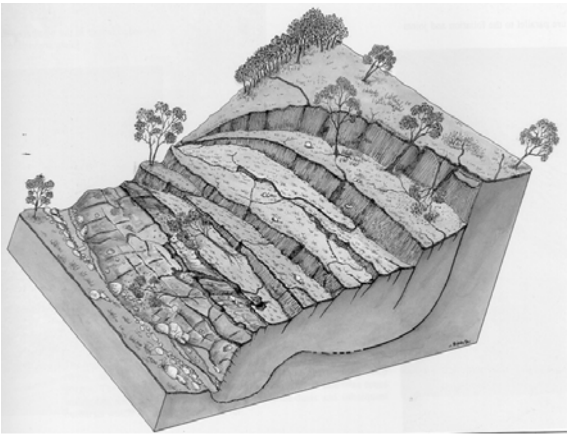


Figure 2.4: Block diagram of a rotational slide

The movement doesn’t necessarily initiate or occur at the same moment over the whole slip surface. Initial movements on one place can be the trigger for the enlargement of the total movement. The term successive slides is used when distinct ruptures occur one after the other, often due to a decrease of lateral support of the next sliding block. The term multiple slide is used for those slides which are composed out of different slide blocks, but which took place more or less at the same moment.

Slides can be sub-differentiated in two essentially different groups: (1) rotational slides which show a more or less circular failure surface and (2) translational slides where the sliding mass moves along a pre-existing failure plane (bedding, schistosity, joint or the discontinuity between slope debris and the underlying rock).

Rotational slides show in general a steep, almost vertical headscarp (crown), with the slided mass in front of it. The rotational movement makes that the slide mass (body) is backtilting towards the headscarp. Tensional cracks sometimes in combination with small steps are normal on the body. The “run-out” initiates there where the body comes out of the former slope line. From there the slope along which the movement takes place coincides with the former slope and is automatically steeper than the circular failure surface. Therefore the movement can accelerate and a more or less lobular depositional tongue can mark the end of the slide body. Water infiltrating in the body at the backtilting upper part and along cracks and on the hummocky upper surface of the body will flow along the slip surface and seepage is common in front of the slide. Due to these hydrological conditions it is common that the slide mass crumbles at the front part and the saturated soil continues it path as an earth flow. In certain cases the lower part of the failure surface does not outcrop, which in such cases is known as a confined slide. The slight bulging in the frontal part (roll-over structure) is characteristic for this type. Graben-like depressions in the backpart of the confined slides is an associated feature with these movements. Similar forms are common with deep-seated slides, which are rare, or with deep-seated gravitational deformations in rock slopes, a slope movement known as sagging (Guerrichio and Melidoro,1979).

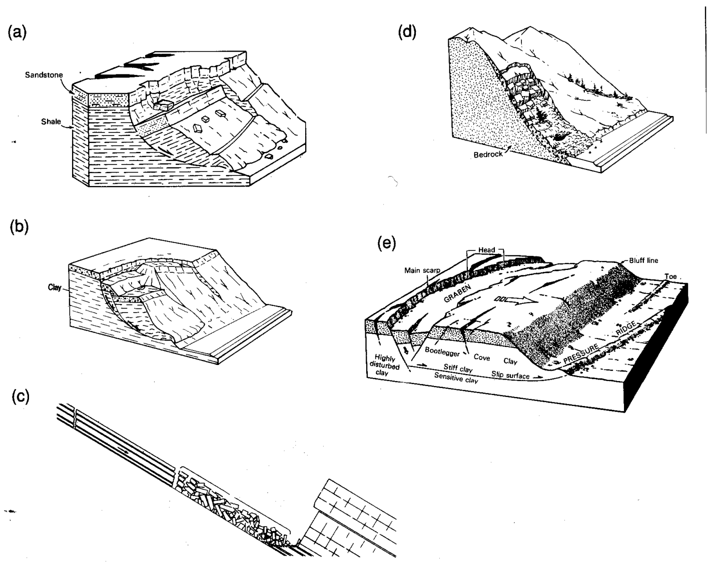


Figure 2.5: Different types of slides. a: rotational rock slide; b: rotational earth slide; c: translational rock slide (upper portion is rock block slide); d: debris slide; e: translational earth slide (Varnes, 1978)

The existence of a already defined failure surface makes that the total displacement along the failure plane is generally longer and that results in a characteristic smaller depth/length ratio for translational slides, which is in the order of magnitude of 1/10. For rotational slides this is approximately 1/3. Translational slides are also frequently showing a considerable larger width than a rotational slide.

Hutchinson defines besides these two types also the hybrid form, a compound slide in which the back part is clearly rotational, while at higher depth the failure surface intersects with a pre-existing plane and the movement continues along this surface. A typical feature associated with compound slides are graben-like depressions in the rear of the slided mass.

Within the group of translational slides a differentiation can be made between rockslides and soil slips or slides (both words are in use). The rockslides are sub-divided into (1) planar slides, when the movement takes place along one and the same failure plane, (2) stepped slides, where the movement occurs along a number of parallel failure planes, and (3) wedge failures, where the failure is controlled by two planes which define a wedge shaped block, which is loosened from the rock slope. Hoek and Bray (1977) are describing in their book "Rock slope engineering" the failure criteria for planar, wedge and toppling failures in a rock slope.

In rockslides not only the failure surface is defined by a pre-existing plane, also the head scarps and the lateral limits are often associated with joints in the rock. This gives that large angular rock masses are sliding downwards, blocks which on their way down disintegrate into progressively smaller pieces. When the rocks, which are subject to sliding, overly a softer plastic deformable type of rock, a transitional form towards spreading failures will originate. Although no definite rules or thresholds are described, it can be stated that we will speak of rockslides when the movement takes place on a considerable sloping surface, while spreading failures are limited to very gentle slopes (< 10 %).

The translational soil slips are divided according to Hutchinson into sheet and slab slides, both very shallow slides in unlithified material along gentle to moderate slopes (up to a max. of 20^0) and differing from each other in type of material and the water content at the moment of sliding. Sheet slides occur in almost cohesionless and dry soils (comparable to the sand run in the classification of Varnes). Slab slides are on the contrary almost saturated with water. The material consists normally of soils with appreciable amounts of fines. This type is on one side passing into the mudslides as defined by Hutchinson under the heading of debris movements of flow-like form and on the other hand slab slides will be common in areas affected by creep.

Translational debris slides are slope movements occurring on considerable steeper slopes (25^0 - 35^0), where the slope debris slides off along the discontinuity with the underlying weathered rock. This type of slope movement is common on mountain slopes directly after the snow melt when soils are saturated with water. Similar slides also occur on steep deforested slopes in the tropics in the wet season after a number of days of antecedent rainfall. When in such cases the final failure is triggered by a rainstorms, it is possible that a large number of debris slides, occurring at the same moment, are causing a debris flow. The classification of Varnes considers debris slides as soil or debris avalanches of the flow type, although the non-coherent displaced material does not really flows, but is disintegrated and moves far down due to the steep slope. In this way debris slides reach a D/L ratio similar to debris movements of flow-like forms.

Sagging

Sagging is defined as large scale deep seated deformations, under influence of gravity, occurring in competent rocks and occurring in zones where erosion has created deep valleys and therefore an unstable situation (Hutchinson, 1988). This type of slope movement, sometimes due to its size almost transitional to gravitational sliding tectonism, has been described as “sackung” (Zischinsky;1969) or gravitational spreading (Radbruch-Hall, Varnes;1976). The type has also been defined as a deep seated rock creep, considering its very low rate of movement (mm’s to cm’s per year). The morphological features are resembling confined slides on long and steep rock slopes. Considering that long and large scarps are limiting the upper part of the mass movement, often close to the highest part of the slopes, gives a morphology of double crests, one related to the slided block and the other the original one. The bulging on the lower slope results in antithetical reversed faults, creating elongated depressions along the frontal slopes. The bulging also gives an oversteepening of the already steep slopes and is therefore often associated with rockfall and toppling, which results in extensive scree slopes.

Two basic forms have been describes (Rengers and Soeters; 1982). The first one occurs in homogeneous competent rocks, and consists of a collapse of the mountain on the valley side. The other type occurs when competent rocks are overlying softer more plastic deformable materials, such as shales. The weight of the overlying rocks induces a slow plastic deformation of the softer material which is squeezed into the valley and exerts tensional stresses on the overlying rocks, braking it up in pieces allowing their sliding. This form of sagging is similar to lateral spreads, with the difference that in sagging the movement is basically downwards while in spreads the horizontal component in the movement is considerable.

Lateral spreads

Spread is defined here as an extension of a cohesive soil or rock mass combined with a general subsidence of the broken mass of cohesive material into softer underlying material. From the definition it is clear that the horizontal (lateral) component is more important than the vertical movement. The horizontal movement is a sliding of the detached blocks of cohesive material over the softer and often also partly induced by a plastic deformation of the underlying material.

Common are block spreads, where the cohesive material is rock of which large joint controlled blocks are sliding into the valley. The movement causes sometimes clear anomalies to the drainage and valley morphology. When only slight cohesive sandy soils are affected by spreads, than the blocks are falling out quickly diminishing in size and the soil can mix up with the soft underlying material. Flow type movements result often from such a mixture, of course when the existing relief is sufficient steep.

Turner and Schuster (1996) are also considering liquefaction spreads within this group of slope movement.

These are movements induced by the liquefaction, which implies the abrupt lowering to zero of the cohesion and the effective stress and therefore a behaviour as a liquid of the underlying layer, carrying on its back the overlying more cohesive material. The abrupt liquefaction is common in sensitive clays (quick clays) and in collapsible soils (loess) or loose saturated sands (quick sands). A distortion of the equilibrium, for example due to the shaking during an earthquake, causes a change in internal structure of the sediment and therefore the abrupt increase of the porewater pressure, resulting in the liquefaction.

Quick clays failures are common in formerly glaciated areas in fine loosely sedimented deposits in marine or lagunar environments. Sands and silts deposited on tidal flats are an example for sediments which can be subject to liquefaction. Extensive loess failures are known from different parts of the world, although the failures in China have been the most catastrophic (e.g. the earthquake triggered loess slide in the Kansu province; 200.000 deaths).

Spreads and particularly liquefaction spreads are grading into flowslides as defined by Hutchinson for the failures along the British chalk coast and as used by van Westen (1993) for failures in volcanic ashes. In this respect it has to be observed that Hutchinson considers loess failures also as flowslides. The essential difference between the two types is perhaps the thickness of the layer which fails. A layer of considerable thickness is liquefied in cases when we speak of liquefaction, while in flowslides the layer where the failures occurs is more reduced, certainly in comparison to the overlying packet, which creates the impression that a slab or large blocks are sliding away over a slippery horizon instead of the liquefaction of that horizon.

Flows or debris movements of flow-like form

A very large variety of mass movements of flow-like form exist and most of the other types of slope movement can grade into movements of flow-like form. Considering these types of slope movements, it becomes clear that water plays an essential role in the occurrence and behavior of slope movements, although water isn’t the carrying agent. Undrained loading of almost saturated soils by a sliding block can lower the effective normal stress in such a way that slight cohesive soils start to flow (liquefy). Debris flows can be generated from debris slides sliding into a stream, increasing the volume (and density) of the discharge and increasing the erosion in the valley, which can undercut slopes and generate new slides, creating a cardhouse effect. However, debris flows are also originated by extreme rainstorms on slopes with easy erodable sediments (e.g. volcanic ashes), whereby the streamflow changes from sediment laden to hyper-concentrated flow and finally till debris flow. Sturzstroms are generated from exceptional large rockfalls or rockslides (Elm rockslide, the Vaiont slide).

Earthflows are often originated by large slides whereby the more or less saturated sliding material disintegrates and continues its way down in flow-like form. It has been observed that slab slides are grading into solifluction and in the same way creep can accelerate to debris slides (progressive failure).

