Chapter 8

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SLOPE INSTABILITY RECOGNITION, ANALYSIS, AND ZONATION

1. INTRODUCTION

Slope instability processes are the product of local geomorphic, hydrologic, and geologic conditions; the modification of these conditions by geodynamic processes, vegetation, land use practices, and human activities; and the frequency and intensity of precipitation and seismicity.

The engineering approach to landslide studies has focused attention on analysis of individual slope failures and their remedial measures. The techniques used in these studies were in accordance with their required large scale and did not allow for zonation of extensive areas according to their susceptibility to slope instability phenomena. The need for this type of zonation has increased with the understanding that proper planning will decrease considerably the costs of construction and maintenance of engineering structures.

Considering the many terrain factors involved in slope instability, the practice of landslide hazard zonation requires

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

Some methodological aspects of slope instability hazard zonation are dealt with in Section 2 of this chapter. The essential role of the earth scientist in modeling the spatial distribution of terrain conditions leading to instability is noted, and a scheme is given for a hierarchical approach to slope instability zonation that is similar to the phases recognized in engineering projects. By following such a systematic approach, the necessary steps to a hazard assessment are defined, taking into consideration both direct and indirect mapping techniques. An overview of current practice is given.

In Section 3 emphasis is on the application of remote-sensing techniques to landslide studies and hazard zonation. A systematic guide is presented for recognition and interpretation of slope movements. The applicability of different remote-sensing data to landslide recognition is evaluated, considering their characteristic spatial, spectral, and temporal resolutions.

The capabilities of a geographic information system (GIS) for analyzing terrain factors that lead to slope instability are highlighted in Section 4. An integration of data collection and analysis techniques is proposed for slope instability zonation at different scales.

The terminology concerning hazards used in this chapter conforms to the definitions proposed by Varnes (1984):

- *Natural hazard* means the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area;

- *Risk* means the expected number of lives lost, persons injured, damage to property, or disruption of economic activity because of a particular natural phenomenon; and
- *Zonation* refers to the division of land in homogeneous areas or domains and the ranking of these areas according to their degrees of actual or potential hazard caused by mass movement.

To determine risk, Varnes gave 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, and so on, at risk in a given area; and
- *Specific risk* means the expected degree of loss due to a particular natural phenomenon.

Landslide hazard is commonly shown on maps that display the spatial distribution of hazard classes (or landslide hazard zonation). Landslide hazard zonation requires a detailed knowledge of the processes that are or have been active in an area and of the factors leading to the occurrence of the potentially damaging phenomenon. This knowledge is considered the domain 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 disciplines other than the earth sciences, such as specialists in urban planning and social geography, economists, and engineers.

As discussed in Chapter 6, fully developed examples of risk analysis on a quantitative basis are still scarce in the literature (Einstein 1988; Kienholz 1992; Innocienti 1992; Keaton 1994), partly 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 such triggering factors as earthquakes or rainfall, as discussed in Chapter 4, or the application of complex models. In most cases, however, there is no clear relationship between these factors and the occurrence of landslides. Therefore, in most hazard maps the legend classes used generally do not give more information than the susceptibility of certain areas to landsliding or relative indications of the degree of hazard, such as high, medium, and low. From the review of many example studies, it appears that susceptibility usually expresses the likelihood that a phenomenon (in this case, a landslide) will occur in an area on the basis of the local terrain conditions; the probability of occurrence, which depends also on the recurrence of triggering factors such as rainfall or seismicity, is not considered. The terms *hazard* and *susceptibility* are frequently used synonymously.

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

2. PRINCIPLES OF HAZARD ZONATION

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 (Hartlén and Viberg 1988). A reliable landslide inventory defining the type and activity of all landslides, as well as their spatial distribution, is essential before any analysis of the occurrence of landslides and their relationship to environmental conditions is undertaken. The differentiation of slope instability according to type of movement is important, not only because different types of mass movement will occur under different terrain conditions, but also because the impact of slope failures on the environment has to be evaluated according to type of failure.

2.1 General Considerations

Prediction of landslide hazard for areas not currently subject to landsliding is based on the assumption that hazardous phenomena that have occurred in the past can provide useful information for prediction of future occurrences. 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, two basic methodologies can be recognized:

1. The first mapping methodology is the experience-driven applied-geomorphic approach, by which the earth scientist evaluates direct relationships between landslides and their geomorphic and geologic settings by employing direct observations during a survey of as many existing landslide sites as possible. This is also known as the *direct mapping methodology*.
2. The opposite of this experience-based, or heuristic, approach is the *indirect mapping methodology*, which consists of mapping a large number of parameters considered to potentially affect landsliding and subsequently analyzing (statistically) all these possible contributing factors with respect to the occurrence of slope instability phenomena. In this way the relationships between the terrain conditions and the occurrence of landslides may be identified. On the basis of the results of this analysis, statements are made regarding the conditions under which slope failures occur.

Another useful division of techniques for assessment of slope instability hazard was given by Hartlén and Viberg (1988), who differentiated between *relative-hazard assessment techniques* and *absolute-hazard assessment techniques*. 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 also be divided into three main groups (Carrara 1983; Hartlén and Viberg 1988):

1. *White box models*, based on physical models (slope stability and hydrologic models), also referred to as *deterministic models*;
2. *Black box models*, not based on physical models but strictly on statistical analysis; and
3. *Grey box models*, based partly on physical models and partly on statistics.

2.2 Scale-Related Objectives

The development of a clear hierarchical methodology in hazard zonation is necessary to obtain an acceptable cost/benefit ratio and to ensure the practical applicability of the zonation. The working scale for a slope instability analysis is determined by the requirements of the user for whom the survey is executed. Because planners and engineers form the most important user community, the following scales of analysis have been differentiated for landslide hazard zonation (International Association of Engineering Geology 1976):

- National scale (< 1:1 million)
- Regional scale (1:100,000 to 1:500,000)
- Medium scale (1:25,000 to 1:50,000)
- Large scale (1:5,000 to 1:15,000)

The national hazard zonation mapping scale is intended to give a general inventory of problem areas for an entire country that can be used to inform national policy makers and the general public. The level of detail will be low because the assessment is done mostly on the basis of generally applicable rules.

The regional mapping scale is meant for planners in the early phases of regional development projects or for engineers evaluating possible constraints due to instability in the development of large engineering projects and regional development plans. The areas to be investigated are large, on the order of 1000 km^2 or more, and the required level of map detail is low. The map indicates areas in which mass movements can be a constraint on the development of rural or urban transportation projects. Terrain units with an areal extent of several tens of hectares are outlined and classified according to their susceptibility to 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. The areas to be investigated may cover upward of a few hundreds of square kilometers; yet a considerably higher level of 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 their 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, when appropriate, than an adjacent straight or convex slope.

Large-scale hazard zonation maps can be used at the level of the site investigation before the design phase of engineering projects. This scale allows evaluation of the variability of a safety factor as a function of variable slope conditions or under the influence of triggering factors. The size of area under study may range up to several tens of square kilometers. 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 clearly defined.

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 type of problem and availability of data, financial resources, and time for the investigation, as well as the professional experience of those involved in the survey.

2.3 Input Data

Slope instability phenomena are related to a large variety of factors involving both the physical environment and human interaction. Thus, assessment of landslide hazard requires knowledge about these factors, ranging from geologic structure to land use. For this reason landslide hazard assessments should preferably involve multidisciplinary teams.

The input data needed to assess landslide hazard at the regional, medium, and large scales are given in Table 8-1. The list is extensive, and only in an ideal case will all types of data be available. However, as will be explained in Section 2.4, the amount and type of data that can be collected will determine the type of hazard analysis that can be applied, ranging from qualitative assessment to complex statistical methods.

The input data needed for landslide hazard analysis can be subdivided into five main groups: geomorphology; topography; engineering geology, geotechnology, or both; land use; and hydrology. Each group may be subdivided to form a sequence of so-called *data layers*. Each data layer may be represented by an individual map containing that one type of data. As discussed in Section 4, when GIS techniques are employed, it is important that each data-layer map be composed of only one type of data element (points, lines, or areas and polygons) and have one or more accompanying tables to define the characteristics of each. Of course, the data layers required by landslide hazard analysis may vary to account for the characteristics of different environments.

In the second column of Table 8-1 the various parameters that are stored in "attribute tables" connected to each map are indicated. In the third column a summary is given of the method by which each data layer is collected, which refers to the three phases of data collection (image interpretation, fieldwork, and laboratory analysis). A number of data layers, such as material sequences, seismic acceleration maps, and water table maps, require the use of specific models in addition to the conventional data collection techniques. Specific algorithms within a GIS may be used to convert topographic elevation values into slope categories or to perform other topographic analyses (see Section 4).

The ratings in the last three columns of Table 8-1 indicate the relative feasibility of collecting certain data types for each of the three scales under consideration. The feasibility of collecting data for a certain scale does not imply that the specific type of data is also useful for that particular scale. A map using terrain mapping units, for example, can be prepared at a 1:10,000 scale but will be of limited use because of its generalized content.

Because of the large areas to be studied and the objectives of a hazard assessment at the regional scale (see Section 2.2), detailed data collection for individual factors (geomorphology, lithology, soils, etc.) is not a cost-effective approach. Data gathered for this scale should be limited to the delineation of homogeneous terrain mapping units, for example, with the use of stereoscopic satellite imagery and the collection of regional tectonic or seismic data.

For the medium scale almost all data layers given in Table 8-1 can be gathered easily with the exception of detailed groundwater and geotechnical information. The data collection at this scale should be focused on the production of detailed multitemporal landslide distribution maps and the various parameters required in statistical analysis.

For large-scale hazard zonation, in which work is carried out in relatively small areas, all of the proposed data layers can be readily collected. Data collection at this scale should relate to the parameters needed for slope stability modeling (for example, material sequences, seismic accelerations, and hydrologic data).

2.4 General Trends

A great deal of research concerning slope instability hazard has been done over the last 30 years.

Table 8-1
Overview of Input Data for Landslide Hazard Analysis

Data Layers for Slope Instability Hazard Zonation	Accompanying Data in Tables	Method Used	Scale of Analysis		
			Regional	Medium	Large
Geomorphology					
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 Geology					
10. Lithologies	Lithology, rock strength, discontinuity spacing	Existing maps + API + fieldwork, field and laboratory testing	2	3	3
11. Material sequences	Material types, depth, USCS classification, grain-size distribution, bulk density, c and φ	Modeling from lithological map + geomorphological map + slope map, field descriptions, field and 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 + modeling	3	3	3
Land Use					
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. Land use map (recent)	Land use types, tree density, root depth	API + classification of satellite imagery + fieldwork	2	3	3
17. Land use map (older)	Land use types	API	2	3	3
Hydrology					
18. Drainage	Type, order, length	API + topographical maps	3	3	3
19. Catchment areas	Order, size	API + topographical maps	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 modeling	2	3	3
23. Water table maps	Depth of water table in time	Field measurements of K_{sat} + hydrological model	1	1	2

Note: The last three columns indicate the possibility for data collection for the three scales of analysis: 3 = good, 2 = moderate, and 1 = poor. Abbreviations used: SII = satellite image interpretation, API = aerial photointerpretation, DTM = digital terrain model, GIS = geographic information system, K_{sat} = saturated conductivity testing.

Initially the investigations were oriented mainly toward solving instability problems at particular sites. Techniques were developed by engineers for the appropriate design of a planned structure as well as the prevention of slope failure. Therefore, research emphasized site investigation techniques and the development of deterministic and probabilistic models. However, the heterogeneity of the natural environment at the regional scale and the large variability in geotechnical properties such as cohesion and internal friction are in sharp contrast to the homogeneity required by deterministic models. This contrast, coupled with the costly and time-consuming site investigation techniques required to obtain property values, makes the engineering approach unsuitable for application over large areas.

In engineering projects, such large areas must often be assessed during early phases of planning and decision making. To solve this problem, several other types of landslide hazard analysis techniques have been developed during the last decades. These techniques provide hazard assessment based on a careful study of the natural conditions of an area and analysis of all the possible parameters involved in slope instability processes. These various methodological approaches, which were reviewed in detail by Hansen (1984) and Varnes (1984), are summarized in the following sections. Some examples are included in this chapter for illustration.

2.4.1 Landslide Inventory

The most straightforward approach to landslide hazard zonation is a *landslide inventory*, based on any or all of the following: aerial photointerpretation, ground survey, and a data base of historical occurrences of landslides in an area. The final product gives the spatial distribution of mass movements, which may be represented on a map either as affected areas to scale or as point symbols (Wieczorek 1984). Such mass movement inventory maps are the basis for most other landslide hazard zonation techniques. They can, however, also be used as an elementary form of hazard map because they display the location of a particular type of slope movement. They provide information only for the period shortly preceding the date that aerial photographs were taken or the fieldwork was conducted. They provide no insight into temporal changes in mass movement distribution. Many landslides that occurred some time before photographs were taken may have become undetectable. Therefore a refinement is the construction of *landslide activity maps*, which are based on multitemporal aerial photointerpretation (Canuti et al. 1979). Landslide activity maps are indispensable to the study of effects of temporal variation of a factor, such as land use, on landsliding.

Landslide distribution can also be shown in the form of a *density map*. Wright et al. (1974) presented a method for calculating 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.

2.4.2 Heuristic Approach

In heuristic methods the expert opinion of the geomorphologist making the survey is used to classify the hazard. These methods combine the mapping of mass movements and their geomorphologic setting as the main input factor for hazard determination. Two types of heuristic analysis can be distinguished: geomorphic analysis and qualitative map combination.

2.4.2.1 Geomorphic Analysis

The basis for *geomorphic analysis* was outlined by Kienholz (1977), who developed a method for producing a combined hazard map based on the mapping of "silent witnesses" (*Stumme Zeugen*). The geomorphic 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 individual experience and the use of reasoning by analogy. The decision rules are therefore difficult to formulate because they vary from place to place. Examples of this methodology for the appraisal of terrain to determine its susceptibility to slope instability are especially common from Europe, where ample experience exists in geomorphic and engineering geologic mapping (Carrara and Merenda 1974; Kienholz 1977, 1978; Malgot and Mahr 1979; Kienholz et al. 1983, 1988; Ives and Messerli 1981; Rupke et al. 1988). There are many other examples from other regions, however (Hansen 1984; Varnes 1984). The French program that produces 1:25,000-scale ZERMOS maps (Meneroud and Calvino 1976) is probably the best example, but the reproducibility of these maps has been much debated (Antoine 1977). The same is true for the method used by Brunsden and his collaborators (1975), who do not even present a hazard zonation analysis for a project related to a road alignment. Rather, they directly suggest the alignment for the best possible road according to their assessment of the slope stability.

2.4.2.2 Qualitative Map Combination

To overcome the problem of the "hidden rules" in geomorphic mapping, other qualitative methods, based on *qualitative map combination*, have been developed. In qualitative map combination the earth scientist uses the expert knowledge of an individual to assign weighting values to a series of parameter maps. The terrain conditions at a large number of locations are summed according to these weights, leading to hazard values that 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 of the causal factors of slope instability, he assigned weighting values to different classes on a number of parameter maps. Qualitative map combination has become very popular in slope instability zonation. The problem with this method is in determining the exact weighting of the various parameter maps. Often, insufficient field knowledge of the important factors prevents the proper establishment of the factor weights, leading to unacceptable generalizations.

2.4.3 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 areas currently free of landslides but where similar conditions exist. Two different statistical approaches are used in landslide hazard analysis: bivariate and multivariate.

2.4.3.1 Bivariate Statistical Analysis

In *bivariate statistical analysis* each factor map (for example, slope, geology, land use) is combined with the landslide distribution map, and weighting values based on landslide densities are calculated for each parameter class (for example, slope class, lithologic unit, land use type). Brabb et al. (1972) provided the first example of such an analysis. They performed a simple combination of a landslide distribution map with a lithologic map and a slope map. Several statistical methods have been applied to calculate weighting values; these have been termed the *landslide susceptibility method* (Brabb 1984; van Westen 1992, 1993), *information value method* (Yin and Yan 1988; Kobashi and Suzuki 1988), and *weight-of-evidence modeling method* (Spiegelhalter 1986). Chung and Fabbri (1993) described several methods, including *Bayesian combination rules*, *certainty factors*, *Dempster-Shafer method*, and *fuzzy logic*.

2.4.3.2 Multivariate Statistical Analysis

Multivariate statistical analysis models for landslide hazard zonation were developed in Italy, mainly 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, the presence or absence of landslides is also 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 in areas with only a few types of slope instability processes, as shown in the work of Jones et al. (1961) concerning mass movements in terrace deposits. When complex statistics are applied, as was done by Carrara and his collaborators (Carrarra et al. 1990, 1991, 1992), by Neuland (1976), or by Kobashi and Suzuki (1988), a subdivision of the data according to the type of landslide should be made as well. Therefore, large data sets are needed to obtain enough cases to produce reliable results. The use of complex statistics implies laborious efforts in collecting large amounts of data, because these methods do not use selective criteria based on professional experience.

2.4.4 Deterministic Approach

Despite problems related to collection of sufficient and reliable input data, deterministic models are increasingly used in hazard analysis of larger areas, especially with the aid of GIS techniques, which can handle the large number of calculations involved in determination of safety factors over large areas. Deterministic methods are applicable only when the geomorphic and geologic 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 methods is their high degree of oversimplification. A deterministic method that is usually applied for translational landslides is the infinite slope model (Ward et al. 1982). These deterministic methods generally require the use of groundwater simulation models (Okimura and Kawatani 1986). Stochastic methods are sometimes used to select input parameters for the deterministic models (Mulder and van Asch 1988; Mulder 1991; Hammond et al. 1992).

2.4.5 Evaluation of Trends in Methodology

As discussed in Section 2.2, not all methods of landslide hazard zonation are equally applicable at each scale of analysis. Some require very detailed input data, which can only be collected for small areas because of the required levels of effort and thus the cost (see Section 2.3). Therefore, suitable methods have to be selected to define the most useful types of analysis for each of the mapping scales while also maintaining an acceptable cost/benefit ratio. Table 8-2 provides an overview of the various methods of landslide hazard analysis and recommendations for their use at the three most relevant scales.

Evaluation of the methodological approaches (see Table 8-2) and the literature on slope instability hazard zonation practices suggests that heuristic methods, described in Section 2.4.2, aim to establish the real causes for slope instability on the basis of scientific and professionally oriented reasoning. However, considering the scale of slope failures and the complexity of the conditions that may lead to slope instability, these direct mapping methods have to be executed on a large scale. Therefore, they are impractical to use over large areas and do not support implementation of a hierarchical approach to hazard zonation. The combination of geomorphic analysis with the application of weights to the contributing parameters, as used by Kienholz (1977; 1978), improves the objectivity and reproducibility of these heuristic methods. This is particularly the case when the weights are based on the contribution of various parameters to slope instability, with the contributions established by simple statistics.

For regional landslide hazard zonations at small scales (1:50,000 to 1:100,000), many approaches combine indirect mapping methods with more analytical approaches. At these scales a terrain classification can be made using stereo satellite imagery, thereby defining homogeneous lithomorphologic zones or terrain mapping units (Meijerink 1988). These terrain mapping units are further analyzed by photointerpretation and ground surveys. The characteristics of each terrain mapping unit are defined by attributed values, which define their probable values, or range of values, for a suite of parameters. An attribute data base is created in which the characteristics of all the terrain mapping units are defined in a series of tables. Relevant parameters are identified on the basis of an evaluation of slope instability in the area, and these are then used to define hazard categories. These categories are extrapolated to the terrain mapping units throughout the region being mapped according to the presence or absence of these relevant parameters (sometimes referred to as contributing factors) in the attribute data base.

As the project continues, the landslide zonation evolves. The size of the area being studied decreases and the scale of the investigation increases. Additional analytical studies are possible because more time and money become available. Factor maps, displaying the spatial distribution of the most important factors, together with increased analysis of possible contributing parameters based on statistics increase the accuracy of predictions of susceptibility to instability. An adjustment or refinement of the decision rules for the hazard assessment can be obtained by verifying the results of the initial assessment through comparison with the real situation in the field. If necessary, weights assigned to parameters can be adjusted and a new hazard assessment produced. This iterative method becomes necessary when the hazard assessment decision rules are extrapolated over areas with a similar geologic or geomorphic setting but where little ground truth is available because studies have shown that areas with apparently equal conditions may produce weighting values that vary considerably.

In detailed studies of small areas, large amounts of data may become available; thus, simple deterministic or probabilistic models, discussed in Section 2.4.4, become increasingly practical as methods for landslide hazard zonation. They allow the approximation of the variability of the safety factor for slope failure and thus yield information useful to design engineers.

Table 8-2
Analysis Techniques in Relation to Mapping Scales

Type of Analysis	Technique	Characteristics	Required Data Layers[a]	Scale of Use Recommended: Regional (1:100,000)	Medium (1:25,000)	Large (1:10,000)
Inventory	Landslide distribution analysis	Analyze distribution and classification of landslides	3	Yes [b]	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 [b]	No	No
Heuristic analysis	Geomorphological analysis	Use in-field expert opinion in zonation	2,3,4	Yes	Yes [c]	Yes [c]
	Qualitative map combination	Use expert-based weight values of parameter maps	2,3,5,6,7,8,9,10, 12,14,16,18	Yes [d]	Yes [c]	No
Statistical analysis	Bivariate statistical analysis	Calculate importance of contributing factor combination	2,3,5,6,7,8,9,10, 12,14,16,18	No	Yes	No
	Multivariate statistical analysis	Calculate prediction formula from data matrix	2,3,5,6,7,8,9,10, 12,14,16,18	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 [e]

[a] The numbers in this column refer to the input data layers given in Table 8-1.
[b] But only with reliable data on landslide distribution because mapping will be out of an acceptable cost/benefit ratio.
[c] But strongly supported by other more quantitative techniques to obtain an acceptable level of objectivity.
[d] But only if sufficient reliable data exist on the spatial distribution of the landslide controlling factors.
[e] But only under homogeneous terrain conditions, considering the variability of the geotechnical parameters.

2.5 Accuracy and Objectivity

The most important question to be asked in each landslide hazard study relates to its 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 accuracy of a landslide prediction depends on a large number of factors, the most important of which are

- Accuracy of the models,
- Accuracy of the input data,
- Experience of the earth scientists, and
- Size of the study area.

Many of these factors are interrelated. The size of the study area determines to a large degree what kind and density of data can be collected (see Table 8-1) and what kind of analysis technique can be applied (see Table 8-2).

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—the so-called "wait and see" procedure. However, this is often not a very useful method, for obvious reasons. There are two possible forms of prediction inaccuracies: landslides may occur in areas that are predicted to be stable, and landslides may actually not occur in areas that are predicted to be unstable. Both cases are undesirable, of course. However, the first case is potentially more serious, because a landslide occurring in an area predicted to be free of landsliding may cause severe damage or loss of life and may lead to lawsuits. The second case may result in additional expenses for unnecessary exploration, for design of complex structures, or for the realignment of facilities from what are in actuality perfectly acceptable areas to areas in which construction is more expensive.

The two possible cases of error in prediction are not equally easy to evaluate. In estimating the magnitude of the first case, in which a landslide occurs in an area predicted to be stable, the investigator is faced with the task of proving the presence of something that does not currently exist.

Accordingly, one of the most frequently used methods for checking the accuracy of hazard maps is the comparison of the final predictive hazard map with a map showing the pattern of existing landslides. A frequency distribution is made relating the hazard scores to identified landslide-prone and non-landslide-prone areas. From this frequency distribution the percentage of mapped landslides found in areas predicted to be stable (non-landslide-prone) can be calculated. This error is then assumed to be the same as the error in predicting landslides in currently 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 to see if newer movements confirm the predictions (Chung et al. in press). The comparison of landslide hazard maps made by different methods (for example, by statistical and by deterministic methods) may also provide a good idea of the accuracy of the prediction.

Related to the problem of assessing the accuracy of hazard maps is the question of their 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 on the personal judgment 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 is used or if only a few parameters are taken into account, the procedure may be highly objective but will produce an inaccurate map. On the other hand, subjective studies, such as detailed geomorphic slope stability analyses, when made by experienced geomorphologists may result in very accurate hazard maps. Yet such a good, but subjective, assessment may have a relatively low objectivity because its 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 that is required for creating the parameter maps. Studies were conducted by Dunoyer and van Westen (1994) to assess the degree of subjectivity involved in the interpretation of landslides from large-scale aerial photographs (at a scale of 1:10,000) by a group of 12 photointerpreters, several of whom had had considerable experience and some who had local knowledge. These comparisons have shown that differences between interpretations can be large (Dunoyer and van Westen 1994). These findings confirm other similar investigations on the subjectivity of photointerpretation 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 photointerpretation and will therefore include a large degree of subjectivity. Even data concerning factors that are obtained by means of precise measurements, such as soil strength, may have a high degree of subjectivity in the resulting parameter maps because the individual sample values, representing the conditions at the sampled location, have to be linked to mapped units on a material map produced by photointerpretation and fieldwork in order to provide a regional distribution of the sampled property.

For each type of data collection and analysis, different levels of objectivity and accuracy may be encountered at the various hierarchical levels corresponding to the various scales of hazard analysis. The demand for higher levels of objectivity has led several researchers to replace the subjective expert's opinion on the causative factors related to slope failure with statistical analysis of all 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 as to the accuracy of the assessment, especially when the experience and skill required in the data collection and the labor required to complete the extensive data sheets are considered (Figure 8-1).

Because of the limitations inherent in the data collection and analysis techniques and the restrictions imposed by the scale of mapping, a landslide hazard survey will always retain a certain degree of subjectivity, which does not necessarily imply inaccuracy. The objectivity and reproducibility of the hazard assessment can be improved considerably by interpretation of sequential imagery, by use of clear and if possible quantitative descriptions of

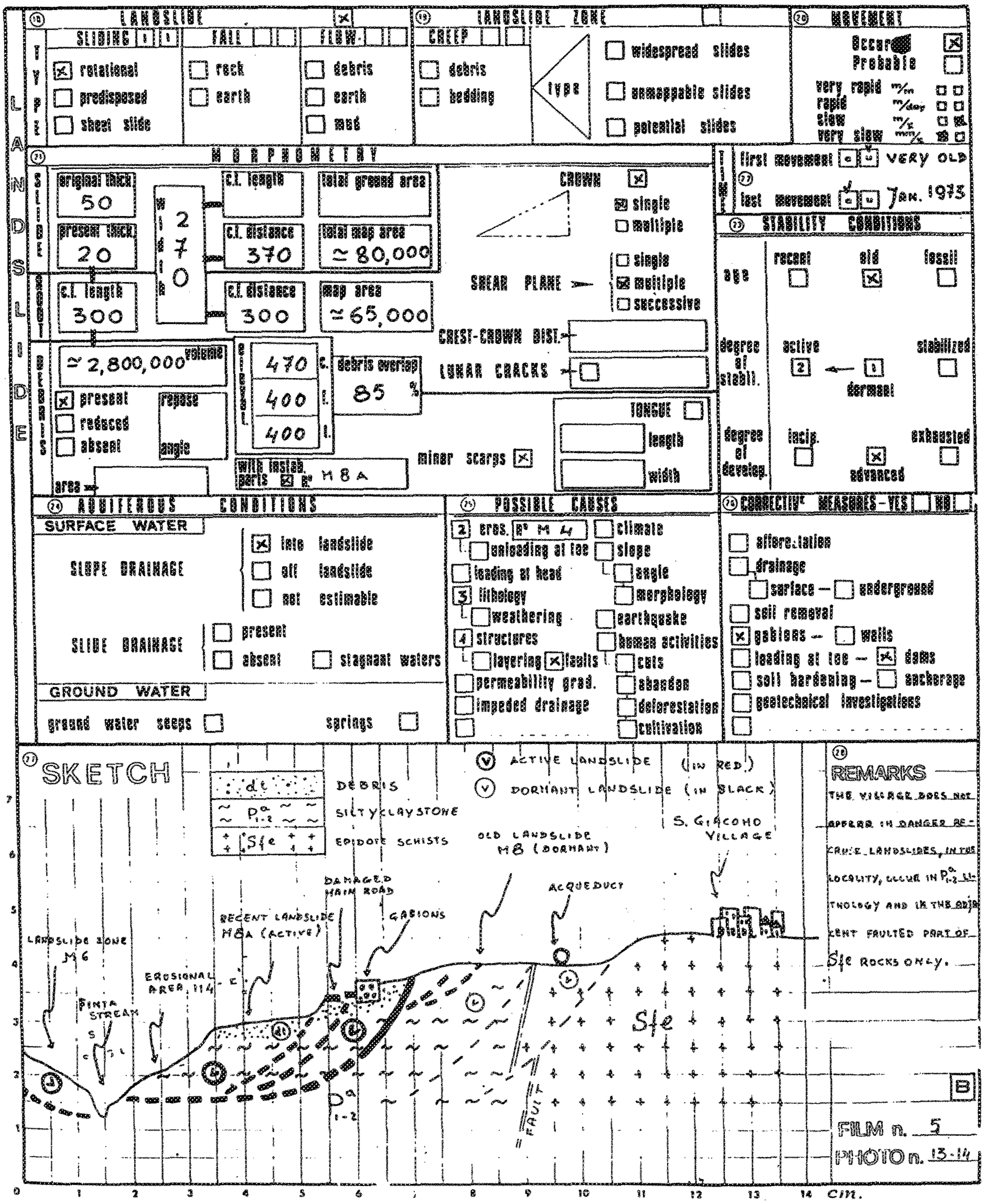


FIGURE 8-1
Page from data form used by Carrara and collaborators (Carrara and Merenda 1974).

the factors considered, and by application of well-defined analytical procedures and decision rules. The most important aspect, however, remains the experience of the interpreter with regard to both the various factors involved in slope instability hazard surveys and the specific conditions of the study area.