Debris movements of flow-like form exhibit a clear and important flow-like morphology. This is on the first place characterised by a very small D/L ratio (< 1/100), but also by a clear lobular depositional landslide body (the tongue). Crozier (1973) refers in this respect to the dilatation index, which is the width ratio of the transportation pass and the accumulational lobe. Flow-like structures on the material, such as transversal and longitudinal cracks and pressure lobes are common. The morphology of flows is often comparable to glaciers, and therefore the term "earth-glacier" has been used. The material is rapidly channelized, following valleys and infilled valleys in areas where V-shaped valleys are common are a feature used to discover flows.

Creep is a very too extremely slow diffuse slope movement, occurring under the effect of a continued stress close to the ultimate or peak stress. The movement can be deep seated and continue, which is the case in moderate to steep slopes in rather soft rocks (in hard rocks the movement is classified as sagging). In this case the creep will normally occur in association with a variety of other types of landslides. On the other hand the shallow and generally seasonal type of creep is known. This type of creep occurs on slopes with soils containing appreciable amounts of fines. When these slopes are saturated with water during the rainy season or after the snow melt, a diffuse movement in the material is initiated. Under drier conditions the movement stops again. The movement grades into solifluction, which is a rapider form of creep, and furthermore creep is frequently occurring in association with other types of slope movements mostly of flow-like form (mudslides, earthflows).

Progressive creep is a special form whereby the rate of movement slowly increases and at a moment abruptly accelerates and manifesting itself as a landslide. Due to the plastic deformation in the creeping mass a reorientation of the (finer) particles occurs, causing a decrease of the angle of internal friction. The peak strength of the material lowers locally to residual strength values and a rapid failure can take place. It is also possible that within the mass subject to creep small failures are taking place, defining small segments of a large future failure plane than associated with a slide.

The general appearance of creep is a micro-morphology of the slope, which is more irregular than would be expectable considering the soft material. This micro-morphology creates also differential drainage conditions reflected in the vegetation. Leaning or bending trees are traditional indicators, as well as locally disrupted vegetation cover or small steps or scarps in the terrain. Boundaries with stable areas are confuse, as creep is a diffuse type of movement.

Mudslides, as defined by Hutchinson (1988), are initiating generally as shallow translational slides in more or less saturated soils with a considerable amount of fines (clays, marls, clayey sands), although the movement can also start as a typical rotational slide. The displaced material continues its way down as a viscous flow, overloading the lower slope. A continued failure due to undrained overloading of the slope deposits over which the mudslide moves, will take place as long as the slope material and gradient are similar to the area from where the failure took off. This has on one side as consequence that the flow mass increases and on the other side that a channel is created along the flow path. Elongated pressure ridges and marginal deposits (comparable to natural levees) are frequently observed, as well as longitudinal cracks and slicken sided friction planes along the margins of the "channel" or flow path. The dilatation or spreading out of the flow mass occurs after the run-out of the slope. Form and shape of the run out flow body depends on the viscosity of the mass, varying from a wide and flat body when fluidity was high to a narrow elongated convex tongue comparable to a thick lava flow. The rate of movement is rapid to very rapid (many meters per day) and depends highly of the type of material and the slope gradient. Transversal cracks (like crevasses in glaciers) are common on places where the gradient and thus the flow speed increases, disrupting the flow mass.

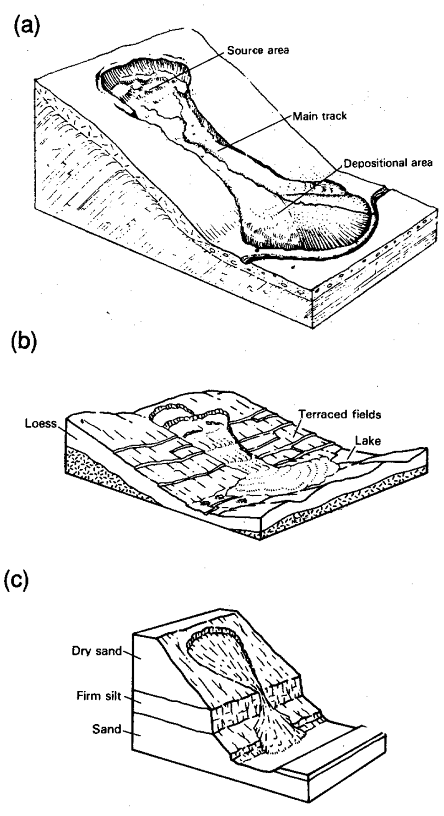


Figure 2.6: Examples of flows: a: slow earth flow, B: Loess flow, c:dry sand flow (Cruden and Varnes, 1996)

Mudslides and earthflows are grading into each other. In mudslides the content of fines is a dominant factor and the movement occurs on moderate to steep slopes. In earthflows the differentiation within the material is much larger and the slope is generally steeper and the D/L ratio is often smaller than in mudslides. The origin of earthflows is slide, a rockfall or a complex of slope failures whereby the disrupted mass of the landslide bodies, saturated with water, moves further downwards in a form which shows often a strong comparison to glaciers. The flow velocity is generally not faster than a few meters per hour or even per day (thus in the class rapid according to the scale of Varnes). Water infiltrating into the body can be high, considering the irregular surface morphology and the large amounts of cracks and therefore intermittent movement of the flow body is thought to be possible.

Flowslides have been discussed partly under the heading of liquefaction. When the mobilisation of the flow horizon hasn't been strong, the movement appears often as a (rotational) slide or a sheet slide. Examples of flowslides in a mantle of volcanic ashes in the Manizales region in Colombia show backtilting blocks or a wavy surface of the moved sheet of volcanic ashes The movement is headed by a clear scarp at the back. When the weak or sensitive horizon outcrops in the slope, the flow movement is clearer and the body will flow farther away from the site of origin. Hutchinson defines the ratio between the height difference from the crown to the toe against the length of the flowslide, which is in the order of 1.5 for normal slides on the chalk cliffs on the English coast to 0.3 - 0.5 for flowslides on the chalk cliffs and flowslides in coalmine waste dumps (e.g. Aberfan flowslide with a H/L ratio of 0.3). The volumes of material involved in these flowslides is in the order of $10^3 – 10^6$ m^3. Hutchinson gives in comparison to these types of movements also the data corresponding to sturzstroms and alpine "bergsturzen", which have a H/L ratio in the order of 0.2 and a mass volume of $10^7 – 10^9$ m^3. The hypothesis is that flow in the weak porous chalk is caused by the collapse of the grain structure and the upbuilding of pore pressures, resulting in a fluidization.

Debris flows are extremely rapid mass movements of intimate mixtures of solids with water. Debris flows can be initiated by the sudden release of a large amount of water on a slope where considerable quantities of easy erodible material are available. Examples of this type are the breakthrough of a crater lake or a glacial lake (glacial lake outburst flood; GLOF), the sudden snow melt of an ice capped volcano (Ruiz volcano, 1985). Lahars, debris flows of pyroclastic materials caused by heavy rainstorms, are another example of this type. However, debris flows can also be caused by the sudden occurrence of a large amount of soil slips, which are triggered off by a heavy rainstorm after several days of antecedent rain. These soil slips (small debris avalanches) slide into the stream channel, where the amount of water mixes with the solids transforming the sediment laden stream transport into a debris flow. The effect of the debris flow can be amplified due to slope failures along the stream channel caused by the enormous erosion generated by the debris flow. The disastrous character of these flows is due to the extreme high velocity, the enormous mass and the density of the flow mass, allowing blocks of many tens of cubic meters to be transported in the flow. Aspects involved in the flow mechanism and allowing for the slurry of solids and water are turbidity, the viscous drag related to the slow settling velocity of blocks in a high density mass, and the dispersive stress or the bouncing of the blocks in between themselves. The deposits from debris flows are characterized by an enormous chaotic internal structure without any layering and a texture that is typically matrix supported, in which large blocks are "floating" in a much finer matrix. This in contrast with fluvial deposits where the clasts are forming the structure and the matrix is filling in the pores.

Strurzstroms are a rather exceptional form of dry rock flows, generally originated by an enormous rockslide or fall. Such a rock fall liberates an extreme high amount of kinetic energy. Due to this a dust cloud is formed of a high density which will move along the slope, through valleys over the ground surface. Within this cloud enormous blocks are transported mainly due to the fact that they are bouncing in between each other (dispersive stress) or they are jumping over the surface. A sturzstrom is in this respect comparable to pyroclastic flows, whereby an enormous column of (warm very hot) volcanic tephra mixed with gases and water vapor is ejected into the atmosphere, comes to stillstand and collapses and flows down along the slopes of the volcano.

Slope movements of complex form

As complex can be classified those slope movements whereby different types of landslides together are responsible for the occurrence or continuation of the slope movement in the area. An example for such a complex movement is found with the example of the "Complex slope failures on the frontal part of the fluvio-volcanic deposits of Manizales" in the sequence of stereogrammes coming as exercises to this programme. In the Manizales area fluvio-volcanic deposits due to an extreme strong explosive volcanic activity largely filled in the highly dissected Pliocene relief. Fluvial erosion of the Rio Chinchina and Rio Olivares dissected along the boundary of the Paleozoic and Cretaceous bedrock, consisting of fine clastic and schistose rocks, and the volcano-clastic deposits, leaving a mesa-like terrace on which the city Manizales was founded.

The headward erosion of the streams west of Manizales is at this moment reaching the city and in the upper part of their catchments steep slopes exist. The lower slopes are eroded into the low grade fine grained metamorphic rocks, which are overlain by the volcano-clastic sequence, outcropping on the highest part of the slopes just below the city. The crests in this relief are normally covered with a mantle of recent volcanic ash deposits.

Although the small scale photographs (scale 1:30.000 approx.) gives an excellent overview of the general setting of the area, it is hardly possible to obtain an adequate idea on the slope instability problems. The large scale images (1:10.000) give the necessary detail for the interpretation of the area. The two stereogrammes are picturing both flanks of the suburb La Francia. On one side the slope movements are extremely well defined and scarps and the associated hummocky surface of the slide mass is well distinguished. On the other stereogramme the slope movements are less distinct, but the irregularities in the relief are revealing the (dormant) slope instability.

The third large scale stereogramme depicts the area about 10 years after the other two other stereogrammes. The slope movements seem to have stabilized, as most of the area is overgrown with secondary vegetation. However field observations show the opposite. The whole area, also the part covered by grass fields and with the few houses is subject to a continuous intermittent process of mass movement. This observation also shows the difficulty to make statements on activity of slope movements on the basis of aerial photointerpretation alone, even on large scale photographs (1:10.000 in this case).

The whole movement is highly intermittent and it appears that the sliding mass has to be removed through the valley outside the area on the large scale stereogrammes, in which bedrock is acting as a funnel. As long as stream erosion and the slumping of the steam banks have not moved out the lower part of the landslide body, the material behind is acting as counterweight for the sliding mass and an apparently stable situation exist. However, once when the fluvial erosion has removed this material, it frees the way for a reactivation of the slope instability. Various types of slope movements (rotational slides in the ashes, debris slides in the weathered bedrock, slides and debris movements of flow-like form in the Plio-Pleistocene deposits) occur in one and the same area. Hereby one movement often triggers the other by overloading the slope, changing the drainage conditions, decrease of lateral support, etc.

This situation as analyzed on the large scale photographs in a small sub-catchments can be extrapolated on the small scale photographs for the whole scarp west of Manizales, where similar geological, geomorphological and hydrological conditions exist

This illustrates another working methodology, in which detailed knowledge obtained in large scale photographs or/and in the field is used in combination with small scale images to evaluate the more regional implications.