3. REMOTE SENSING IN SLOPE INSTABILITY STUDIES

Because landslides directly affect the ground surface, remote-sensing techniques are well suited to slope instability studies. The term *remote sensing* is used here in its widest sense, including aerial photography and imagery obtained by satellites or any other remote-sensing technique. Remote sensing is particularly useful when stereo images are used because they depict in the stereo model the typical morphologic features of landslides, which often can provide diagnostic information concerning the type of movement (Crozier 1973). Also, the overall terrain conditions, which are critical in determining the susceptibility of a site to slope instability, can profitably be interpreted from remote-sensing data.

The value of photointerpretation of aerial photographs for identifying slope instability has been reported by many investigators. Rib and Liang (1978) discussed these photointerpretation techniques in considerable detail. Mollard (1977) also demonstrated the utility of aerial photography in examining landslides. Several basic textbooks on slope instability refer to the importance of aerial photographs in the study of landslides (Brunsden and Prior 1984). Scientists at the University of Bari in Italy have successfully used aerial photographs to evaluate both active landslides (Guerricchio and Melidoro 1981) and historic movements (Cotecchia et al. 1986). However, during the past two decades, considerable development in remote sensing has occurred; thus an overview is presented here of the types of images available and their relevant characteristics for landslide investigations.

3.1 Remote-Sensing Products

There has been little development in aerial photography during the past two decades. Panchromatic black-and-white and color film are available to cover the visible part of the electromagnetic spectrum, and black-and-white infrared and false-color infrared film extend the imagery sensitivity into the reflective near-infrared regions. The spatial resolution of these films is excellent, and the aerial photographs are normally taken so as to provide stereoscopic coverage, producing a three-dimensional picture of the terrain that gives detailed morphologic information. However, the spectral resolution is much less than that provided by multispectral data imagery sources because the photography integrates the broad spectral band into a single picture. The organization of an aerial photographic mission is time-consuming, and in some locations the number of days during the year with climatic conditions suitable for acceptable aerial photography may be very limited. Thus temporal resolution, that is, the number of images of the same area over time, of aerial photography can be much less than that provided by satellite imagery. On the other hand, constraints imposed by orbital mechanics restrict satellite imagery to a fixed schedule of viewing opportunities, and these may not coincide with optimum weather conditions at a landslide site. In this regard, aerial photography may have more flexibility in scheduling, but at some considerable economic cost.

The application of satellite data has increased enormously in the past decade. Table 8-3 compares the specifications of resolution for LANDSAT and SPOT satellite images. After the initial low-spatial-resolution images of the LANDSAT MSS (which were about 60 by 80 m), LANDSAT now offers thematic mapper (TM) images with a spatial resolution of 30 m and excellent spectral resolution. LANDSAT TM provides six bands to cover the entire visible, near-infrared, and middle-infrared portions of the spectrum, with one additional band providing a lower resolution of the thermal infrared. LANDSAT satellite orbits are arranged to provide good coverage of a large portion of the earth's surface. The satellite passes over each location every 18 days, offering a theoretical temporal resolution of 18 days, although weather conditions are a serious limiting factor in this respect. Clouds frequently hamper the acquisition of data from the ground surface. The degree of weather interference naturally varies with climate regions. The weakest point of the LANDSAT system is the lack of an adequate stereovision capability. Theoretically a stereomate of a LANDSAT TM image can be produced with the help of a good digital elevation

Table 8-3
Comparison of Specifications of Different Multispectral Remote-Sensing Products

	LANDSAT MSS	LANDSAT TM	SPOT Multispectral	SPOT Panchromatic
No. of spectral bands	4	7	3	1
Spectral resolution (μm)	0.5-1.1	0.45-2.35 10.4-12.5	0.5-0.9	0.5-0.7
Spatial resolution (m)	80	30[a]	20	10
Swath width (km)	185	185	2 × 60	2 × 60
Stereo	No	No	Yes	Yes
Temporal resolution	18 days	18 days	26 days, 5 days off nadir	26 days, 5 days off nadir

[a] 120 m in thermal infrared band.

model (DEM), but this remains a relatively unattractive option because very detailed DEMs are not currently available for most locations.

It should be noted that the terms *digital elevation model* (DEM) and *digital terrain model* (DTM) are frequently used interchangeably. However, some authors prefer to use DEM to refer to values that merely provide topographic elevation values, usually on a regular or gridded basis. They prefer to restrict DTM to those situations in which a more complete description of the terrain is provided, for example, by slope or geomorphic classification. Since the applications concerning the creation of stereoscopic images require only elevation values, the term *DEM* will be used in this chapter.

The French SPOT satellite is equipped with two sensor systems that cover adjacent paths, each with a swath width of 60 km. The sensors have an off-nadir viewing capability, offering the possibility of producing images with good stereoscopic vision. The option of viewing sideways also provides for potentially higher temporal resolution because the satellite can observe a location not directly under its orbital path. SPOT senses the terrain in a single wide panchromatic band and in three narrower spectral bands corresponding to the green, red, and near-infrared portions of the spectrum (see Table 8-3). The spatial resolution in the panchromatic mode is 10 m, whereas the three spectral bands have a spatial resolution of 20 m. The system lacks spectral bands in the middle-infrared and far-infrared (thermal) portions of the spectrum.

Radar satellite images, available from the European ERS-1 and the Japanese JERS satellites, offer all-weather viewing capability because radar systems can penetrate clouds. Theoretically this type of imagery can yield detailed information on surface roughness and micromorphology. However, the currently applied radar wavelengths and viewing angles have not been very appropriate for applications in mountainous terrain. Initial results of research with radar interferometry are promising, indicating that detailed terrain models with an accuracy of less than 1 m can be created. Such resolution suggests the possibility of monitoring landslide activity.

New commercial satellites with 1-m panchromatic and 3-m multispectral image resolutions have recently been announced with launch dates in 1996 and 1997. Not only will these satellites provide much higher spatial resolution than the present LANDSAT or SPOT satellites, but they will also provide greater spectral resolution. Only a few simulated image products have been produced to suggest the capabilities of these new satellites. At the present time it is impossible to predict accurately how these new imagery sources will affect landslide mapping efforts, but readers of this report are encouraged to be aware of, and to investigate, the potential of new developments in the rapidly changing satellite image collection field.

3.2 Landslide Interpretation from Remote-Sensing Images

Landslide information extracted from remote-sensing images is mainly related to the morphology, vegetation, and drainage conditions of the slope. Slope morphology is best studied by examination of a 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 or landforms associated with slope instability processes (see Figure 8-2).

The interpretation of slope movements from remote-sensing images is based on recognition or identification of elements associated with slope movements and interpretation of their significance to the slope instability process. The implication is that a particular type of slope failure is seldom recognized directly but is interpreted to exist by analysis of a certain number of elements pertaining to slope instability features that are observed on the remotely sensed images.

As a consequence, the categorization of slope movements obtained by interpretation of aerial photographs is not as detailed as the classifications of Cruden (see Chapter 3 in this report) or those of other authors (Hansen 1984; Crozier 1986; Hutchinson 1988). These classifications include field evidence in their considerations. Experience has shown that photointerpretation of landslides has to use a simpler classification. Local adaptations to existing classifications can be justified to prevent ambiguities and therefore misclassifications. Table 8-4 shows a checklist constructed on one recent project to provide a systematic characterization of slope failures as observed on aerial photographs. The types of slope movements considered were based on local knowledge in this specific region in the Colombian Cordillera (van Westen 1992, 1993). Table 8-4 also gives an indication of the type of information that can be obtained by experienced photointerpreters using aerial photographs at a scale of 1:20,000. The degree of landslide activity, as classified by aerial photointerpretation, is determined in this region by the freshness of the features related to the landsliding. The morphology of older landslides, showing a degradation of their morphologic forms and usually already overgrown by vegetation, is classified as stable.

Table 8-5 is a summary of the terrain features frequently associated with slope movements, the relationship of these features to landslides, and their characterization on aerial photographs. These elements are used to develop an interpretation and classification of slope failure according to the characteristics in Table 8-6. The interpretation of these various types of mass movements is discussed in the following sections.

3.2.1 Falls and Topples

Falls and *topples* are always related to very steep slopes, mostly those steeper than 50 degrees, where bedrock is directly exposed. Falls are mainly con-

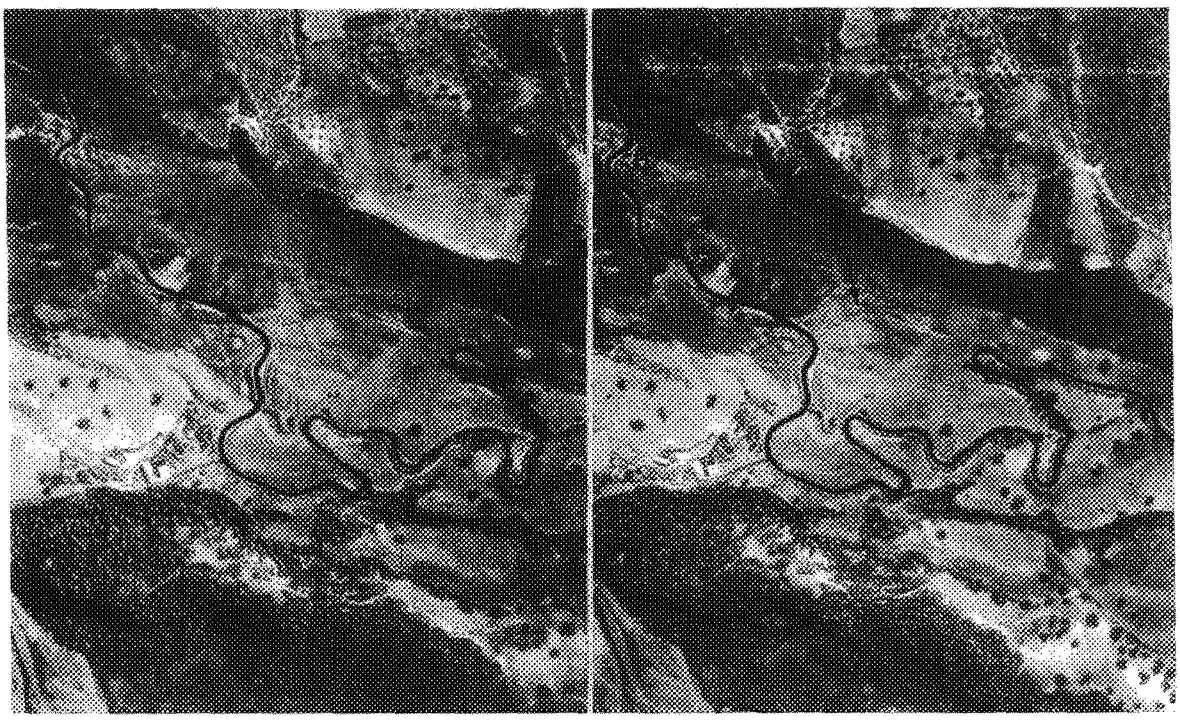


FIGURE 8-2 Faint tonal and textural differences characterizing surficial mud slides in marly clays. Slope failures can be readily interpreted when stereogram is viewed with pocket stereoscope. Although these mass movements are significant because they frequently damage roads, their size precludes them from being interpreted on smaller-scale images (original photograph scale 1:17,000, Basilicata, Italy).

Table 8-4
Interpretation of Landslides in Colombia Using Aerial Photographs and GIS (Van Westen 1993)

CODE	TYPE	SUBTYPE	ACTIVITY	DEPTH	VEGETATION	BODY
1	Slide	Rotational	Stable	Surficial	Bare	Landslide sca
2	Lateral spread	Translational	Active	Deep	Low	Runout body
3	Flow	Complex			High/dense	
4	Debris avalanche	Unknown				

NOTE: Landslide delineations were digitized and stored in georeferenced image data base, and digital codes, representing the ID number and landslide info mation, were stored in attribute data base.

Table 8-5
Morphologic, Vegetation, and Drainage Features Characteristic of Slope Instability Processes and Their Photographic Characteristics

TERRAIN FEATURES	RELATION TO SLOPE INSTABILITY	PHOTOGRAPHIC CHARACTERISTICS
MORPHOLOGY		
Concave/convex slope features	Landslide niche and associated deposit	Concave/convex anomalies in stereo model
Steplike morphology	Retrogressive sliding	Steplike appearance of slope
Semicircular backscarp and steps	Head part of slide with outcrop of failure plane	Light-toned scarp, associated with small, slightly curved lineaments
Back-tilting of slope facets	Rotational movement of slide blocks	Oval or elongated depressions with imperfec drainage conditions
Hummocky and irregular slope morphology	Microrelief associated with shallow movements or small retrogressive slide blocks	Coarse surface texture, contrasting with smooth surroundings
Infilled valleys with slight convex bottom, where V-shaped valleys are normal	Mass movement deposit of flow-type form	Anomaly in valley morphology, often with lobate form and flow pattern on body
VEGETATION		
Vegetational clearances on steep scarps, coinciding with morphological steps	Absence of vegetation on headscarp or on steps in slide body	Light-toned elongated areas at crown of mass movement or on body
Irregular linear clearances along slope	Slip surface of translational slides and track of flows and avalanches	Denuded areas showing light tones, often with linear pattern in direction of moveme
Disrupted, disordered, and partly dead vegetation	Slide blocks and differential movements in body	Irregular, sometimes mottled grey tones
Differential vegetation associated with changing drainage conditions	Stagnated drainage on back-tilting blocks, seepage at frontal lobe, and differential conditions on body	Tonal differences displayed in pattern associated with morphological anomalies in stereo model
DRAINAGE		
Areas with stagnated drainage	Landslide niche, back-tilting landslide blocks, and hummocky internal relief on landslide body	Tonal differences with darker tones associated with wetter areas
Excessively drained areas	Outbulging landslide body (with differential vegetation and some soil erosion)	Light-toned zones in association with convex relief forms
Seepage and spring levels	Springs along frontal lobe and at places where failure plane outcrops	Dark patches sometimes in slightly curved pattern and enhanced by differential vegetation
Interruption of drainage lines	Drainage anomaly caused by head scarp	Drainage line abruptly broken off on slope by steeper relief
Anomalous drainage pattern	Streams curving around frontal lobe or streams on both sides of body	Curved drainage pattern upstream with sedimentation or meandering in (asymmetric) valley

able 8-6
nage Characteristics of Mass Movement Types

'ype of Movement	Characterization Based on Morphological, Vegetational, and Drainage Aspects Visible on Stereo Images	
'all and topple	Morphology:	Distinct rock wall or free face in association with scree slopes (20 to 30 degrees) and dejection cones; jointed rock wall (>50 degrees) with fall chutes
	Vegetation:	Linear scars in vegetation along frequent rock-fall paths; vegetation density low on active scree slopes
	Drainage:	No specific characteristics
'turzstrom	Morphology:	Extremely large (concave) scars on mountain, with downslid blocks of almost geological dimensions; rough, hummocky depositional forms, sometimes with lobate front
	Vegetation:	Highly irregular/chaotic vegetational conditions on accumulative part, absent on sturzstrom scar
	Drainage:	Irregular disordered surface drainage, frequent damming of valley and lake formed behind body
'otational slide	Morphology:	Abrupt changes in slope morphology characterized by concave (niche) and convex (runout lobe) forms; often steplike slopes; semilunar crown and lobate frontal part; back-tilting slope facets, scarps, hummocky morphology on depositional part; *D/L* ratio 0.3 to 0.1; slope 20 to 40 degrees
	Vegetation:	Clear vegetational contrast with surroundings, absence of land use indicative for activity; differential vegetation according to drainage conditions
	Drainage:	Contrast with nonfailed slopes; bad surface drainage or ponding in niches or back-tilting areas; seepage in frontal part of runout lobe
'ompound slide	Morphology:	Concave and convex slope morphology; concavity often associated with linear grabenlike depression; no clear runout but gentle convex or bulging frontal part; back-tilting facets associated with (small) antithetic faults; *D/L* ratio 0.3 to 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 rear part of slide
Translational slide	Morphology:	Joint controlled crown in rock slides, smooth planar slip surface; relatively shallow, certainly in surface material over bedrock; *D/L* ratio <0.1 and large width; runout hummocky, rather chaotic relief, with block size decreasing with larger distance
	Vegetation:	Source area and transportational path denuded, often with lineations in transportation direction; differential vegetation on body, in rock slides; no land use on body
	Drainage:	Absence of ponding below crown, disordered or absent surface drainage on body; streams deflected or blocked by frontal lobe
Lateral spread	Morphology:	Irregular arrangement of large blocks tilting in various directions; block size decreases with distance and morphology becomes more chaotic; large cracks and linear depressions separating blocks; movement can originate on very gentle slopes (<10 degrees)
	Vegetation:	Differential vegetation enhancing separation of blocks; considerable contrast with unaffected areas
	Drainage:	Disrupted surface drainage; frontal part of movement is closing off valley, causing obstruction and asymmetric valley profile
Mudslide	Morphology:	Shallow concave niche with flat lobate accumulative part, clearly wider than transportation path; irregular morphology contrasting with surrounding areas; *D/L* ratio 0.05 to 0.01; slope 15 to 25 degrees
	Vegetation:	Clear vegetational contrast when fresh; otherwise differential vegetation enhances morphological features
	Drainage:	No major drainage anomalies beside local problems with surface drainage
Earth flow	Morphology:	One large or several smaller concavities, with hummocky relief in source area; main scars and several small scars resemble slide type of failure; path following stream channel and body is infilling valley, contrasting with V-shaped valleys; lobate convex frontal part; irregular micromorphology with pattern related to flow structures; slope > 25 degrees; *D/L* ratio very small

continued on next page

Table 8-6 *(continued)*

Type of Movement	Characterization Based on Morphological, Vegetational, and Drainage Aspects Visible on Stereo Images	
Earth flow, *continued*	Vegetation:	Vegetation on scar and body strongly contrasting with surroundings, land use 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 body in valley; deflected or blocked drainage by frontal lobe
Flowslide	Morphology:	Large bowl-shaped source area with steplike or hummocky internal relief; relatively great width; body displays clear flow structures with lobate convex frontal part (as earth flow); frequently associated with cliffs (weak rock) or terrace edges
	Vegetation:	Vegetational pattern enhancing morphology of scarps and blocks in source area; highly disturbed and differential vegetation on body
	Drainage:	As with earth flows, ponding or disturbed drainage at rear part and deflected or blocked drainage by frontal lobe
Debris avalanche	Morphology:	Relatively small, shallow niches on steep slopes (>35 degrees) with clear linear path; body frequently absent (eroded away by stream)
	Vegetation:	Niche and path are denuded or covered by secondary vegetation
	Drainage:	Shallow linear gully can originate on path of debris avalanche
Debris flow	Morphology:	Large amount of small concavities (associated with drainage system) or one major scar characterizing source area; almost complete destruction along path, sometimes marked by depositional levees; flattish desolate plain, exhibiting vague flow structures in body
	Vegetation:	Absence of vegetation everywhere; recovery will take many years
	Drainage:	Disturbed on body; original streams blocked or deflected by body

trolled by rock discontinuities (joints and fractures), giving the rock slope a rough appearance; these discontinuities are expressed in the image by a coarse texture. Toppling is favored by the presence of a steeply inclined joint set with a strike aligned approximately parallel to the slope face. Therefore, fine lineaments at the crest that are oriented parallel to the free face may be related to open joints behind toppling blocks. The accumulation of talus at the foot of the slope or the occurrence of coarse scree on slopes below the rock face is associated with rough micromorphology and results in a relatively coarse textural appearance in the image.

Talus accumulations and colluvial slopes formed by fall processes typically have slopes between 25 and 35 degrees. Scattered trees or bushes are the most frequent vegetation on these slopes. The density of this vegetation is indicative of the degree of slope-movement activity. At specific places where falls occur more frequently, chutes are eroded in the rock wall and talus cones are formed at its base. Linear patterns, also visible in the vegetation, are indicative of the paths along which the blocks are falling.

Large rock falls may create large, rapidly moving rock or debris avalanches, or *sturzstroms* (see Chapter 3, Section 8.1.2). These failures are associated with major morphologic anomalies and scars on mountain slopes (see Figure 8-3). The accumulation of these materials may spread a considerable distance from the source area, often creating rather chaotic landforms in which enormous blocks form an extremely irregular, rough morphology. This chaotic morphology is enhanced in the image by the very irregular vegetational pattern. Lobate convex forms are sometimes associated with the front of the mass. The drainage pattern in the whole area is generally seriously disturbed by these large, complex landslide deposits. Surface drainage can be blocked by the accumulated mass, creating lakes, or rivers are deflected, finding their way around the mass. Abrupt changes in the width and pattern of the river and clearly asymmetric valley slopes at the location of the accumulative mass are other characteristics. It is quite often observed that the deflection of river channels by larger mass movements induces slope instability features on the opposite valley side caused by the resulting erosion and undercutting of these slopes.

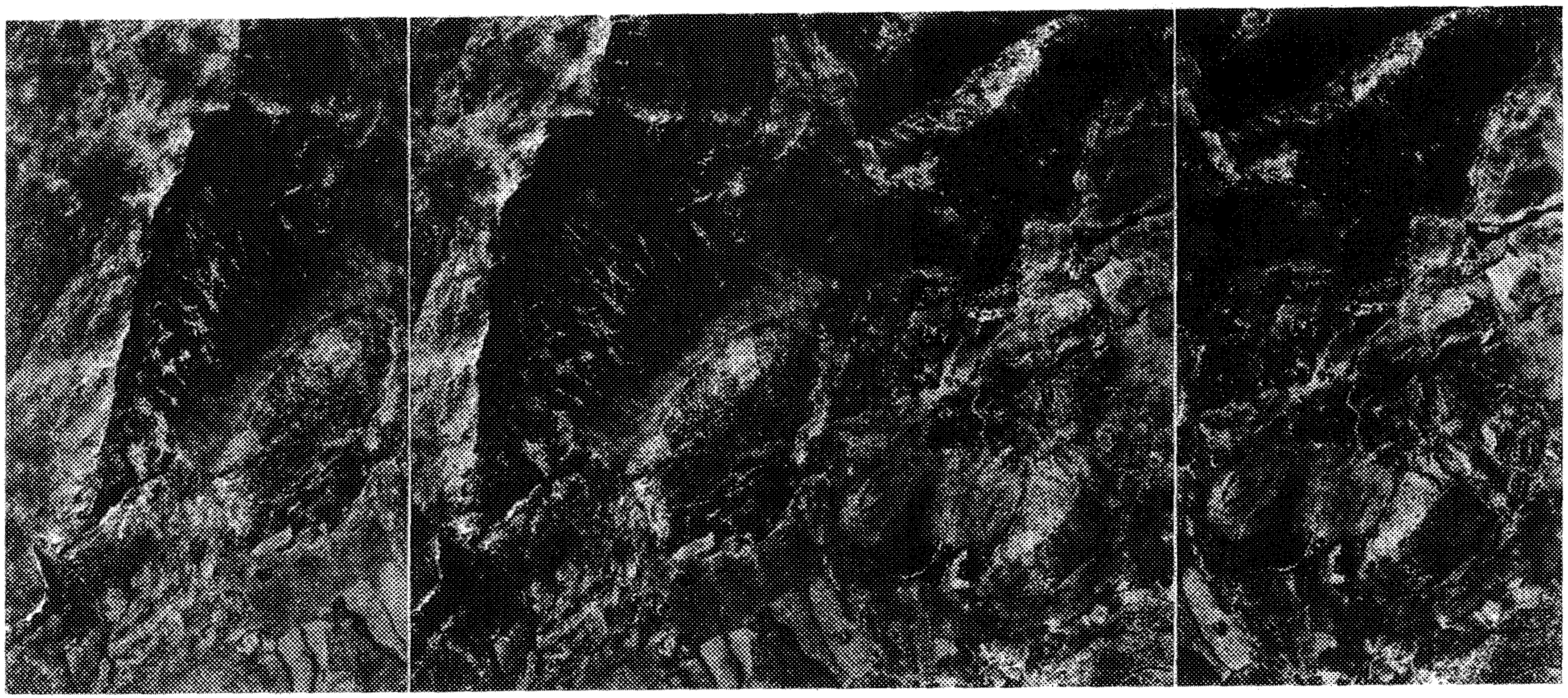


FIGURE 8-3
Major complex rock fall (*sturzstrom*) or rock slide occurring in limestones overlying sequence of mudstones. All morphologic features associated with such gigantic mass movements are clearly defined: large back scarp and huge block that has slid (*left side*); runout of material onto slope underlain by fine pelitic materials (*right side*). Tonal changes around larger block (*lower part of stereogram*) are associated with soft clays squeezed out of slope by impact of block. Block field begins within stereogram and continues for almost a kilometer farther eastward. Disturbed drainage conditions at interface of limestones and fine pelitic sequence are causing ongoing slope instability, mainly in form of flow-type features, as can be observed by grey tones and elongated patterns along contact (original photograph scale 1:18,000, Province of Malaga, Spain).

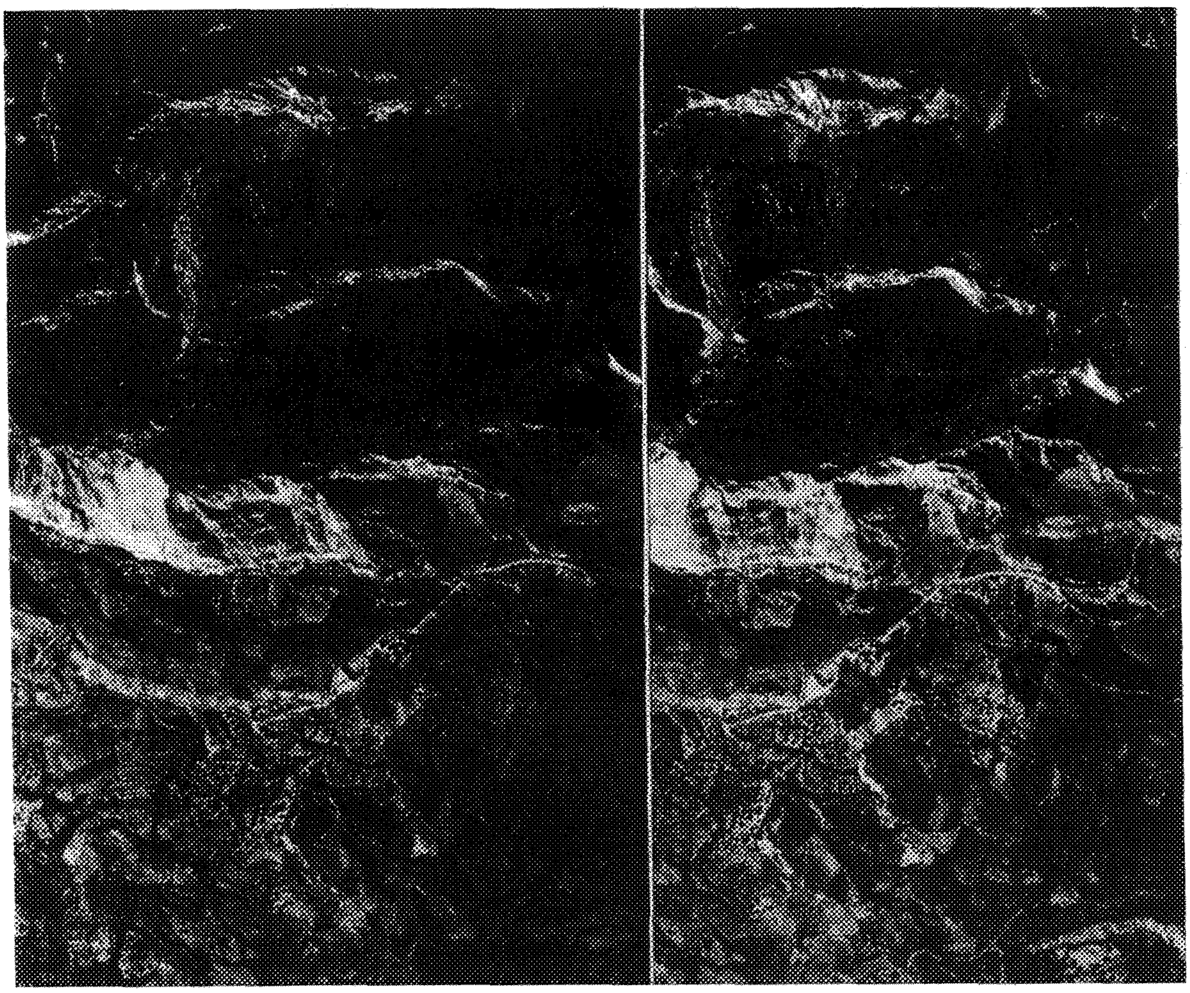


FIGURE 8-4
Translational slides controlled by dip slopes in sequence of very friable sandstones alternating with siltstones and mudstones. Joint-controlled back scarp, linear patterns, and micromorphology of area where the sandstones have slid away (*lower part*) are diagnostic for landslides. Somewhat comparable morphology and change in land use (*upper part*) are indicative of landslides that have rapidly transformed into earth flow because of higher clay content (orginal photograph scale 1:17,000, Basilicata, Italy).