CHAPTER 3

Application of remote sensing in slope instability studies

Considering that landslides are directly affecting the ground surface, makes the application of remote sensing techniques very suited to slope instability studies. The use of remote sensing images is particular useful when stereo images are used, depicting in the stereomodel the typical morphological features of landslides, which can give on itself already diagnostic information on the type of movement (Crozier, 1973). Furthermore hydrologic conditions and vegetation changes associated with slope instability features may also be observed on remote sensing imagery. Also the overall terrain conditions, determining the susceptibility of a site to be subject to sliding, can profitably be interpreted from remote sensing data. The term remote sensing is used here in its widest sense, including aerial photography, as well as imagery obtained by satellites or any other remote sensing technique.

The value of image interpretation in slope instability studies has been reported by many investigators. Rib and Liang dedicate 25 well documented pages to the subject in the first edition of the manual of the Transportation Research Board on landslides (edited by Schuster and Krizek;1978). Several basic textbooks on slope instability are referring to the importance of aerial photographs in the study of landslides (e.g. Brunsden and Prior, 1984). Mention can also be made of the successful use of aerial photographs by scientists of the University of Bari in Italy, who are showing in a large number of publications the application of aerial photographs in active slides (for example Guerricchio and Melidoro, 1981) as well as in historic movements (Cotecchia et al., 1986). However, the development in remote sensing has been such over the last two decades, that an overview is given of the types of images available and their relevant characteristics in relation to their application in slope instability studies.

Remote Sensing products

Little development can be noted in aerial photography. Panchromatic black and white and colour films are covering the visible part of the electromagnetic spectrum, while black and white infrared and false colour infrared films are extending their sensitivity into the reflective near infrared. The spatial resolution of these films is excellent and they are normally coming in stereoscopic coverage, enabling a three dimensional picture of the terrain and giving thus detailed morphological information. The spectral resolution is bad in comparison to multispectral data, as the image is the integral picture over one broad spectral band. The organisation of a aerial photographic mission is rather time consuming and the number of days with good climatic conditions for acceptable aerial photography are very limited over the year. This makes that the temporal resolution (number of images of the same area over time) is bad in comparison to satellite imagery.

Besides conventional aerial photographs, the application of satellite data has increased enormously. After the initial low spatial resolution images of the LANDSAT MSS (60 x 80 metres), LANDSAT is also offering Thematic Mapper images with a spatial resolution of 30 meters (except for the thermal infrared band) and an excellent spectral resolution with 6 bands covering the whole visible and the near and middle infrared part of the spectrum and with one band in the thermal infrared. LANDSAT has an overpass every eighteen days, offering a theoretical temporal resolution of eighteen days, although weather conditions are a serious limiting factor in this respect, as clouds are hampering the acquisition of data from the ground surface. The weakest point of the LANDSAT System is the lack of an adequate stereovision. Theoretically a stereomate of an TM image can be produced with the help of a good digital terrain model (DTM), but this remains a poor compensation as long as very detailed DTM's are not currently available.

The French SPOT satellite is equipped with two sensor systems, covering adjacent paths each one with a 60 kilometres swath width. The sensors have an off-nadir looking capability, offering the possibility for images with good stereoscopic vision. The option for sidewards looking results also in a higher temporal resolution. SPOT is sensing the terrain in a wide panchromatic band and in three narrower spectral bands (green, red and infrared). The spatial resolution in the panchromatic mode is 10 meters, while the three spectral bands have a spatial resolution of 20 meters. The system lacks spectral bands in the middle and far (thermal) infrared.

Radar satellite images, available from the European ERS-1 and the Japanese JERS, are offering an all weather capability, as the system is cloud penetrating. Theoretically this type of images can yield detailed information on surface roughness and micromorphology. However, the till now applied wavelengths and looking angle have not been very appropriate for application in mountainous terrain. The first results of the research with radar interferometry are very promising and indicate that detailed terrain models to an accuracy of around one metre can be created, which creates the possibility to monitor landslide activity, however vegetation is interfering strongly in the creation of detailed DTM’s..

	LANDSAT MSS	LANDSAT TM	SPOT

			XS	PAN
Nr. of spectral bands	4	7	3	1
spectral resolution	0.5 - 1.1 µm	0.45 - 2.35 µm 10.4 - 12.5 µm	0.5 - 0.9 µm	0.5 - 0.7 µm
spatial resolution	80 m	30 m 120 m in TIR	20 m	10 m
swath width	185 km	185 km	2 x 60 km	2 x 60 km
Stereo	no	no	yes	yes
Temporal resolution	18 days	18 days	26 days 5 days off nadir	26 days 5 days off nadir

Table ?: Comparison of the specifications of different multi spectral remote sensing products (TIR = Thermal infrared).

Image resolution and interpretability

Knowing the characteristic features associated with slope movements and the image characteristics associated with them, which are essential for the interpretation, attention should be paid to the image specifications required for an adequate interpretation. It has to be realised that the interpretability is influenced by the existing contrast between the slope movement and its background. In image interpretation this contrast may be considered as the spectral or spatial differences that exist between the object of interest (landslide features) and its surroundings. In the case of slope failures, the contrast of the feature with its surroundings depends on:

(1) the period elapsed since the failure, as erosional processes and the recovery of the vegetation are tending to obscure the cicatrices which the landslide has left in the surface, and,

(2) the severity with which the morphology, drainage and vegetational conditions have been affected by the landslide.

The successful interpretation of a landslide on a remote sensing depends largely on the recognition of individual features associated with the landslide (scarp, hummocky aspect of the slided mass, ponding, etc.) on the image. Therefore, the interpretability of slope instability phenomena and thus the applicability of the type of remote sensing data to be used in landslide studies, depends in the first place on the spatial resolution of the images. This spatial resolution has to be compared to the size of the features which are characterising the slope movement and which can be recognised or identified. The spectral and temporal resolution of the remote sensing images are other elements influencing the use of aerospace data for landslide studies but are not that important. For the comparison of the spatial resolution in photography and non-photographic remote sensing the term ground resolution cell (GRC) has been introduced (Rengers et al., 1992), which is equal in size to a scene element in non-photographic remote sensing. The scene element represents the dimensions on the ground of the basic element (pixel) of the picture.

According to Naithani (1990) the size of a ground resolution cell in aerial photography will be rounded off to 1/2.5 x the value of the ground resolution cell in non-photographic remote sensing. To obtain the relation between ground resolution cell and photo scale, the formula of Strandberg (1967) may be used:

$$GRC = \frac{S}{1000R}$$

where:

GRC = ground resolution cell in metres, S = scale number of the image,

R = resolution of the photographic system in linepairs/millimetre

The resolution of the photographic system is in the order of 40 1p/mm, when considering conventional aerial photography with extreme contrast.

It will be clear that a certain amount of pixels is needed for the recognition of an object in an image on the basis of its shape. The required amount of pixels will give an idea of the minimum size a landslide should have for the adequate interpretation of a slope movement. The before mentioned contrast of the feature against its background is a variable defining the amount of pixels needed. Other factors that are also influencing the necessary amount of pixels are personal ones, such as professional experience, local knowledge and expectancy, which are defining together the reference level of the interpreter. A high reference level is very important for an adequate interpretation, as demonstrated by Fookes et al. (1991), who compared the photo-interpretation of an unknown area previous to a large landslip made by five recognised professionals. Although it is difficult to give precise data on the amount of pixels needed, on the basis of experience with visual interpretation of remote sensing imagery, it may be stated, that for various greytone contrast relationships between object and background, the number of ground resolution cells needed to recognize or identify objects in an image are as listed in table 7. The implication of table 7 is illustrated by the figures 10 and 11, which were derived from a pair of large scale aerial photographs, which were digitized with a raster size corresponding to a ground resolution cell of 0.3 metre. The individual pictures were then printed with artificially aggregated pixels as if the ground resolution cell had been 1m, 3m, 10m, and 30m.

Figure 10 shows pictures with varying groundresolution cells of a landslide in the Spanish Pyrenees (Sissakian et al., 1983). The landslide scar with shadow, giving high contrast, is observed in the upper part of the image and a depositional area of landslide debris in the central lower part. The area of accumulation is recognisable by a characteristic surface texture, due to an irregular micro relief (low contrast features) and by the surrounding line of higher vegetation recognisable as such in the pictures with small ground resolution cell sizes. The set of pictures in figure 10 are forming stereopairs to demonstrate also the enormous advantage of stereoscopic viewing in the interpretation of mass movements. The values in table 8 are only giving an indication of the order of magnitude of the minimum size of objects, which may be recognised or identified on the bases of shape and pattern. Tonal or spectral aspects are only considered for what concerns the contrast of the feature against the background.

CONTRAST LEVEL	**number of GRC identification**	**numb inter**
Extreme Contrast: white or black object against a variable grey tone background	**20 - 30**	**4**
High contrast: dark or light object in grey tone background	**80 - 100**	**12**

Low contrast: grey feature with a grey tone background	1000 - 1200	160

Table 7: Number of ground resolution cells needed to identify and interpret an object of varying contrast in relation to its background.

		MSS	TM	SPOT XS	SPOT PAN	Airphotos 1:50.000	Airphotos 1:15.000
Ground resolution cell size		80 m	30 m	20 m	10 m	1 m	0.3 m
HIGH CONTRAST	Identification	160,000	22,500	10,000	2,500	25	6.5
	Interpretation	288,000	40,500	18,000	4,500	45	11.5
LOW CONTRAST	Identification	7,040,000	990,000	440,000	110,000	1,100	300
	Interpretation	11,520,000	1,620,000	720,000	180,000	1,800	450

Table 8: Minimum sizes (in m²) needed for a landslide to be identified or interpreted, depending on the conditions of contrast between the elements of the slide and the background. The data for aerial photographs are somewhat flattered, as optimal photographic conditions and processing are considered.

For the evaluation of the suitability of remote sensing images for landslide inventory mapping the size of individual slope failures in relation to the ground resolution cell is of crucial importance. Although sizes of landslides vary enormously, also according to the type of slope failure, some useful information can be found in literature. Crozier gives in his article on the morphometric analysis of landslips (Crozier, 1973) average values for several types of movements, while Carrara et al. (1977) give for a total of almost four hundred slope failures a mean crown - tip distance of 262 metres. An interesting figure in this respect is the average total area involved in a failure of 42000 m^2. This total map area per failure corresponds with 20 x 20 pixels on a SPOT Pan image and 10 x 10 pixels on SPOT multispectral images, which would be sufficient to identify a landslide displaying a high contrast, but it is insufficient for a proper analysis of the elements pertaining to the failure to establish characteristics and type of landslide. Cleaves (1961) gives mean values, also based on a large number of observations, which are even lower than those of Crozier and Carrara and he concludes that the most appropriate photoscale for analysis is 1:15.000.

Based on own experiences, obtained in various climatic zones and under very different terrain conditions, it is believed that if 1:15.000 might be the most appropriate scale, 1:25.000 should be considered as the smallest scale to analyze slope instability phenomena on aerial photographs. Using smaller scales a slope failure may be recognised as such, if size and contrast are sufficiently large. However, the amount of analytical information, enabling the interpreter to make conclusions on type and causes of the landslide, will be very limited at scales smaller than 1:25.000. Furthermore, a considerable amount of slope movements may be overlooked at smaller scales.

In this respect the smaller scales are more useful to analyze the overall geological and geomorphological setting in which slope failures are occurring. This coincides with the conclusions of Scanvic when exploring the applicability of SPOT to slope instability mapping in the surroundings of La Paz, Bolivia, who states that SPOT yields excellent data complimentary to large scale photographs (Scanvic, 1990). In this respect it may be concluded that large photoscales allow for the inventory and analysis of landslides and the interpretation of the possible causal factors, while the small scale photographs are enabling the determination of the spatial distribution of the variables involved in the mass movement. Given good quality photography, aerial photography of a relatively small scale and used in reconnaissance stages of a project can be enlarged for the use in detailed studies, making a special flight to take new photographs not necessary. Table 9 is giving the results of a comparative study on the interpretability of slope instability features at the original photoscale and three levels of enlargement (Sissakian et al. 1983).