3.2.2 Slides

A *rotational slide* is mainly associated with slopes ranging from 20 to 40 degrees and is recognized by a characteristic slope morphology. The crown of the slide, with its frequently semilunar shape, initiates an abrupt change in the slope. Concave and convex slope forms are related to the landslide niche and the deposit, which are directly connected to each other. These landslides generally have a depth-to-length (*D/L*) ratio on the order of 0.3 to 0.1. Successive or retrogressive sliding results in a steplike morphology. The lower frontal part (or toe) of the landslide has a generally convex lobate form. The rotational movement often results in back-tilting of slope facets. The overall micromorphology of these landslides is irregular, resulting in textural and tonal variations on the aerial photograph. The differential drainage conditions on these landslides and their disturbed vegetational conditions enhance textural and tonal variations. When the scale of the image is appropriate, these variations form a characteristic pattern in association with slide scars and back-tilted blocks. Poor surface drainage, or even ponding, occurs on the main landslide mass and behind back-tilting blocks. Wet zones and springs are characteristic along the toe of the slide. These wetter conditions and their distinctive vegetation influence the tone on the photographs. The vegetation on a slide shows a disturbed and chaotic aspect. The absence of cultivation or differences in land use in comparison with those in the surrounding area are often remarkable and also indicative of the activity of the movements.

In a *translational slide* the failure surface usually reflects a weak layer or preexisting structural discontinuity (see Figure 8-4). This characteristic has clear consequences for the morphologic aspects of the mass movement. In the first place, the *D/L* ratio for translational slides is many times smaller than that for rotational slides, whereas the width of the zone of movement in translational slides is greater than that for most rotational slides. When the failure is controlled by the interface between surficial materials and bedrock, the movement will be shallow and the displacement may extend over a considerable distance. Such slope failures are also commonly relatively wide. Flowage features in the runout material are frequently observed, especially when the coherence of the material is low and strong rainfall is the triggering mechanism. The source area and the path along which the material moved are denuded of vegetation, resulting in a clear tonal contrast with the surroundings. Lineaments parallel to the direction of the movement are common. Vegetation conditions are chaotic on the displaced mass, and most land use activities will be absent when the movement is recent (only a few years old). Also, the drainage conditions are disordered on the displaced material, although the typical poorly drained areas associated with rotational slides are normally absent.

A *compound slide* is a form that is transitional between a rotational and a translational slide. From the point of view of the photointerpreter, these slides are in many respects similar to rotational slides but their upper portions often contain grabenlike depressions and have a less pronounced runout. Their *D/L* ratio is normally smaller than that for rotational slides, whereas their width is generally greater.

A *rock slide* is also characterized by a small *D/L* ratio (usually less then 0.1) and a large width. Joints and fractures provide structural control of the failure surface and at the crown of the slide, and these joints and fractures are often distinct on the photograph. The morphology in the runout area is very rough, and decreasing block size with increasing distance is characteristic. Enormous slabs occur close to the source area, whereas chaotic and irregular "block fields" occur at a greater distance. Vegetation is absent in the source area and along the path. On the slide mass, vegetation is chaotic and in patches. Drainage conditions are normally good because most of the drainage will be internal. Springs may be found at the toe of the slide, and the front of the mass can obstruct local streams.

In the category of complex and composite slides, *mudslides* can be differentiated by photointerpretation. Mudslides are generally shallow mass movements occurring on slopes of between 15 and 25 degrees composed of fine clayey materials. The clearly differentiated source area, transportation path, and accumulative zone are diagnostic features of mudslides. The morphology of mudslides is characterized by a clear concave niche from which the material was derived, comparable with the landslide scar of shallow slides. The transportation path is often represented by a more-or-less straight channel originated by failure due to undrained loading. Mudslide runout deposits are spread over a much wider area than the width of the source area or the transportation path, where the material was confined as in a channel. The tongue of the mudslide displays a lobate form. The dilation of the material and the flatness of the lobe are characteristic and relate to the fluid nature of the material during movement. The *D/L* ratio for mudslides is on the order of 0.05 to 0.01, much smaller than that for rotational slides.

The term *flowslide* has been used to describe a sudden collapse of material that then moves a considerable distance very rapidly to extremely rapidly. Hutchinson (1988) pointed out that at least three phenomena can cause this behavior:

1. Collapse of weak rocks, such as chalk, along cliffs;
2. Destruction of the normal structure of saturated material by shocks such as earthquakes; and
3. Movement of loosely dumped materials in waste piles or in rapidly deposited, loosely compacted silts and fine sands.

Depending on the material in which the failure occurs, the size of the failure, and the place from which the movements are derived, the overall morphology of flowslides can resemble large rock avalanches (sturzstroms), translational slides produced by failure along a weak horizon, or liquefaction spreads, which are described in the following section. For these reasons, Cruden and Varnes (see Chapter 3 in this report) suggest that the term *flowslide* is redundant, confusing, and potentially ambiguous. They suggest that these different kinds of landslides be described with more appropriate terms.

Nevertheless, the sudden collapse of loose, saturated, almost cohesionless soils or weak rocks occurring on moderate to gentle slopes or even in almost flat terrain produces a distinctive pattern that can be readily evaluated by photointerpretation. The area from which the landslide is derived

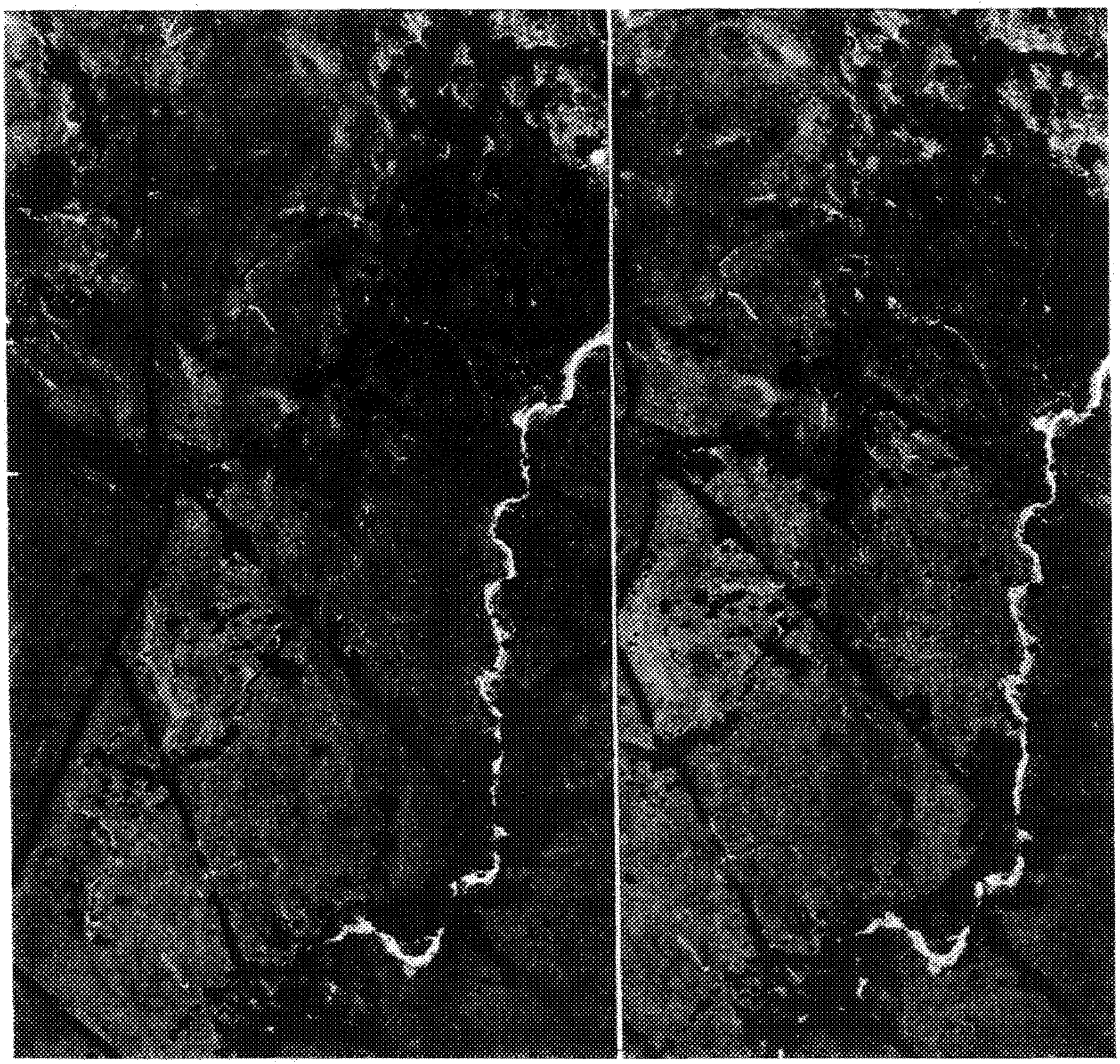


FIGURE 8-5
Highly unstable zone with numerous rotational landslides, mud slides, and earth flows.
Well-cemented but strongly jointed volcanoclastic sequence, dipping gently to southwest (*north is up*), overlies series of almost unconsolidated sandstones and mudstones and claystones deposited in shallow marine to coastal environment. Steplike morphology in volcanoclastic material, sometimes showing slight back-tilting, is characteristic for rotational slides. Hummocky morphology with varying grey tones and faint linear elements is indicative of more flow-type movements on slopes near creek (original photograph scale approx. 1:10,000, Antioquia, Colombia).

is often an extensive flat concave zone with an irregular hummocky or undulating micromorphology. Within this area the drainage conditions are completely disturbed and ponded water is frequently encountered. These conditions are in strong contrast to the surroundings, which usually show a smooth topography with mostly complete internal drainage. A relatively narrow opening or neck indicates the place through which the landslide movement occurred. The transportation path, which varies in length according to the slope of the area and the fluidity of the mass, is clearly recognized 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 in both the micromorphology and the vegetation because of differential drainage conditions (see Figure 8-5).

3.2.3 Spreads

Spreads are mass movements occurring on gentle to moderate slopes where a slow plastic deformation or liquefaction occurs in a subsurface horizon overlain by a more coherent surface layer. This upper layer is broken up by the movements of the underlying material and moves and slides outward on the underlying layer. The areal extent of the movement is often considerable (up to several square kilometers), and the limits of the movement at the surface can be diffuse and difficult to distinguish both on aerial photographs and on the ground. Linear features corresponding to cracks and tilting of blocks of surface material are visible on remote-sensing images, forming indicators of the initial movements. The presence of these cracks is often enhanced by vegetation differences. The morphologic anomalies increase in the middle portions of the landslide. The surface material breaks up into irregular blocks that are chaotically disposed. These chaotic conditions are reflected by the morphology, the drainage, and the vegetation conditions. Bulging of the lower slopes, which usually display a typical convex form, indicates extrusion of the unstable subsurface material. Poor drainage conditions and seepage horizons are characteristic for this zone, causing tonal differences in the photographs. Lateral spreads often result in overall drainage anomalies because the movements may narrow or block valleys and deflect streams. These drainage anomalies usually result in increased stream erosion at the location where the spread blocks the valley, which in turn results in development of numerous local rotational slides of considerably smaller size than the lateral spread.

3.2.4 Flows

Flows comprise a large range of slope failures, including relatively slow-moving earth flows, extremely fast debris avalanches, devastating debris flows induced by the failure of the barrier forming a natural or artificial lake, or the equally devastating lahars caused by volcanic activity.

Earth flows often originate as one of various types of mass movements. The coherence within the initial landslide mass is lost because of the initial failure, and the mass continues as a viscous flow down the slope. Water contained within the mass may contribute to this flowage. Earth flows may continue long distances, following stream channels and reaching main valleys where they may obstruct the drainage. The source area of earth flows often has the aspect of a zone with complex mass movements, landslides coming from various directions and showing generally a clear retrogressive progression. The transportation path is distinct, following first the maximum slope and then a stream channel. The earth-flow material exhibits morphologic features that are often comparable with those of glaciers or lava flows, with cracks (lineaments on the aerial photograph) parallel to the movement and transverse cracks at places where the slope and flow velocity increase. The transverse section of an earth flow shows a slightly convex ground profile, which may be readily visible in the three-dimensional photoimage because of the exaggerated stereoscopic relief. Earth flows infilling valleys create a clear morphologic anomaly, contrasting with the V-shaped valleys in mountainous areas (see Figure 8-6). The frontal portions of earth flows have clearly lobate convex forms. The source area is generally devoid of any vegetation, whereas the vegetation on the earth flow, if any, looks patchy because of differential surface drainage conditions in the material. The drainage conditions in the source area are disturbed, and local ponding can occur. Two small streams normally develop in a valley subjected to an earth flow, one on each side of the flow. These form an easily recognizable drainage anomaly, as does the deflection of the stream channel around the frontal lobe.

Debris avalanches are extremely fast and sometimes relatively small slope failures on straight steep slopes with inclinations generally greater than 35 degrees. They are characterized by a concave niche from which a long, narrow, light-toned tail originates. The linear character remains visible on aerial photographs even when secondary vegetation has invaded the area affected by the debris avalanche. Debris avalanches are most common on steep slopes that are at almost their maximum angle of stability. They are especially common where the slope equilibrium has been disturbed by a vegetation or land use change or by engineering work such as road construction. They are often triggered by earthquakes.