Subject	**Size**	**Photoscale**		
		1:20,000	**1:10,000**	**1:5,000**
Recognition of instability phenomena	< 20 m.	0	0	2
	20 - 75 m.	0 → 1	1 → 2	3
	> 75 m.	1 → 2	2	3
Recognition of the activity of unstable areas	< 20 m.	0	0	1
	20 - 75 m.	0	0 → 1	2
	> 75 m.	1	1 → 2	3
Recognition of instability elements (cracks, steps, depressions etc.)	< 10 m.	0	0	0
	10 - 75 m.	0	0 → 1	1 → 2
	> 75 m.	1	2	3

Table 9: Relative suitabilities of different scales of aerial photographs for different elements in slope instability mapping (modified after Sissakian et al., 1983) 0 = less adequate, 1 = limited use, 2 = useful, 3 = very useful.

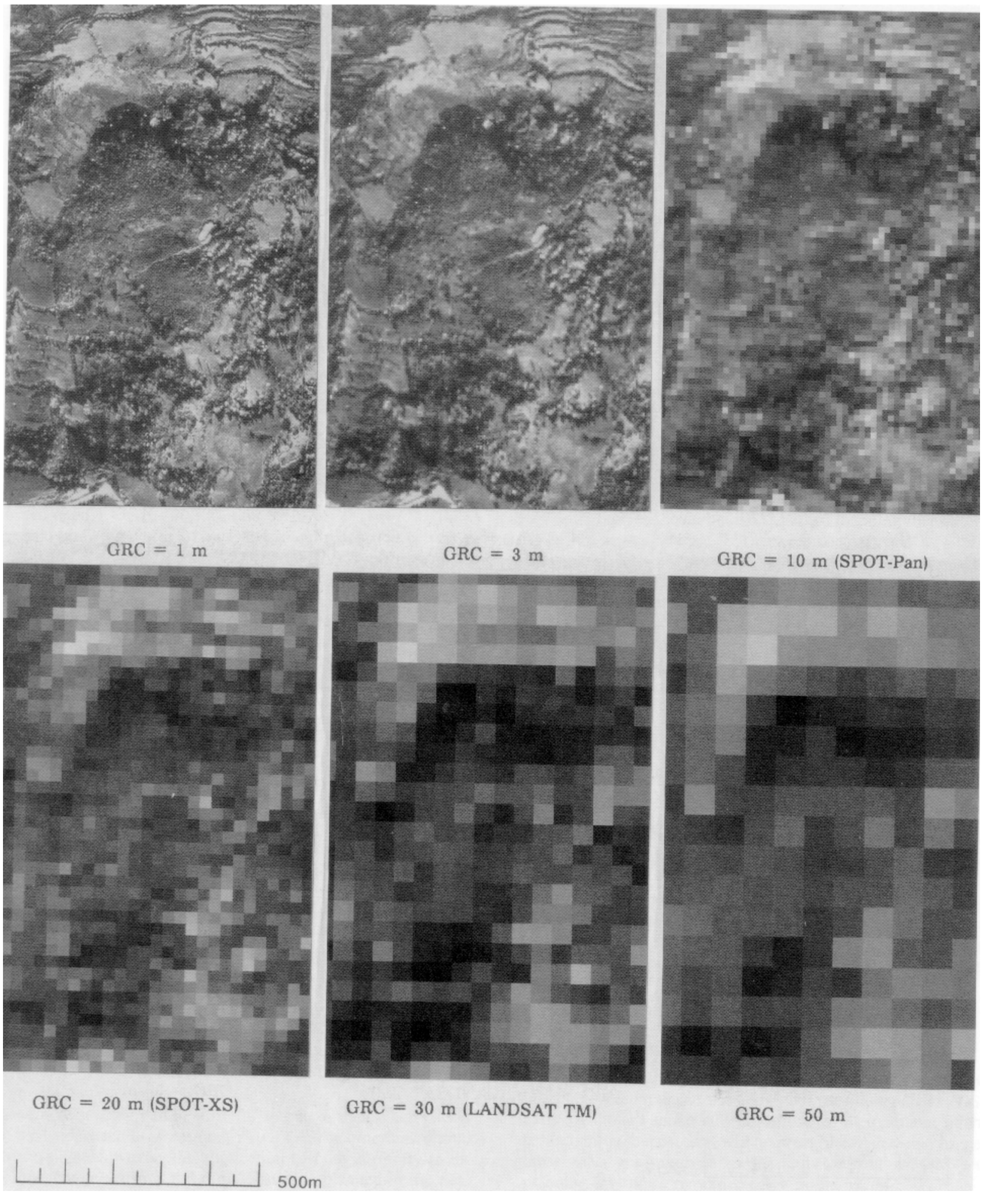


Figure ?: An area showing a landslide scar that is in shadow (high contrast) in the central upper part of the picture and a depositional area of landslide debris (low contrast) in the central to lower part of the picture. The pictures were show how the same landslide would be displayed on aerial photos , SPOT Pan, SPOT XS, and LANDSAT TM

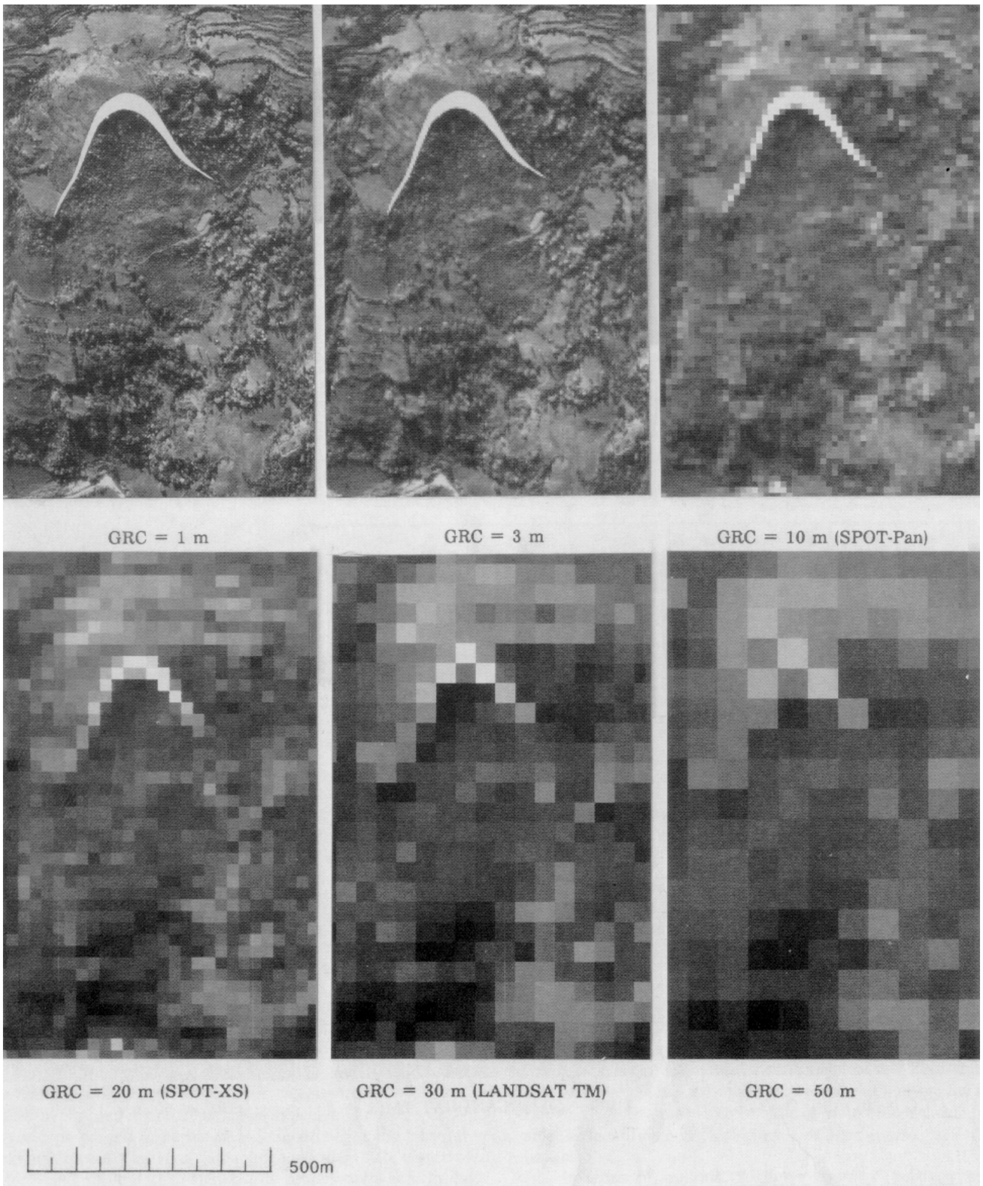


Figure ?: The same area as in the previous figure, bu t now with an artifically enhanced landslide scar.

Spectral and temporal resolution of remote sensing data

Considering the larger differentiation in the spectral reflectance of vegetation in the near infrared and the characteristic low response of water in the infrared and thermal part of the electromagnetic spectrum, makes that differences in vegetation and drainage conditions are particularly registered by detectors sensitive in this part of the spectrum. This implies that the use of infrared sensitive film and particularly false colour infrared film, is highly recommended for landslide studies in view of their capability to register small vegetation or drainage anomalies. Optimal differences in the vegetation conditions may be expected in the early or very late stage of the growing season, while differential drainage conditions are optimal shortly after the first rainstorms of the rainy season or in cold and temperate climates shortly after the snowmelt.

Also satellite imagery is offering detailed spectral information, as the reflection intensity is obtained in various wavelength bands. Black and white images obtained in different spectral bands are combined into colour composites of which the *false colour composite*, comparable to the false colour infrared photography, is the most common. Digital processing of the spectral data is offering the possibility for an analysis of the reflectance obtained from the ground and to enhance small spectral variations which seem to be correlated with slope instability features.

The size of areas with anomalous drainage conditions or a disturbed vegetation, causing an anomalous spectral response, is often too small to enable the interpretation of a single instability features on the basis of spectral criteria. However, spectral interpretation of satellite data has been used successfully in slope instability studies when spectral information is used in conjunction to other data related to slope failures, giving in this way converging evidences for the slope movement. Practical applications of spectral information from satellite imagery are also possible when, based on terrain evidences, a direct relationship is known between slope instability and vegetation or drainage anomalies. McKean and co-workers demonstrated that spectral vegetation indices can be used in mapping spatial patterns of grass senescence which were found to be related with soil thickness and slope instability. In another case landslides in a homogeneous forested area exposed differences in understorey vegetation and soils, altering also the site spectral characteristics (McKean et al., 1991).

In general it can be stated that spectral information, in the same way as spatial data, can be used for the delineation of terrain variables (in this case mostly related to vegetation and drainage conditions), which are correlated or assumed to be related with slope movements. In special cases (high contrast and/or large dimensions) the feature itself may be identified on the basis of spectral information. Seldomly this type of information alone will be sufficient for the analysis of the type of failure.

Satellite systems, orbiting around the earth, are giving also the opportunity to obtain regularly data from the same areas, allowing for the monitoring of processes in time. Images obtained shortly after a period of slope instability will show high contrasts between the zones affected by slope instability and the stable surroundings, resulting in clearly detectable spatial and spectral changes. This enables the interpreter to establish a slope instability impact assessment, as is observable from figure 12, which shows an area in Thailand affected by mudslides and debris flows as the effect of an exceptionally heavy rainstorm. The interpretation of sequential images allows for the correlation of climatic or seismic events with the occurrence and intensity of slope movements. Finally, the comparison of imagery obtained at different moments may give indications on the activity of the slope processes in an area. However, it has to be observed that even twenty years of satellite images is still a rather short period to obtain a good idea on the activity of slope instability processes, as they are mainly triggered off by low frequency spasmodic events. Furthermore adverse weather conditions or certain system limitations are other limiting factors in the acquisition of satellite data at the right moment, to take full advantage of the temporal resolution.

Sequential aerial photographs (coverage's obtained at different dates) are extremely useful for landslide studies. In the first place a considerable better inventory is obtained of the instability features active in an area. Old landslides are frequently wiped out by erosion and obscured by overgrowing vegetation. Furthermore sequential photography gives an idea on the activity of landslides in time, while the occurrence of landslides can also be associated with eventually changed terrain conditions, as for example agricultural practices.

Figure ?: SPOT multispectral satellite image with good spatial resolution can be used in the assessment of areas affected by slopemovements. Example from Thailand where a large number of landslides were generated after a major storm event.

Conclusive observations on the applicability of satellite remote sensing

Based on the foregoing it can be concluded that the application of presently available satellite remote sensing is limited, as far as it refers to the direct mapping of slope instability features. The spatial resolution does not allow for the identification of landslide features smaller than 100 m in conditions of a favourably strong contrast between the landslide and the background. If contrast conditions are less favourable, then identification is even limited to features up to 400 metres.

The lack of stereo imagery, necessary for the interpretation of the characteristic and diagnostic morphological features of slope failures, is another limitation in the applicability of an important part of the presently available remote sensing imagery.

This lead to the conclusion that, accepting the limitations related to the spatial resolution, only stereo SPOT images may be used for small regional scale hazard zonation. Thematic Mapper images could be used as well, when stereomates for stereoscopic viewing are made with the help of a detailed Digital Terrain Model.

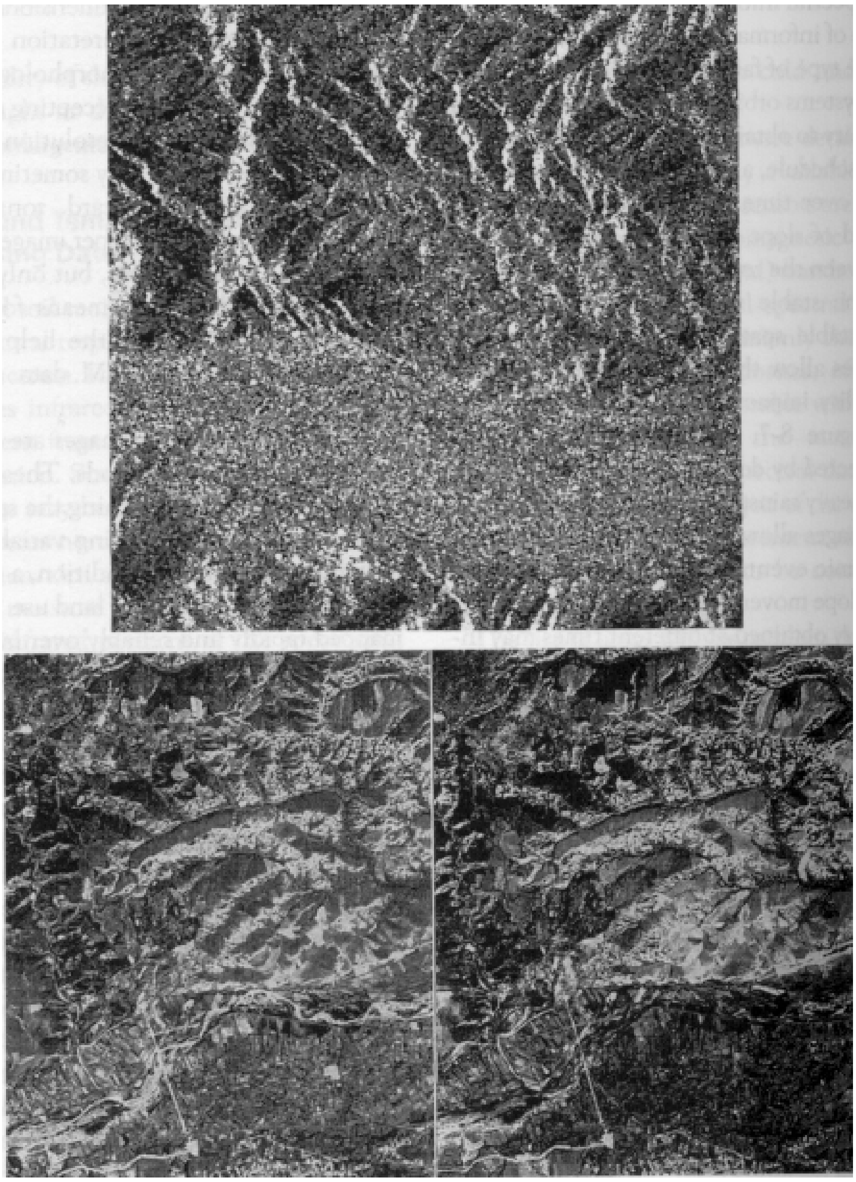
The most evident applicability of satellite images is in the indirect mapping methods, when the spatial distribution of landslide controlling variables, such as a particular geomorphological condition, a specific lithology or a particular type of landuse are identified and outlined on the satellite images. In practice it implies a combined use of satellite imagery and large scale photography. For the inventory mapping and the analytical part of the slope instability assessment, large scale aerial photography is used. The extrapolation of the findings is executed on smaller scale imagery. This combined use of aerial photographs and satellite imagery in slope instability studies is highlighted by Tonnayopas (1988) and particularly by Van Westen (1993), who integrates the use of different images/data by the application of a geographic information system (GIS).

When interpreting small scale images, the importance of the local reference level of the interpreter is of great influence. When local large scale information is combined with regional small scale synoptic data, the value of stereo SPOT can hardly be overestimated, as demonstrated by Scanvic and Girault (1989) in his case on La Paz, Bolivia.

The potentials of radar imagery for landslide hazard zonation still need further investigations. The results with radar interferometry are promising and terrain roughness classification (Slaney and Singhroy, 1991) seem encouraging. Evans (1992) is giving an overview of applicability of synthetic aperture radar (SAR) in the study of geologic processes. However, the geometric distortions due to foreshortening and the speckling are resulting in a rather poor ERS-1 image of an area in Southern Italy, characterised by intensive slope processes but in a zone where the internal relief is not higher than 100 meters (figure 13).

The application of thermal infrared (TIR) remote sensing imagery for slope instability studies is still in an early research phase, as the spatial resolution of the thermal band of the LANDSAT Thematic Mapper is far to coarse and a higher spatial resolution would decrease the thermal resolution of the detectors (from tenth of a degree C. to degrees C). Some promising research has been executed in Italy (Bison et al.,1990), where thermal detectors, installed in the field, registered variations in temperature of the soils on a slope, which could be correlated with variations in the soilmoisture content. However, no threshold values were established yet for the degree of soil moisture content in relation to the occurrence of slope failures.

Finally mention has to be made of the potentials of small format oblique aerial photography, obtained with a hand held camera from (ultra) light aircraft or helicopter. By this way almost real time synoptic information on landslides can be obtained, which is extremely useful for the evaluation of large complex slope failures. This non-conventional type of photography is becoming even more promising, as software programmes have been developed for detailed quantitative work with a minimum of ground control points (oral communication by V.Kaufmann, Techn.Univ. Graz, Austria).



Figure?: Comparison of ERS-1 radar image in Basilicata, southern Italy, with SPOT image of the same zone. Internal topographic relief is less than 100 m. Nevertheless, radar image already shows considerable geometric distortion of slopes (foreshortening). Sepckling is characteristic for radar images.

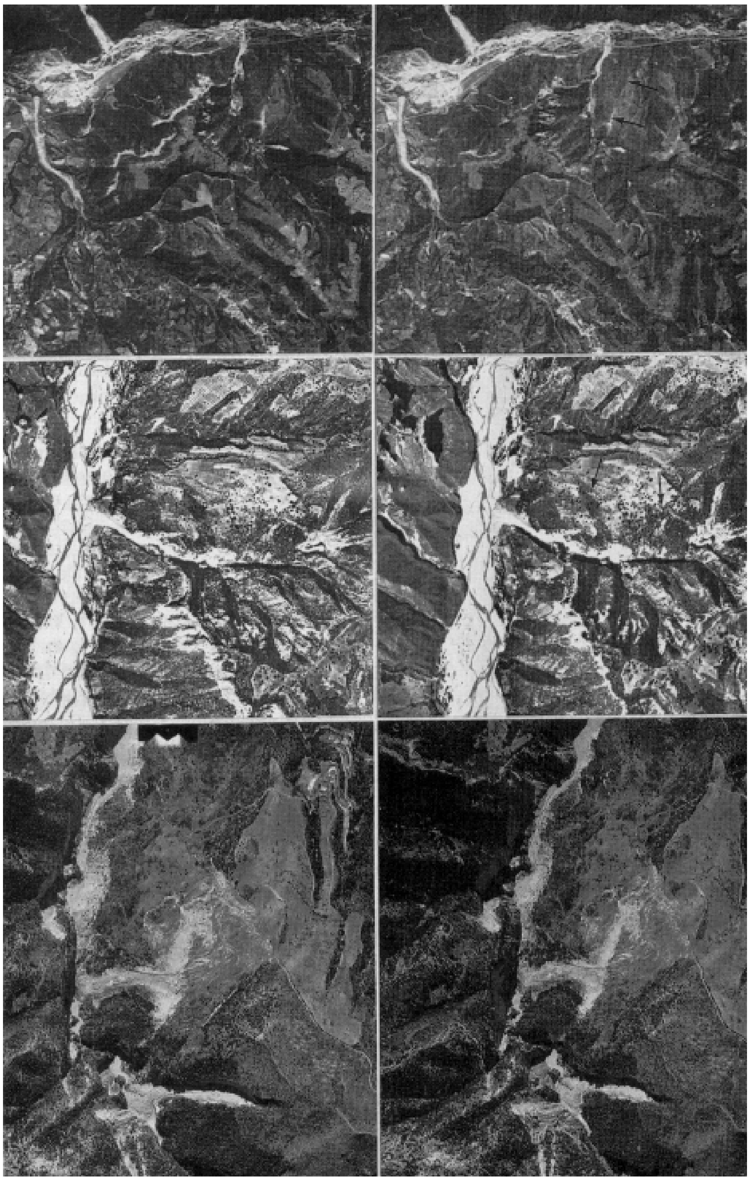


Figure ?: Comparison of interpretability of huge complex landslide in Sant Arcangelo Basin (Basilicata, Italy) shown on stereo SPOT image (scale approx. 1:70,000), medium scale aerial photographs (1:33,000) and large-scale aerial photographs (1:17,000). Flight line on medium scale photographs is north-south, and viewinf direction on SPOT and flight line on large-scale photographs is east-west.

CHAPTER 4

Interpretation of landslide from Airphoto’s

The information on landslides extracted from remote sensing images is mainly related to the morphological, vegetational and drainage conditions of the slope. The slope morphology is studied by the examination of the stereoscopic model. The study of variations in tone and texture, or of pattern, shape and lineaments has to be related to the expected ground conditions and to landforms associated with slope instability processes.