Debris flows can be caused by a large number of factors, but in all cases considerable amounts of loose material are suddenly moved by an excessive amount of water and transported in an extremely fast and destructive flow through a valley. Depending on the origin of the debris flow, the morphologic characteristics of the source area may vary. The zone can be characterized by a large number of surficial debris slides. Figure 8-7 shows a debris flow in Thailand. Extremely intense rainfall triggered a large number of superficial landslides in weathered granitic rocks, and these flowed together to form a devastating debris flow. However, debris flows may also originate from a single slope failure or be caused by the failure of a dam. Extremely large volumes of debris-flow deposits caused by massive glacial-lake outburst floods

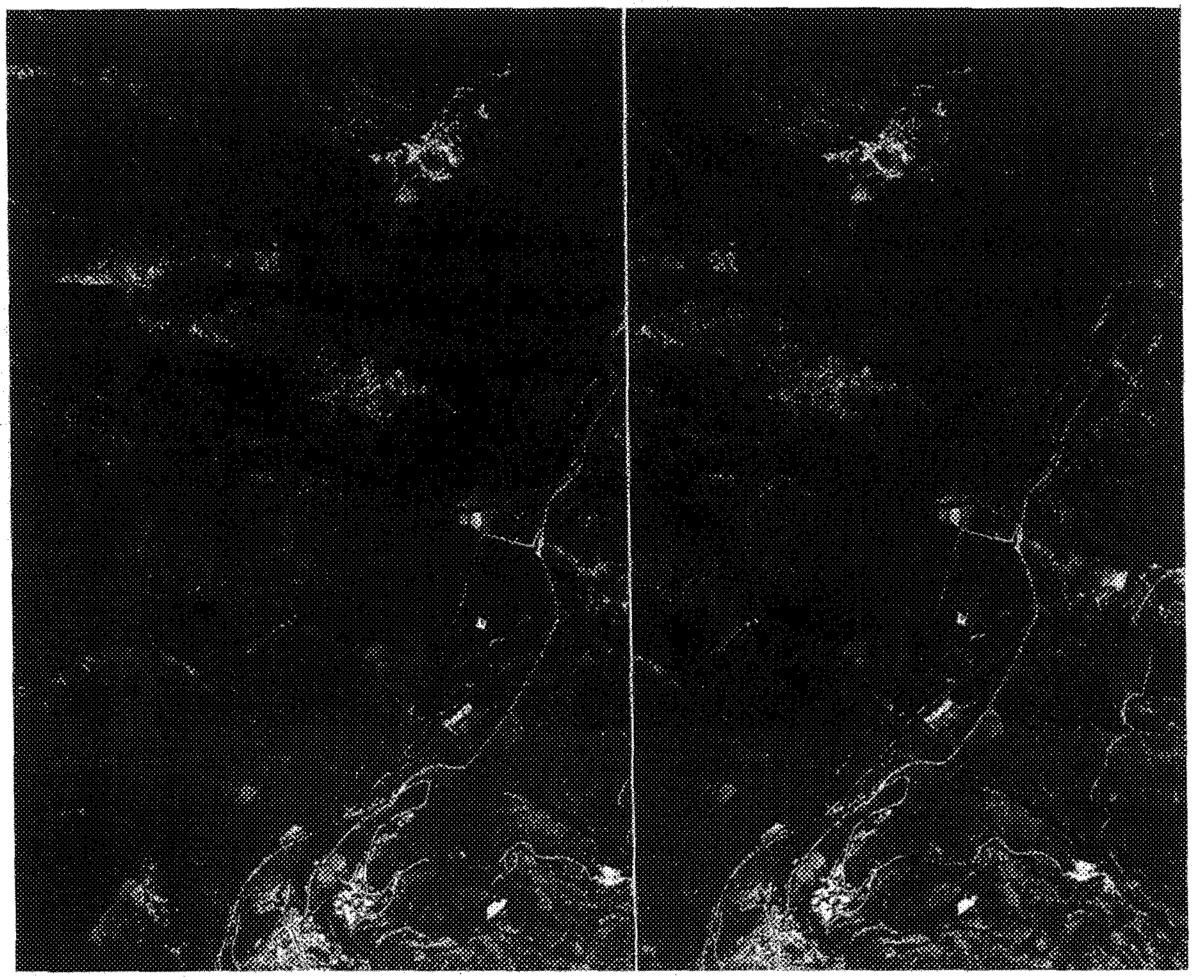
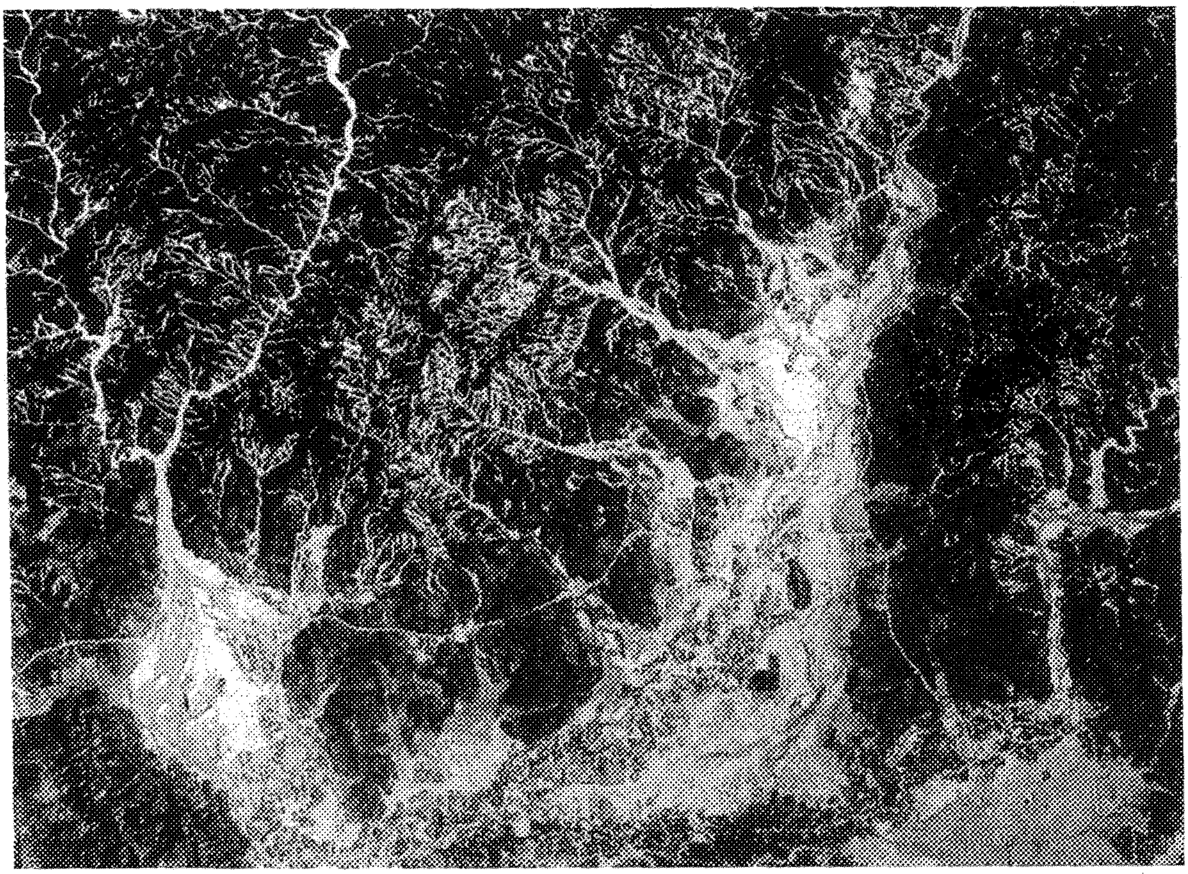


FIGURE 8-6
Major earth flow within small valley and almost blocking main valley. Convex form of earth-flow lobe is characteristic of earth flows and contrasts with concave forms of alluvial fans. River is pressed against opposite valley side and may cause undercutting and slope failures on that side. Earth flow occurred in prehistoric time following a rock fall in conglomerates (*just beyond upper left part*). Impact of rock fall triggered earth flow in weathered slates underlying conglomerates (original photograp scale 1:22,000, Province of Lleida, Spain).

have been identified in the northwestern portions of the United States and elsewhere. *Lahars* are debris flows originated from loose pyroclastic deposits on volcanic slopes. They display morphologic forms similar to those of other debris flows.

Common to all debris flows are the marks left behind by the devastating flow. Some debris flows have such large dimensions that these marks are clearly recognizable even on small-scale images and for a considerable time after the event occurs. The appearance of the depositional mass varies with the type of material transported but generally consists of a desolate, flat area engulfing isolated small higher vegetated areas that correspond to an older topographic surface. Large blocks of rock floating in the mud may create an irregular micromorphology, which is recognizable 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 disturbed, and the mass itself deflects or obstructs streams in the area of deposition.

Bedrock flows, or deep-seated creep, generally do not affect the morphologic conditions sufficiently to be interpreted in a preliminary photointerpretation. These flows can only be mapped with good knowledge of the local conditions. Once the characteristic features for creep are known in an area, this knowledge may successfully be extrapolated on the aerial photographs. Creep can create an irregular micromorphology, sometimes reflected in the drainage and vegetation, that causes a contrast with the zones not affected by creep. The surrounding areas typically show very smooth forms with subdued photographic grey tones in comparison with the creep-affected areas. Bulging of slopes is associated with deep-seated creep. When sagging develops, it is generally accompanied by elongated depressions along the slope and back-tilting slope facets (see Chapter 3 in this report).



IGURE 8-7
POT multispectral atellite image with elatively good patial resolution an be used rofitably in ssessment of areas ffected by slope novements. xample shows area n Thailand where arge number of hallow debris slides enerated large debris flow that traveled through valleys, damaging agricultural fields and houses.

3.2.5 Cartographic Aspects

Mass movements may be represented cartographically at two levels of generalization. In those cases in which the area affected by the slide is too small to represent the real outlines of the slope movement at the scale of the map, mass movements are represented by a symbol defining the type of movement, thus differentiating falls and topples, slides, and flows. At larger map scales, or for larger landslides, the outlines of the mass movement may be shown on the map (see Figure 8-8). In these situations the map usually also shows all the valuable information related to the slope movement processes, such as scarps, cracks, steps in slopes, backtilted blocks, and depressions. Indirect evidence of instability, such as seepage horizons, stagnated drainage, or ponding, may also be mapped. In large or complex mass-movement areas, simple symbols are commonly combined to represent morphologic details. The degree of activity may be indicated by using solid and dashed lines or by using symbols of different colors, for example, red for active areas and black for inactive areas. However, such interpretations must be used with caution because the differentiation between active and inactive landslides, especially when using satellite imagery, is based only on the degree of freshness of the morphologic features associated with the movement. In large or complex slides, small active movements are frequently indicative of ongoing activity within the larger mass.

When an inventory map of landslides is prepared for a GIS-based hazard analysis, the landslides are delineated on the image and labeled with an identification number and a digital code defining the landslide type, subtype, activity, and depth. Standard landslide classifications and uniform photointerpretation methods should be used as much as possible. However, experience has shown that photointerpretation of landslides may require slight modifications to these classifications in order to produce an unambiguous and consistent interpretation.

3.3 Mapping Terrain Parameters from Remote-Sensing Images

As discussed in Section 2.3, a landslide hazard assessment should not be based only on the production of a landslide inventory map. A complete landslide hazard assessment also requires an analysis of the factors leading to instability and the classification of the terrain into susceptibility classes for slope failures. These susceptibility classes are defined to reflect the presence and intensity of slope instability causative factors. The interpretation of either satellite images or aerial photographs plays a crucial role in the evaluation of the many factors that must be taken into account for landslide hazard analysis and their display as parameter maps (see Table 8-1). The interpretation process may also be used to perform terrain analysis, thereby producing a single map defining the area characteristics in terms of homogeneous map units. Accordingly, remote-sensing methods can be applied to obtain information concerning landslide hazard assessment factors or parameters by two distinctive processes:

1. *Preparation of individual thematic maps:* This obviously highly desirable method of evaluating landslide hazards involves the representation of the various factors potentially affecting slope instability (such as geomorphology, slope angle, length, convexity, land use, and lithology). However, at relatively detailed scales, such as 1:50,000 or larger, preparing the many individual maps requires a large amount of time for photointerpretation, fieldwork, map creation, and the subsequent digitization of these maps if GIS techniques are to be used (see Section 4 in this chapter). Furthermore, the digitization of identical boundary lines shown on different maps must be conducted with much care and frequently with several editing steps in order for them to coincide exactly. If these lines do not coincide, the overlaying of factor maps produces a large number of small areas containing spurious hazard assessments. For these reasons, this method is most appropriate for the assessment of relatively small areas.
2. *Terrain classification approach:* A terrain classification divides the landscape into homogeneous zones or natural divisions by using the interrelationships among geology, geomorphology, and soils. Because reliable quantitative data on geology, geomorphology, soils, and so forth, are frequently scarce during the early stages of planning for development and engineering projects, terrain classification may be used during these stages to transform the available earth science data into information reflecting applications such as slope stability. Terrain classifications reduce the seemingly infinite variations of the terrain into a manageable number of classes. They also allow landslide hazard analysis to proceed with the creation and digitization of only a single additional map. This process is thus especially attractive during the earlier regional assessment stages.