The interpretability of slope movements on remote sensing images is based on the recognition or identification of elements associated to the slope movements and the interpretation of their significance to the slope instability process. This implies, that a particular type of slope failure is seldom recognized as such, but interpreted by the analysis of a certain number of elements pertaining to the slope instability feature and depictable on the remote sensed imageries. An area subject to sliding can be interpreted by morphological features associated with the landslide niche and the run out mass, differential vegetation conditions compared to the surroundings as well as on the landslide area itself and changes in the hydrological conditions. All these features, when visible, have to be used in a combined analysis to come to an interpretation of the slope movement. As a consequence, the categorization of slope movements, as obtained from the interpretation of aerial photographs, is not that detailed as the classifications used in this manual (mainly based on Cruden;1996) or other authors (Hansen,1984; Crozier,1986; Hutchinson,1988), who are including field evidences in their considerations. Practice has shown that a photo-interpretation has to be done with the use of a simple classification. local adaptations to existing classifications can be justified to prevent ambiguities and therefore misclassifications. Table 4 is showing a checklist, which was made for the systematic characterization of slope failures as observed on aerial photographs. The types of slope movements considered were based on local knowledge in this specific study in the Colombian Cordillera (Van Westen, 1993). The table gives also an idea on the type of information, which can be obtained by experienced photo-interpreters from aerial photographs at a scale of 1:20.000. In this respect it has to be observed that the degree of activity on photographs is mainly defined on the basis of the clearity and freshness of the indications for landslides, suggesting ongoing movement. Stable slides have clear degradated morphological forms and are already overgrown by vegetation.

	Type	Subtype	Activity	Depth	Vegetation	Body

1	Slide	Rotational	Stable	Surficial	Bare	Landslide scar
2	Lateral Spread	Translational	Active	Deep	Low	Run out body
3	Flow	Complex			High/Dense	
4	Debris avalanche	Unknown				

Table 4 : Example of the interpretation of landslides as done on aerial photographs in an area in Colombia (Van Westen, 1993). The data of the inventory were meant to be stored in a GIS.

	Terrain features	**Relation to slope instability**	**Photo characteristics**
M O R P H O L O G Y	Concave/convex slope features	Landslide niche and associated deposit	Concave/convex anomalies in stere
	Step-like morphology	Retrogressive sliding	Step-like appearance of slope
	Semi-circular backscarp & steps	Head part of slide with outcrop of failure plane	Light toned scarp, associated with s
	Backtilting of slope facets	Rotational movement of slide blocks	Oval or elongated depressions with
	Hummocky and irregular slope morphology	Micro relief associated with shallow movements or small retrogressive slide blocks	Coarse surface texture, contrasting
	Infilled valleys with a slight convex bottom, where V-shaped valleys are normal	Mass movement deposit of flow type form	Anomaly in valley morphology, oft pattern on body
V E G E T A T	Vegetational clearances on steep scarps, coinciding with morpho-logical steps	Absence of vegetation on headscarp or on steps in slide body	Light toned elongated areas at the c on the body
	Irregular linear clearances along the slope	Slip surface of translational slides and track of flows and avalanches	The denudated areas showing light direction of movement
	Disrupted, disordered and partly dead vegetation	Slided blocks and differential movements in body	Irregular, sometimes mottled grey t
	Differential vegetation associated with changing drainage conditions	Stagnated drainage on backtilting blocks, seepage at frontal lobe and differential conditions on body	Tonal differences displayed in a pat morphological anomalies in the ster
D	Areas with stagnated drainage	Landslide niche, backtilting landslide blocks and hummocky internal relief on landslide body	Tonal differences with darker tones

R			
A I	Excessively drained areas	Outbulging landslide body (with differential vegetation and some soil erosion)	Light toned zones in association wi
N A	Seepage and spring levels	Springs along the frontal lobe and at places where the failure plane outcrops	Dark patches sometimes in a slight differential vegetation
G	Interruption of drainage lines	Drainage anomaly, caused by the head scarp	Drainage line abruptly broken off o
E	Anomalous drainage pattern	Streams curving around the frontal lobe or streams on both sides of the body	Curved drainge pattern, upstream w in (asymmetric) valley.

Table 5: Morphological, vegetational and drainage features, characteristic for slope instability processes, with their photo characteristics.

TYPE OF MOVEMENT	Characterisation based on morphological, vegetational and drainage aspects as visible on stereo images	
FALL and TOPPLING	**Morphology:**	Distinct rockwall or free face in association with scree slopes (20° -30°) and dejection cones. Jointed rock wall (>50°) with fall chutes.
	Vegetation:	Linear scars in vegetation along frequent rock fall paths. Vegetation density low on active scree slopes.
	Drainage:	No specific characteristics.
STURZSTROMS	**Morphology:**	Extreme large (concave) scars on mountain, with downslided blocks of almost geological dimensions. Rough, hummocky depositional forms, sometimes w
	Vegetation:	Highly irregular/chaotic vegetational conditions on accumulative part,absent on strurzstrom scar.
	Drainage:	Irregular disordered surface drainage, frequent damming of valley and lake formed behind the body.
ROTATIONAL SLIDES	**Morphology:**	Abrupt changes in slope morphology, characterized by concave (niche) – convex (run-out lobe) forms. Often step-like slopes. Semi-lunar crown and lobate slope facets, scarps, hummocky morphology on depositional part. D/L ratio 0.3 - 0.1 , slope 20° - 40°.
	Vegetation:	Clear vegetational contrast with surroundings, the absence of landuse indicative for activity. Differential vegetation according to drainage conditions.
	Drainage:	Contrast with not failed slopes. Bad surface drainage or ponding in niches or backtilting areas. Seepage in frontal part of run-out lobe.
COMPOUND SLIDES	**Morphology:**	Concave - convex slope morphology. Concavity often associated with linear graben-like depression. No clear run-out but gentle convex / bulging frontal pa associated to (small) antithetic faults. D/L ratio 0.3 - 0.1 , relatively broad in size.
	Vegetation:	As with rotational slides, although slide mass will be less disturbed.
	Drainage:	Imperfect or disturbed surface drainage, ponding in depressions and in the rear part of the slide.
TRANSLATIONAL SLIDES	**Morphology:**	Joint controlled crown in rockslides, smooth planar slip surface. Relatively undeep (shallow), certainly in surface mat. over bedrock. D/L ratio <0.1 and lar hummocky rather chaotic relief, with block size decreasing with larger distance.
	Vegetation:	Source area and transportational path denudated, often with lineations in transportational direction. Differential vegetation on body, in rockslides no landus
	Drainage:	Absence of ponding below the crown, disordered or absence of surface drainage on the body. Streams are deflected or blocked by frontal lobe.
LATERAL SPREADS	**Morphology:**	Irregular arrangement of large blocks, which are tilting in various directions. Blocksize decreases with distance and morphology becomes more chaotic. La depressions are separating the blocks. Movement can originate on very gentle slopes (<10°).
	Vegetation:	Differential vegetation is enhancing the separation of the blocks. Considerable contrast with non-affected areas.
	Drainage:	Disrupted surface drainage. Frontal part of movement is closing off valley, causing an obstruction and a asymmetric valley profile.
MUDSLIDES	**Morphology:**	Shallow concave niche with flat lobate accumulative part, clearly wider than transportational path. Irregular morphology is contrasting with surrounding ar slope 15°-25°.
	Vegetation:	Clear vegetational contrast when fresh, otherwise differential vegetation is enhancing morphological features.
	Drainage:	No mayor drainage anomalies associated to mudslides, besides local problems with surface drainage.
EARTHFLOWS	**Morphology:**	One large or several smaller concavities, with hummocky relief in the source area. Main scars and several small scars resembles slide type of failure. Path f and body is infilling valley, contrasting with V shaped valleys. Lobate convex frontal part. Irregular micromorphology with pattern related to flow- structur

		very small
	Vegetation:	Vegetational on scar and body strongly contrasting with surroundings, landuse absent if active. Linear pattern in direction of flow.
	Drainage:	Ponding frequent in concave upper part of flow. Parallel drainage channels on both sides of the body in the valley. Deflected or blocked drainage by frontal
FLOWSLIDES	**Morphology:**	Large bowlshaped source area with step-like or hummocky internal relief. Relative great width. Body displays clear flowstructures with lobate convex fron Frequent associated with cliffs (weak rock) or terrace edges.
	Vegetation:	Vegetational pattern are enhancing morphology of scarps and blocks in source area. Highly disturbed and differential vegetation on body.
	Drainage:	As on earthflows, ponding or deranged drainage at the rear part and deflected or blocked drainage by frontal lobe.
DEBRIS AVALANCHES	**Morphology:**	Relatively small, shallow niches on steep slopes (>35°) with clear linear path. Body frequently absent (eroded away by stream).
	Vegetation:	Niche and path are denudated, or covered by secondary vegetation.
	Drainage:	Shallow linear gully can originate on the path of the debris avalanche.
DEBRIS FLOW	**Morphology**	Large amount of small concavities (associated to drainage system) or one major scar is characterising source area. Almost complete destruction along path, depositional levees. Flattish desolated plain, exhibiting vague flow structures is body.
	Vegetation:	Absence of vegetation everywhere, recovery will take many years.
	Drainage:	Deranged on body, while original streams are blocked or deflected by the body.

Table 6: Image characteristics of mass movement types.

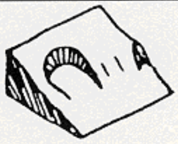
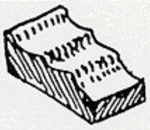
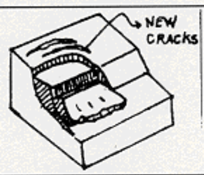
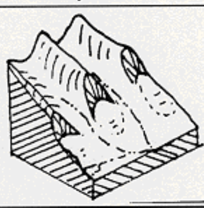
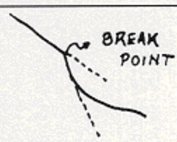
Morphological Characteristics	Block diagram	Plant View/ Profile
1. Concave-convex slopes 		
2. Semicircular niches		
3. Step-like morphology		
4. Back tilting of slope faces		
5. Hummocky relief		
6. Cracks formation		
7. Steeping of the slopes		

Figure ?: Morphological characteristics for identfying slope movements

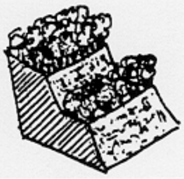
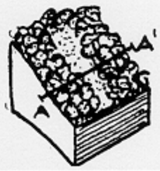
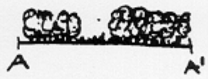
Vegetation Characteristics	Block Diagram	Plan view
8. Disorder and partly dead vegetation		
9. Disrupted vegetation cover across the slope and coinciding with morphological steps		
10. Less dense vegetated areas aligned and with lighter tones		
11. Differences in vegetation inside and Outside of the landslide		
12. Change in vegetation related with drainage conditions		

Figure ?: Vegetation characteristics for identifying slope movements.

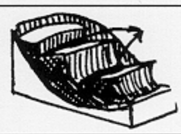
Drainage Characteristics		Sketch
13. Disarranged drainage	Drainage lines broken	
14. Anomaly in drainage pattern		
15. Zones of stagnated water	Ponds formation	
16. Seepage zones or well appearance	Darker tones leading to drainage line	
17. Excessively drained masses (especially dried out landslide bodies)	Light phototones	

Figure ?: Drainage characteristics for identifying slope movements

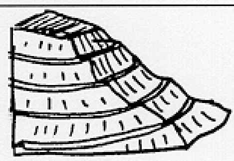
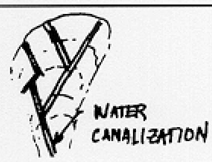
Stabilization Measures		Sketch
18. Terraces on slopes with artificial drainage cannals following contour lines		
19. Water channelize		

Figure ?: Stability measured that can be observed from airphotos, and that can be used to identify slope movements

Non-Active	Active
Scarp body and cracks with rounded edges	Scarp body and cracks with sharp edges
Vegetation is high within the landslide and non tilted trees	Bare soils or disrupted large vegetation
Well developed drainage system	Disarranged drainage system, presence of ponds and undrained depressions
No secondary mass movements on scarp faces	Secondary mass movements on scarp faces
Stabilization measures visible and not disrupted	Stabilization measures are disrupted
Depressions and cracks infilled with material	New cracks developing above the upper scarp

Figure?: Criteria for determining the activity of slope movements.

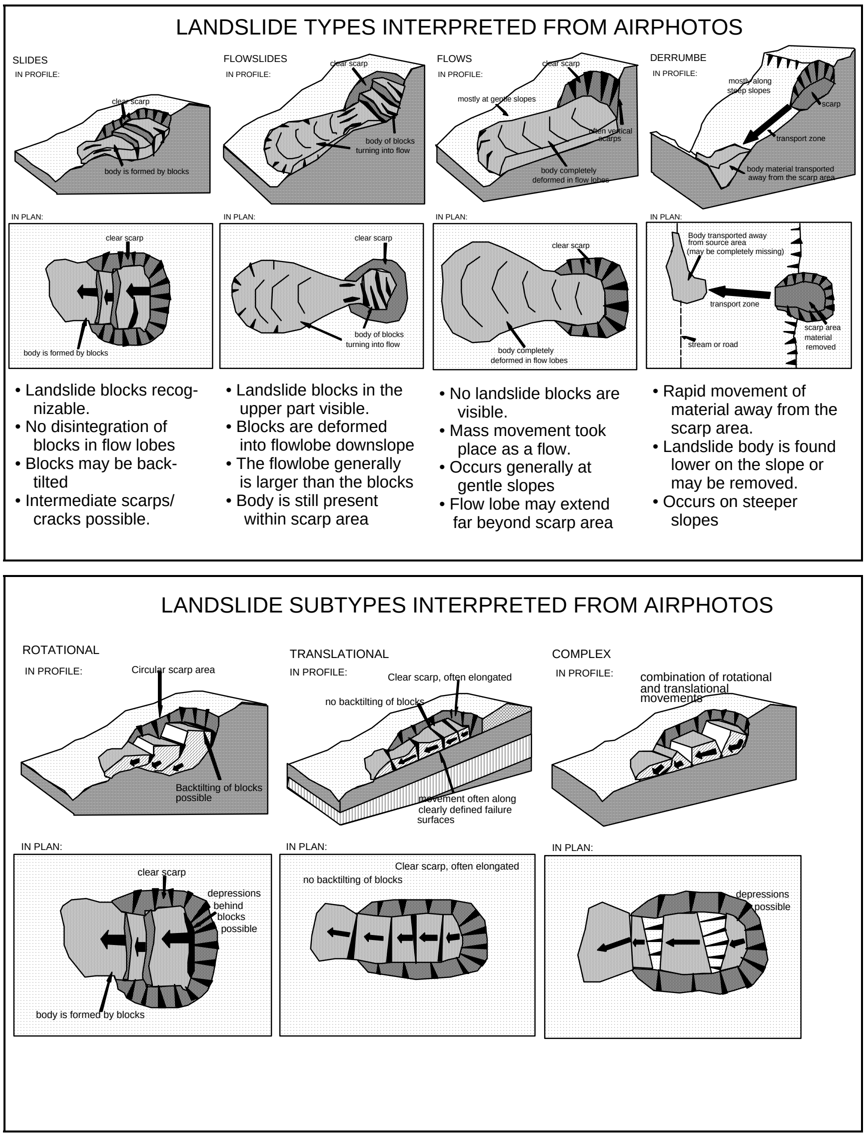
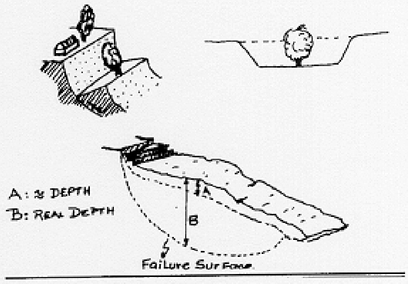


Figure ?: Some characteristics that can be interpreted from aerial photos that are used to describe landslide types and subtypes.

Shallow	Deep
<5Meters	<5 Meters
The depth can be estimated when an object of a known size (houses or trees) are projected within the landslide area. When the size of the landslide is very large the depth is assumed to be >5 mt.	

Figure?: Criteria for determining the depth of slope movements.

Scarp	Body	Scarp & Body
Visible as a concavity in the terrain, the body is absent or erodes away 	Convex shape and irregular surface 	Concave and convex slope connected 

Figure ?: How to differentiate between scarp and body of a mass movement.

Table 5 gives the terrain features which are frequently associated with slope movements, the relation of these features with landslides and their characterization on the photographs. These elements are used to come to an interpretation allowing for a classification of the slope failure according to the characteristics, as given in table 6. In the following sections the interpretation of various types of mass movements will be treated in more detail.

Fall and topples

Fall and topples are always related to very steep slopes (mostly larger than 50°), in which rocks are directly exposed. The fall is mostly controlled by discontinuities (joints, fractures), giving the rock slope a rough appearance, expressed in the image by a coarse texture. Fine lineaments at the crest that are parallel to the free face, can be related to open joints behind toppling blocks, considering that a joint set parallel to the slope is a conditioning factor for toppling. The accumulation of talus at the foot of the slope, or the occurrence of coarse scree on slopes below the free face, is associated with an rough micromorphology, giving also a relatively coarse textural appearance to the image.

Footslopes formed by fall processes have slopes of 25 - 35°. Scattered trees or bushes are the most frequent vegetation on the accumulative slopes. The density of this vegetation is indicative for the degree of activity of the slope movements. At specific places, where fall occurs more frequently, chutes (very steep and narrow channels) are eroded in the rockwall and dejection cones are formed at its base. Linear patterns, also in the vegetation, are indicative for the paths along which the blocks are falling.

Large complex rockfalls or *sturzstroms* are associated with mayor morphological anomalies and scars on the mountain slope. The accumulation of the material, which is spread even at considerable distance from the source area, is creating often rather chaotic landforms, in which enormous blocks create an extremely irregular rough morphology. This chaotic morphology is enhanced in the image by the irregular vegetational pattern. Lobate convex forms are sometimes found in the front of the mass. The drainage pattern in the whole area is generally seriously disturbed by these large complex rock falls. Surface drainage can be blocked by the accumulative mass, creating lakes, or rivers are deflected, finding their way around the mass. Abrupt changes in the width and pattern of the river and clear asymmetric valley slopes at the place of the accumulative mass, are other characteristics. Quite often it is observed that larger mass movements, which have deflected the drainage, are inducing slope instability features on the opposite valley side.

Slides

Rotational slides are mainly associated with slopes of 20 - 40° and are recognised by a characteristic slope morphology. The crown of the slide, with its frequent semi-lunar shape, initiates the abrupt change in the slope morphology. Concave and convex slope forms are related to the landslide niche and the accumulative part, which are directly in connection to each other, giving a D/L ratio in the order of 0.3 - 0.1. Successive or retrogressive sliding results in a steplike morphology. The frontal part has generally a convex lobate form. The rotational movement often results in backtilting slope facets. The overall micromorphology on a landslide is irregular, resulting in textural and tonal variations on the aerial photograph. The differential drainage conditions on a landslide and the disturbed vegetational conditions, are enhancing the textural and tonal variations or are resulting, when the scale of the image is appropriate, in characteristic pattern in association with slide scars and backtilted blocks. Bad surface drainage or even ponding occurs in the main landslide niche and at the rear part of backtilting blocks. Wet zones and springlevels are characteristic along the toe of the slide, influencing the tone on the photographs as well by the wetter conditions as by the differential vegetation. The vegetation on a slide shows a disturbed and chaotic aspect as well by the slope failure itself, as by the differential drainage conditions. The absence or differences in landuse, in comparison to the surroundings, is remarkable and also indicative for the activity of the movement.

Compound slides, a form in between rotational and translational, are in many aspects similar to rotational slides, but often with graben like depressions in the backpart of the slide and a less pronounced run-out. The D/L ratio is normally smaller than for rotational slides, while the width of the compound slide is mostly larger.

In *translational slides* the failure plane is controlled by a pre-existing discontinuity, which has its clear consequences for the morphological aspects of the mass movement. In the first place the D/L ratio is many times smaller than for rotational slides, while the width of the movement is larger than for most rotational slides. When the failure is controlled by the discontinuity of surface material and bedrock, the movement will be shallow and the displacement over a considerable distance. Those slope failures are also relatively wide. Flowtype features in the run-out material are frequent, when the coherence of the material is low and strong rainfall the triggering mechanism. The source area, as well as the path along which the material moved, are denudated from vegetation, resulting in a clear tonal contrast with the surroundings. Lineaments parallel to the direction of the movement are normal on the transportational path. Vegetational conditions are chaotic on the slided mass and landuse will most often be absent when the movement is recent (only a few years old). Also the drainage conditions are disordered on the slide, although the typical bad drained areas associated with rotational slides are normally absent.

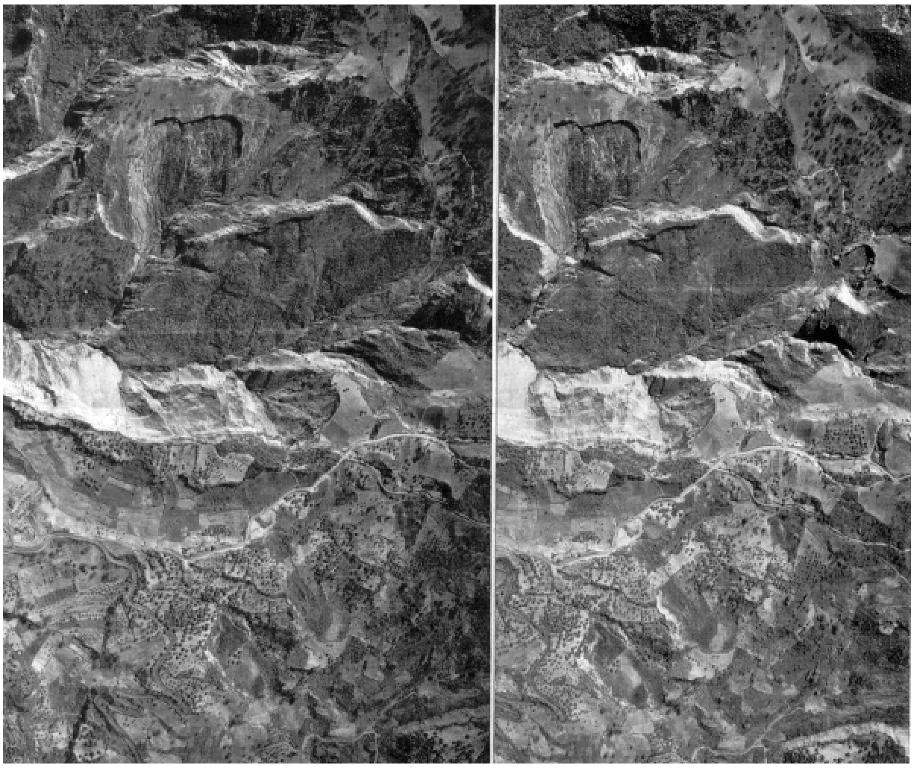


Figure ?: Translational slides controlled by dip slopes in sequence of very friable sandstones alternating with siltstones and mudstones. Joint controlled back scarp, linear patterns, and micromorphology of area where the sandstones have slid away (lower part) are disgnostic for landslides.

Rockslides are also characterised by a D/L ratio < 0.1 and a large width. The structural control of the failure surface and at the crown of the slide by joints or faults is distinct. The morphology on the run-out is very rough and the decrease of the block size with an increase of the transportational distance is characteristic. Enormous slabs occur close to the source area and an irregular blockfield at a larger distance. The vegetation is absent in the source area and along the path. On the slide mass the vegetation is chaotic and in patches. The drainage conditions are normally good, as most of the drainage will be internal. A springlevel is usually found at the toe of the slide and can be enhanced by the vegetation. The front of the mass can obstruct local streams.