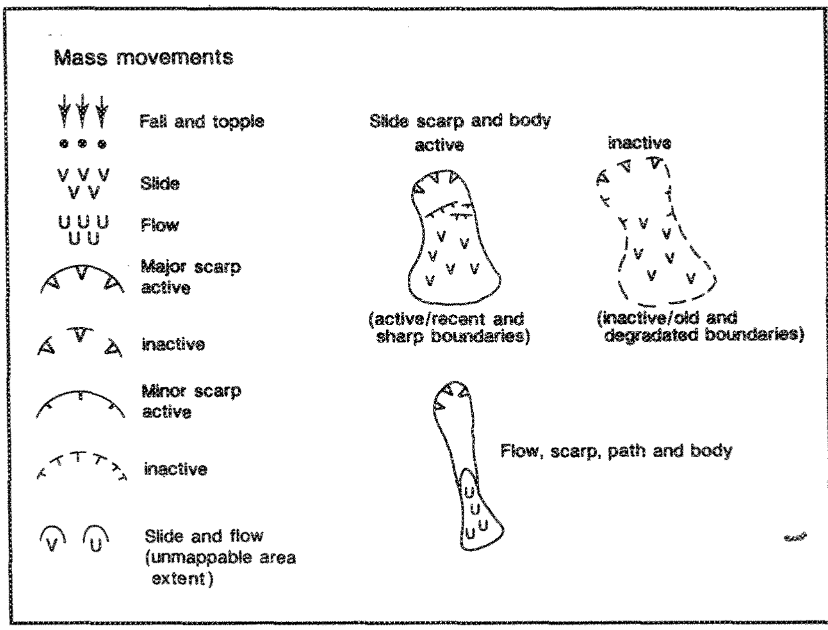


FIGURE 8-8 Example of legend for slope instability map. By use of such symbols, landslide type and activity may be differentiated. Morphologic features and drainage conditions associated with mass movements can also be indicated by symbols (modified from Sissakian et al. 1983).

3.3.1 Geomorphic Mapping

The production of individual thematic maps will normally require the use of specialized mapping procedures. One broad class of such mapping methods is called geomorphic mapping. Many different geomorphic mapping systems have been proposed, either for universal application or for specific areas or regions such as mountainous terrain. Overviews of conventional medium-scale and large-scale geomorphic mapping systems were presented by Demek and Embleton (1978) and van Zuidam (1986). The use of several different systems in prac-

tice suggests that no universally accepted system is adequate for mapping in different environments, in contrast to the case with soil mapping. In the conventional geomorphic mapping systems for scales of 1:25,000 and larger, various symbols, lines, colors, and hatchings are used to represent the morphometry, morphography, drainage, genesis, chronology, and materials of the landscape features or the processes forming them. These systems differ in the importance assigned to each feature and in the method of representation. They all combine the different types of geomorphic data onto one map sheet. Such a system is not amenable to computer-based representations using GIS methods. Thus, the construction of detailed geomorphic maps suitable for use in a GIS representation requires a different, and much more complicated, mapping method (Dikau 1992; van Westen 1993).

3.3.2 Terrain Classification Systems

Terrain classification methods were developed to replace the mapping of individual landscape parameters on multiple maps with a single mapping unit that can be shown on a single map. Many different terrain classification systems have been developed over the years. The principal systems were compared by van Zuidam (1986) and Cooke and Doornkamp (1990). These systems differ in the way they utilize or depend on geomorphic, analytic, morphometric, physiographic, biogeographic, or lithologic-geologic parameters. Most terrain classification systems have a rigid hierarchical structure, which may hinder their flexible use, or they are based on a single parameter or a limited set of parameters.

To overcome these problems, a terrain classification system based on the delineation of *terrain mapping units* (TMUs) was developed by Meijerink (1988). A TMU is defined as a unit that groups zones of interrelated landforms, lithology, and soil. It is a natural division of the terrain that can be distinguished on stereo SPOT imagery or small-scale aerial photographs and verified on the ground. The units are differentiated on the basis of photomorphic properties in the stereo model. Meijerink's TMU system does not have a strict hierarchical structure. The user can construct the legend according to the important parameters encountered in the study area and the purpose of the study. An individual TMU differs from other adjoining TMUs either because the landforms are evidently different or because the phenomena associated with the landform, such as the nature of the weathered zone, the lithology, or the type of soil, are different. The TMU approach has been used successfully in various geomorphic and engineering geologic applications, such as highway planning (Akinyede 1990).

In conventional thematic mapping, a TMU can be considered as a legend unit. In terms of GIS techniques, a TMU may be described as the geographic location of entities (polygons) that relate to a unique set of attributes (terrain conditions). These are linked to the geographic TMU polygons by attribute tables in a data base (see Figure 8-9). TMUs allow the grouping of the following interrelated landscape variables:

- Geomorphic origin and physiography,
- Lithology,
- Morphometry, and
- Soil geography.

3.4 Image Resolution and Interpretability

The interpretation of landslides from remote-sensing sources requires knowledge of the distinctive features associated with slope movements and of the image characteristics associated with these features. An adequate interpretation depends on image characteristics. The interpretability of features in an image is influenced by the contrast that exists between features and their background. For the image interpretation of landslides, this contrast results from the spectral or spatial differences that exist between the landslide and its surroundings. These are affected by

1. The period elapsed since the failure, because erosional processes and vegetation recovery tend to obscure the features created on the land surface by landslide movements, and
2. The severity with which the landsliding affects the morphology, drainage, and vegetation conditions.

The spatial resolution of the remote-sensing images provides the primary control of the interpretability of slope instability phenomena and thus the applicability of any type of remote-sensing data

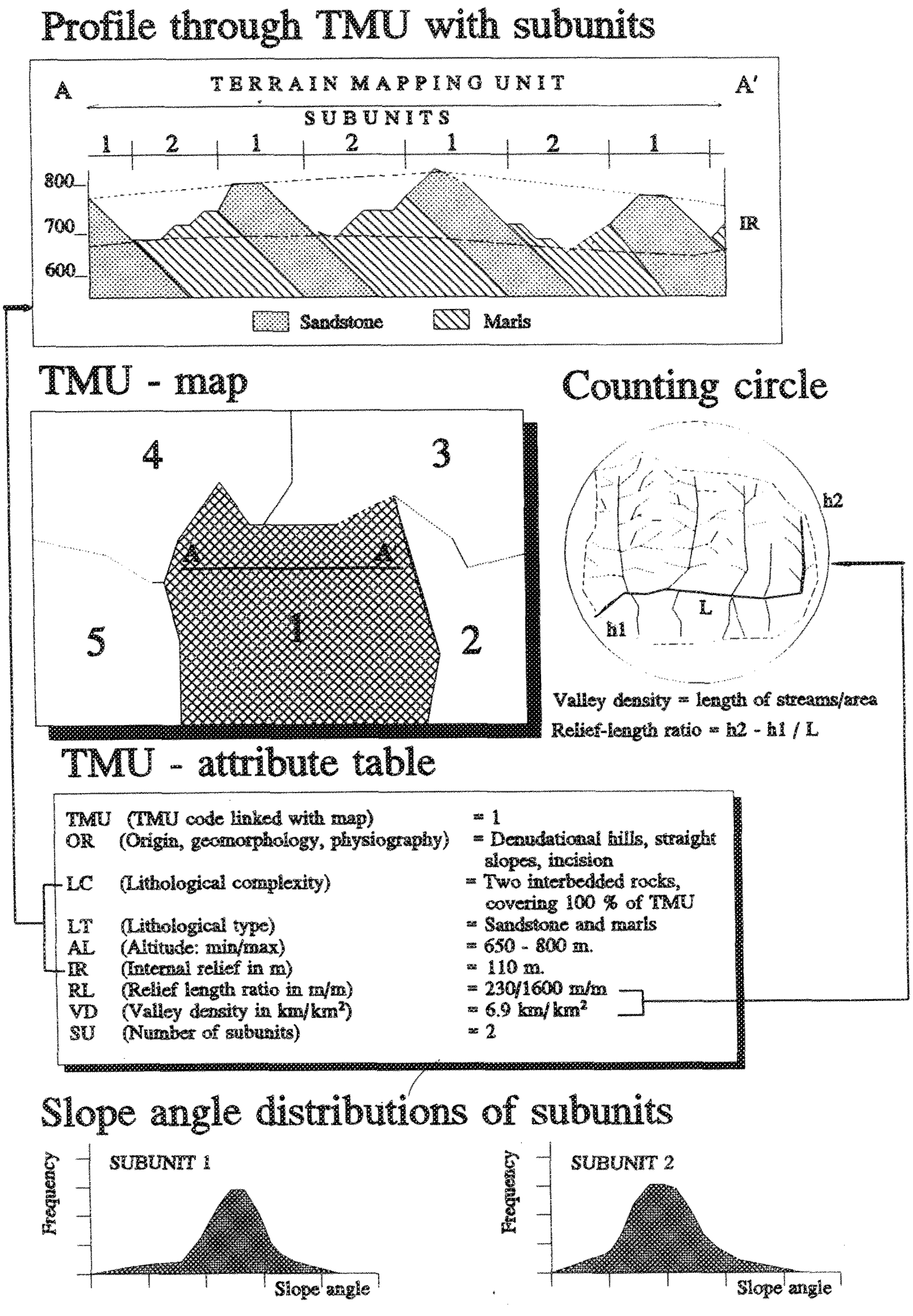


FIGURE 8-9
Mapping by TMU approach (Meijerink 1988). Simplified example of TMU map together with parameters stored in attribute table. Subdivision of units is shown according to lithologic type, determination of internal relief (*IR*) and valley density (*VD*) with help of counting circle, and computation of slope angle distributions.

for landslide studies. The relationship between image resolution and the size of the features necessary to identify or characterize the slope movement is obviously critical. If the resolution is too low, the features cannot be recognized or identified.

Comparison of the spatial resolution of photography and nonphotographic remote sensing requires the use of the concept of a ground resolution cell (GRC), first introduced by Rengers et al. (1992). In nonphotographic remote sensing the GRC is the size of a scene element, the dimensions on the ground of the basic elements (or pixels) of the image.

At any given scale, aerial photography provides a higher resolution, and therefore a smaller GRC size, than remote-sensor imagery at the same scale (see Figure 8-10). According to Naithani (1990), aerial photography provides a GRC with a size equal to 0.4 times the value of the GRC for nonphotographic remote-sensing imagery. Strandberg (1967) suggested that the following formula be used to relate the GRC and the photographic scale:

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

where

GRC = ground resolution cell (m),
S = scale number of image (i.e., denominator of scale ratio), and
R = resolution of photographic system (line pairs/mm).

The resolution of aerial photography systems is on the order of 40 linepairs/mm for conventional aerial photographic cameras and films with extreme contrast.

A certain minimum number of pixels is needed to recognize a feature in an image. The actual minimum number of pixels varies according to the grey-tone contrast between the feature and its background. Although it is difficult to give precise data on the minimum number of pixels required, experience with visual interpretation of remote-sensing imagery suggests that the values shown in Table 8-7 are appropriate.

When the required minimum number of pixels recommended in Table 8-7 is multiplied by the size of the GRC, it will indicate the minimum size of landslide that is likely to be identified. Several other factors may also influence the minimum number of pixels necessary for satisfactory identification of landslides. These include factors related to the skill of the individual interpreter, including professional experience and local knowledge related to type and occurrence of landslides. These factors together define 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 photointerpretations made by five recognized professionals of an unknown area before a large landslide.

The implications of Table 8-7 are illustrated by Figures 8-11 and 8-12, which were derived from large-scale aerial photographs. These photographs were digitized with a raster size corresponding to a GRC of 0.3 m. The individual photographs in Figures 8-11 and 8-12 were then created by artificially aggregating and averaging these pixels to reflect GRC sizes of 1, 3, 10, and 30 m.

Table 8-7
Number of Ground Resolution Cells Needed To Identify and Interpret Object of Varying Contrast in Relation to Its Background

	No. of GRCs	
	For Identification	For Interpretation
Extreme contrast: white or black object against variable grey-tone background	20–30	40–50
High contrast: dark or light object in grey-tone background	80–100	120–140
Low contrast: grey feature with grey-tone background	1,000–1,200	1,600–2,000