In the category of *complex and composite slides* mudslides can be differentiated. Mudslides are generally shallow mass movements occurring on slopes of 15 - 25° in fine clayey deposits. The morphology of mudslides is characterised by a clear concave niche from where the material was derived and which is comparable to those of shallow slides. The transportational path is often represented by a more or less straight channel, where failure occurs due to undrained loading of the slope. The depositional part displays a lobate form, characteristic for a certain viscosity of the material. The D/L ratio, which is in the order of 0.05 - 0.01, is much smaller in comparison to slides and the clear differentiation in space between the source area, a transportational path and an accumulative zone are diagnostic features of mudslides. The runout deposits are showing a dilatation in width in comparison to the width of the source area and the transportational path, where the material was confined.

Another type of complex and composite movements are caused by the sudden collapse of loose saturated almost cohesionless soils or weak rocks. These movements, also known as *flowslides* (Cruden, chapter 3; Hutchinson, 1988), are occurring on moderate to gentle slopes or even in almost flat terrain. The area from where the flowslide is derived is often an extensive flat concave zone with an irregular hummocky or undulating micromorphology. The drainage conditions are completely disturbed and ponding waters are frequent in this area. These conditions are in strong contrast with the surroundings, which are showing a smooth topography with an almost complete internal drainage. A relatively narrow opening or neck indicates the place through which the run-out occurred. The transportational path, which varies in length according to the slope of the area and the fluidity of the mass, is clearly recognised on the images by a tonal contrast and lineaments parallel to the flow. The accumulative mass has a flat slightly convex lobate form. Flow structures are clearly visible as well in the micromorphology as in the vegetational cover due to differential drainage conditions. Flowslides in weak rocks (chalk) are always associated to collapses along cliffs (Hutchinson, 1988). According to the material in which the failure occurs, the size of the failure and the place from where the movements is derived, the overall morphology can resemble large rockfall avalanches (sturzstroms), translational slides produced by the failure in a horizon due to a rapid upbuilding of the porewater pressure, or liquefaction spreads.

Spreads

Spreads are mass movements occurring on gentle to moderate slopes, where a slow plastic deformation or a liquefaction occurs in a subsurface horizon overlain by a more coherent surface layer, which is broken up by the movements of the underlying material and moves and slides outwards on the back of the underlying layer. The areal extent of the movement is often considerable (up to several square kilometres) and the limits of the movement at the surface can be diffuse and difficult to distinguish on the aerial photographs but also in the terrain. Linear features corresponding to cracks and tilting of blocks of the surface material are visible indicators on remote sensing images for the initial movements. The presence of the cracks is often enhanced by vegetational differences. The morphological anomalies are increasing on the middle part of the slide. The surface material is breaking up in irregular blocks chaotically disposed, evidenced by the morphology, the drainage and vegetational conditions. The blocksize in the lateral spreads decreases with increasing transportation distance. The bulging of the lower slopes, displaying a typical convex form, is indicative for the extrusion of the unstable and plastic deformable subsurface material. Bad drainage conditions and seepage horizons are characteristic for this zone, evidenced by tonal differences in the photographs. Lateral spreads are often resulting in overall drainage anomalies, as the movements are narrowing or closing valleys and deflecting streams. This has as consequence an increased stream erosion at the site where the spread tends to close the valley, which results in local rotational slides of a considerable smaller size than the lateral spread.

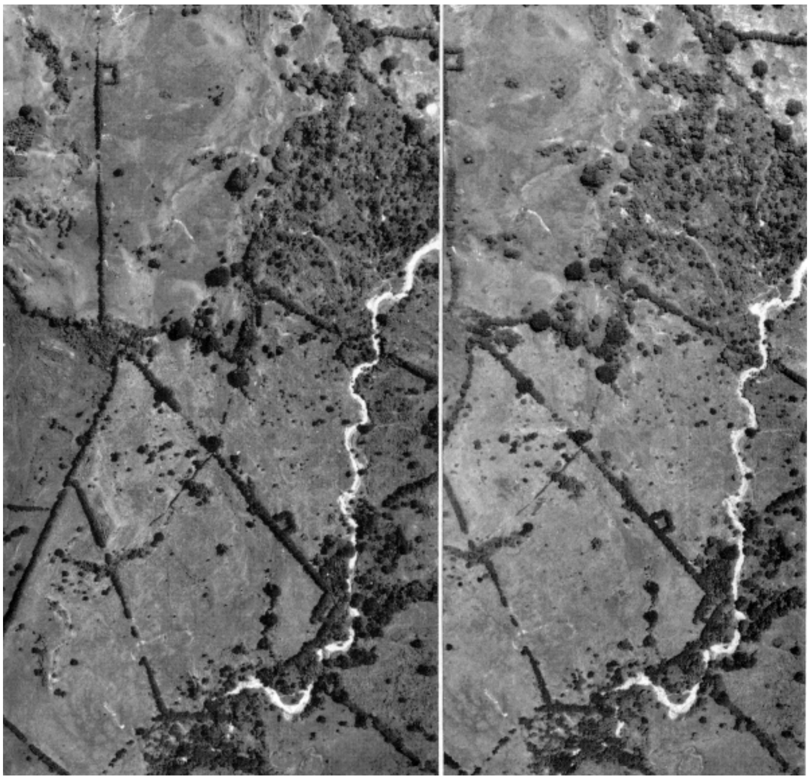


Figure ?: Highly unstable zone with numerous rotational landslides, mud slides, and earth flows. Well-cemented, but strongly jointed volcanoclastic sequence, dipping gently to the southwaet (north is up), overlies series of almost unconsolidated sandstones and mudstones and claystones, deposited in shallow marine to coastal environment. Steplike morhology is characteristic for rotational slides. Hummocky morphology is more indicative for flow-like movements.

Flows

Flows are comprising a large range of slope failures, going from relatively slow moving earthflows to the extremely fast debris avalanches and devastating debris flows of the lahar type or induced by the failure of a natural or artificial lake (GLOF, damburst).

Earthflows are often originated by various types of mass movements. The coherence within the landslide mass is lost, due to the initial slope failure, and given the water content, the mass continues as a viscous flow its way slope downwards. Earthflows are not limited to a slope segment, but continue their way along streamchannels, reaching main valleys where they may obstruct the drainage. The source area of earthflows has often the aspect of a zone with complex mass movements, slides are coming from various sides and generally showing a clear retrogressive progression. The transportational path is distinct, following first the maximum slope and than a streamchannel. The earthflow material exhibit morphological features which are often comparable to glaciers or lavaflows, with cracks (lineaments on the aerial photograph) parallel to the movement and transversal cracks at places where the slope and flow velocity increase. The transversal section of an earthflow is slightly convex, visible in the image due to the stereoscopic relief exaggeration. The earthflow, infilling the valley, creates a clear morphological anomaly, contrasting with the normally V-shaped valleys in mountainous areas. The frontal part has a clear lobate convex form. The source area is generally devastated of any vegetation, while the vegetation on the earthflow, if any, shows a patchy aspect due to differential surface drainage conditions on the material. The drainage conditions in the source area are disturbed and locally ponding can occur.The two small streams, which will develop on both sides of the earthflow, are forming a clear drainage anomaly in the same way as the deflected stream around the frontal lobe.

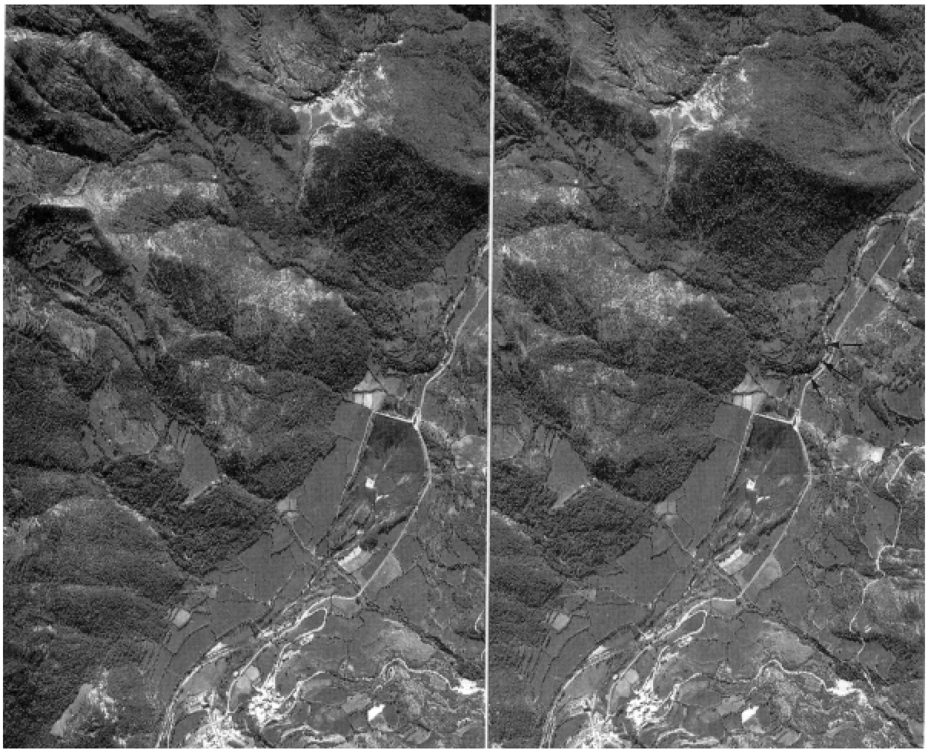


Figure ?: Major earth flow within small valley and almost blocking main valley. Convexc form of earth-flow is characteristic of earth-flows and contrasts with concave forms of alluvial fans. River is pressed against opposite side of the valley and may cause uindercutting and slope failures on that side.

Debris avalanches are extremely fast and sometimes relatively small slope failures on straight steep slopes (generally more than 35°). They are characterised by a concave niche, from which a long narrow light toned tail originates. The linear character remains visible on the aerial photograph even when secondary vegetation has invaded the area affected by the mass movement. Debris avalanches are common on steep slopes, almost in their maximum angle of stability, where the equilibrium has been disturbed by a vegetational/landuse change or an engineering work like a road construction.

Debris flows can be originated by a large number of factors, but in all cases considerable amounts of loose material are suddenly removed by an excessive amount of water and transported in an extremely fast and destructive flow through the valley downwards. According to the origin of the debris flow, the morphological characteristics of the source area may vary. The zone can be characterised by a large number of surficial debris slides, as shown in figure 12, depicting a debris flow in Thailand originated by an extremely intensive rainfall, triggering off a large amount of superficial slides in weathered rocks. However, it is also possible that the debris flow is originated by a single slope failure, caused by the failure of a lake or dam, as for example the glacial lake outburst floods (GLOF).

Common to all debris flows are the marks left behind by the devastating flow, which have such large dimensions, that they are clearly recognisable even on small scale images or a considerable time after the event occurred. The appearance of the depositional mass varies with the type of material transported, but generally consists of a desolated flat area, englobing sometimes small higher vegetated parts corresponding to an old relief. Large blocks of rock, floating in the mud, may create an irregular micromorphology recognisable on large scale photographs by a rough or coarse texture. Flow structures are often absent in this chaotically deposited mass. Drainage conditions on the flow mass are deranged, while the mass on itself is deflecting or obstructing the streams in the area of deposition.

Creep, deepseated creep and *bedrock flows* are processes which generally don't affect the morphological conditions sufficiently to be interpreted in a preliminary interpretation. They can only be mapped having good knowledge of the local conditions. However, once that characteristic features for creep are known, this knowledge can successfully be extrapolated on the aerial photographs. Creep can create an irregular micromorphology, sometimes reflected in the drainage and vegetation, causing a contrast with the zones not affected by creep and which are showing very smooth forms with equal greytones in comparison to the affected area. Bulging of slopes is associated with deepseated creep and when the movement develops into sagging, it is generally accompanied by elongated depressions along the slope, double crested hillcrests and backtilting slope facets. The occurrence of minor slope failures as the result of the slope oversteepening caused by the bulging of the slope and lower slopes covered by large accumulations of loose scree are other features associated with slow deepseated deformations of mountain slopes (sagging, gravitational spreading).