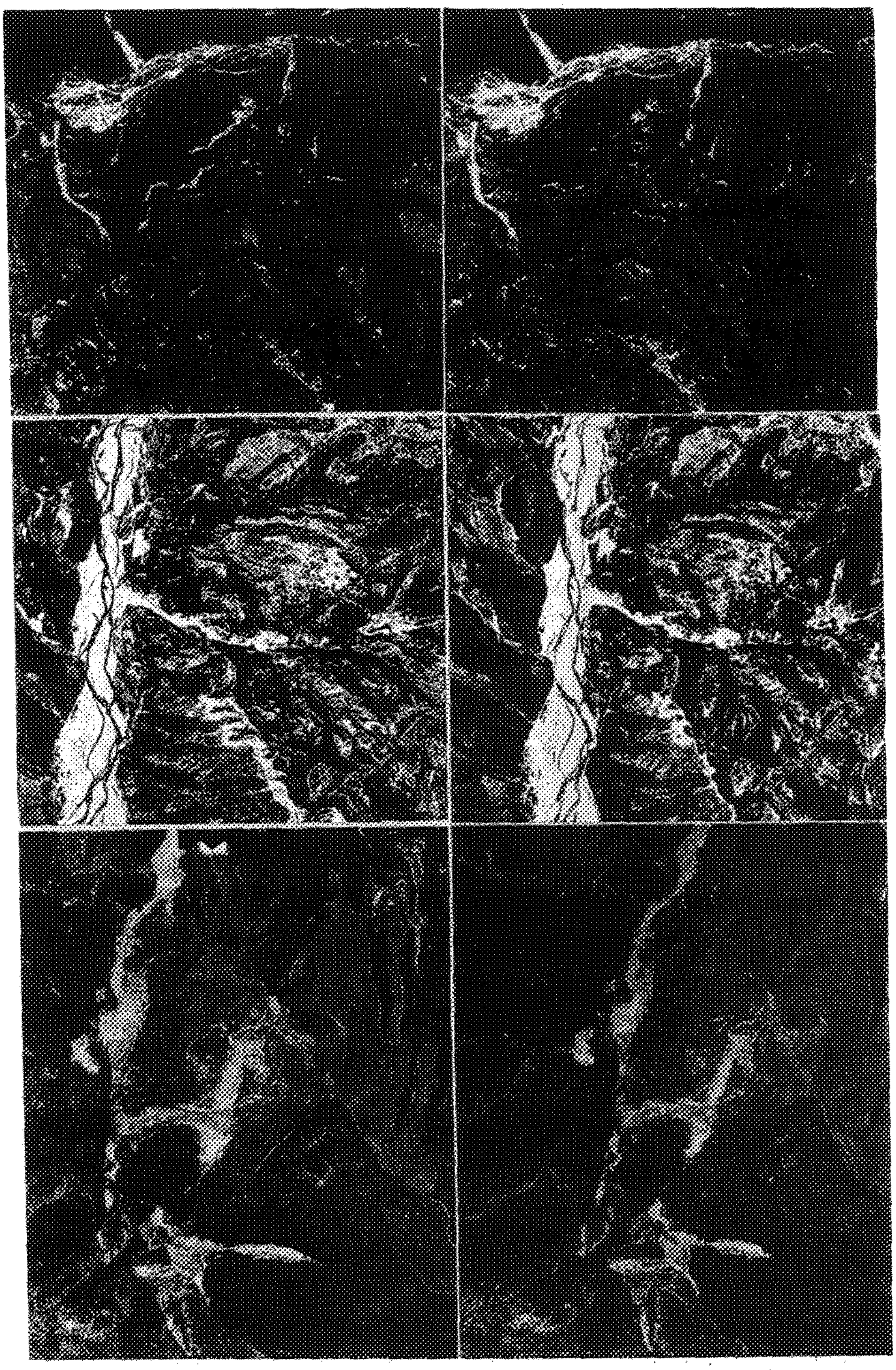
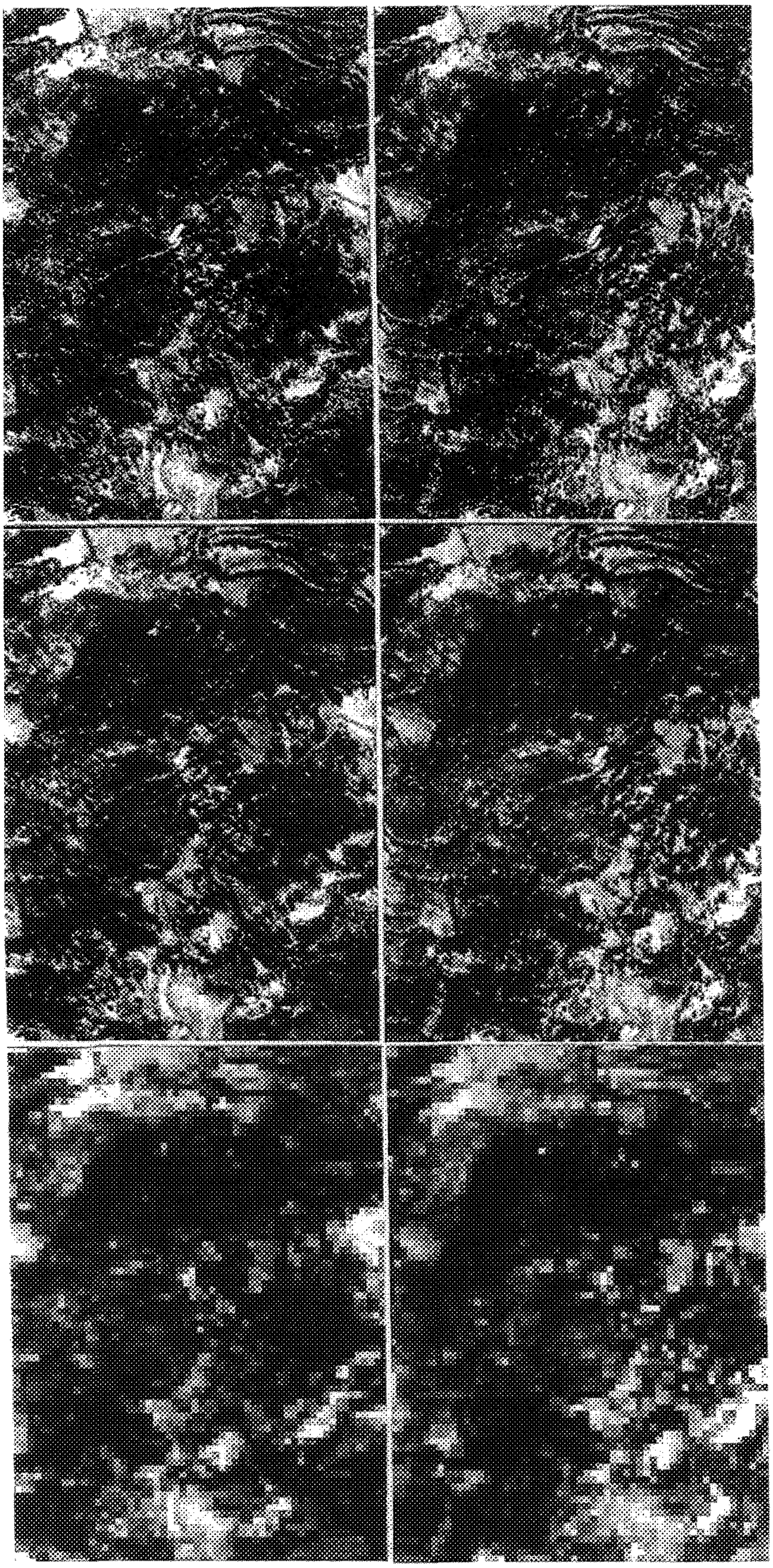


FIGURE 8-10 Comparison of interpretability of huge complex landslide in Sant Arcangelo Basin (Basilicata, Italy) shown on stereo SPOT image (scale approx. 1:70,000), medium-scale aerial photographs (1:33,000), and large-scale aerial photographs (1:17,000). Flight line on medium-scale photographs is north-south, and viewing direction on SPOT and flight line of large-scale photographs is east west.

Figure 8-11 shows photographs with varying GRC sizes of a landslide in the Spanish Pyrenees (Sissakian et al. 1983). The landslide scar with its shadow, which provides high contrast, is observed in the upper part of the image and a depositional area of landslide debris is observed in the central lower part. This area of accumulation is recognizable by a characteristic surface texture due to an irregular microrelief (formed by low-contrast features) and by the surrounding band of higher vegetation recognizable as such in those pictures with small GRC sizes. The photographs in Figure 8-11



are arranged to form stereopairs. They demonstrate the enormous advantage of stereoscopic viewing in the interpretation of mass movements. The values in Table 8-8 give only a general indication of the order of magnitude of the minimum object size that may be recognized or identified on the basis of shape and pattern. Tonal or spectral aspects are considered only in terms of contrast of the feature against the background.

For evaluation of the suitability of remote-sensing images in landslide inventory mapping, the size of individual slope failures in relation to the GRC is of crucial importance. Although sizes of landslides may vary enormously, even within a single type of slope failure, some useful information

FIGURE 8-11 *(left)*
Area in Spanish Pyrenees showing landslide scar in shadow, thereby providing high contrast, and depositional area of landslide debris (*lower center*). These illustrations, which form stereopairs, are derived from digitized large-scale aerial photograph. Artificially aggregated pixels represent ground resolution cell (GRC) sizes of 1, 3, and 10 m. Although image corresponding to 10-m GRC resolution already shows serious degradation, landslide is still clearly interpreted when viewed stereoscopically.

FIGURE 8-12 *(below)*
Same area as that shown in Figure 8-11 but with 30-m GRC resolution. At this image scale, with such a large pixel, no satisfactory stereoscopic image can be obtained.

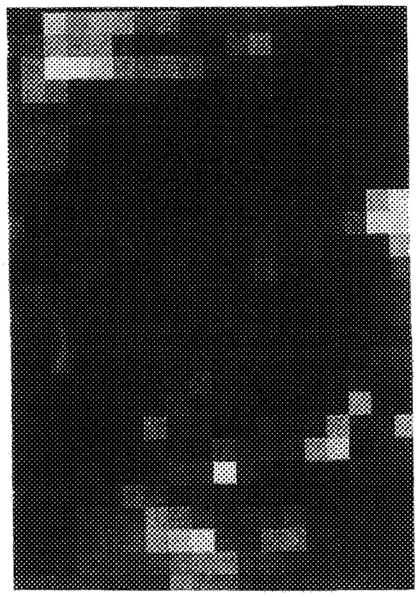


Table 8-8
Minimum Object Size Needed for Landslide Identification or Interpretation

		Size (m²) Needed for			
		High Contrast		Low Contrast	
	GRC Size (m)	Identification	Interpretation	Identification	Interpretati[on]
LANDSAT MSS	80	160,000	288,000	7,040,000	11,520,000
LANDSAT TM	30	22,500	40,500	990,000	1,620,000
SPOT Multispectral	20	10,000	18,000	440,000	720,000
SPOT Panchromatic	10	2,500	4,500	110,000	180,000
Aerial photographs					
1:50,000	1	25	45	1,100	1,800
1:15,000	0.3	6.5	11.5	300	450

Note: The values given depend on the conditions of contrast between the elements of the slide and the background. The data for aerial photographs a[re] somewhat optimistic since optimal photographic conditions and processing are assumed.

can be found in the literature. Crozier (1973) described the morphometric analysis of landslides and provided average values for several types of movements. For a total of almost 400 slope failures, Carrara et al. (1977) computed a mean crown-to-tip distance of 262 m and an average total area involved in a failure of 42 000 m². This total map area per failure approximately corresponds to 20 × 20 pixels on a SPOT Panchromatic image (having a resolution of 10 m), or 10 × 10 pixels on SPOT multispectral images (which have a resolution of 20 m). According to Table 8-7, this number of pixels would be sufficient to identify a landslide displaying high contrast but is insufficient for a proper analysis of the elements pertaining to the failure, thus making it impossible to establish the characteristics and type of landslide. Cleaves (1961) gave mean values of landslide area and size dimensions, also based on a large number of observations, which are even smaller than those of Crozier and Carrara. He concluded that 1:15,000 is the most appropriate photographic scale for analysis of landslides.

Experience at the International Institute for Aerospace Survey and Earth Sciences with the use of photointerpretation techniques in support of landslide hazard investigations in various climatic zones and for a considerable variety of terrain conditions suggests that a scale of 1:15,000 appears to be the optimum scale for aerial photographs, whereas a scale of 1:25,000 should be considered the smallest useful scale for analyzing slope instability phenomena with aerial photographs. A slope failure may be recognized on smaller-scale photography provided that the failure is large enough and the photographic contrast is sufficient. However, such interpretations will lack the analytical information that would enable the interpreter to make conclusions concerning landslide types or causes. Furthermore, many slope movements will not be identifiable on these smaller-scale photographs.

Nevertheless, these smaller-scale aerial photographs are useful for some aspects of landslide hazard assessment, especially for analyzing the overall geologic and geomorphic settings that tend to result in slope failures. Scanvic and Girault (1989) and Scanvic (1990) reached similar conclusions. These authors describe a study in which the applicability of SPOT satellite imagery to slope instability mapping near La Paz, Bolivia, was evaluated. The authors concluded that SPOT yielded excellent data complementary to large-scale photographs.

Thus it appears that small-scale photographs are useful in determining the regional spatial distribution of variables affecting landsliding, whereas large-scale aerial photographs support landslide inventory and analysis activities, including interpretation of possible causal factors. These two types of activities suggest that landslide hazard assessment when larger areas must be evaluated can be most efficiently conducted with small-scale photography, and large-scale photography would be used only in pilot areas to establish the relation between landslide and terrain condition. Furthermore, good-quality, relatively small-scale aerial photography used during the reconnaissance stages of a project can be enlarged and used for more detailed subsequent studies, making an additional flight to obtain new photographs unnecessary. Table 8-9 gives results from a comparative study of

Table 8-9
Relative Suitability of Different Scales of Aerial Photographs for Different Elements in Slope Instability Mapping (modified from Sissakian et al. 1983)

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

Note: 0 = less adequate, 1 = limited use, 2 = useful, 3 = very useful.

the interpretability of slope instability features on aerial photographs at their original scale and at three levels of enlargement (Sissakian et al. 1983).

3.5 Spectral and Temporal Resolution of Remote-Sensing Data

Vegetation and soil moisture conditions produce distinctive spectral responses in the infrared portions of the spectrum. For example, healthy vegetation produces infrared reflectance values that are very different from those of stressed, or unhealthy, vegetation. Strong differences in the infrared responses may be detected even when the vegetation appears normal in the visible portion of the spectrum. In a similar fashion, slight changes in soil moisture conditions are readily detected in the infrared portions of the spectrum. Landslides frequently produce subtle changes in the health and vigor of vegetation and may also cause increases in soil moisture caused by disruption of subsurface water movements. Thus, remote-sensing systems that are sensitive to the infrared part of the spectrum are most effective in landslide inventory studies. The use of infrared-sensitive film, and false-color infrared film in particular, is highly recommended for landslide studies in view of the capability of these films to register small anomalies in vegetation or drainage conditions. Optimal differences in vegetation conditions may be expected in either the very early or very late stages of the growing season. Differences in drainage conditions are optimal shortly after the first rainstorms of the rainy season in many tropical regions or shortly after the spring snowmelt period in cold and temperate climates.

Satellite imagery offers more detailed spectral information than is usually available in photographs because the satellite sensors are designed to obtain the reflected electromagnetic radiation in various wavelength (spectral) bands. Black-and-white images of individual spectral bands may be displayed, but more commonly these are combined to form color composites, of which the *false-color composite*, comparable with false-color infrared photography, is the most common. Digital processing of the spectral data offers the possibility for detailed analysis of the obtained reflectance values and enhancement of small spectral variations that seem to be correlated with slope instability features.

The size of areas with anomalous drainage conditions or disturbed vegetation causing an anomalous spectral response is often too small to allow the interpretation of individual instability features on the basis of spectral criteria. However, spectral interpretation of satellite data has been used successfully in slope instability studies when this spectral information is used in conjunction with other data related to slope failures. Together these multiple information sources provide converging evidence for slope movements. Practical applications of spectral information from satellite imagery are also possible when, on the basis of terrain evidence, a direct relationship is known between slope instability and vegetation or drainage anomalies. McKean and coworkers (1991) demonstrated that spectral vegetation indices can be used in mapping spatial patterns of grass senescence that were found to be related to soil thickness and slope instability. In another case landslides in a homogeneous forested area exposed differences in understory vegetation and soils, thereby altering the spectral characteristics.

In general, it can be stated that spectral information can be used in the same way as spatial data to delineate terrain variables that are correlated or assumed to be related to slope movements. In the case of landslides, these terrain variables are mostly related to vegetation and drainage conditions. In special cases where the landslide conditions produce high contrast or in the case where the landslide has unusually large dimensions, or in both cases, the feature itself may be identified on the basis of spectral information. However, seldom will this type of information alone be sufficient for analyzing the type of failure.

Satellite systems orbiting the earth also provide the opportunity to obtain data from the same areas on a regular schedule, allowing for the monitoring of processes over time. Images obtained shortly after a period of slope instability will show high contrast between the zones affected by slope instability and the stable surroundings, resulting in clearly detectable spatial and spectral changes. These changes allow the interpreter to develop a slope instability impact assessment, such as that shown in Figure 8-7, which shows an area in Thailand affected by debris flows following 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 times may indicate the activity of the slope processes in an area. However, it must be noted that even 20 years' worth of satellite images is still a rather small amount to obtain a good idea of the activity of slope instability processes because they are mainly triggered by low-frequency spasmodic events. Furthermore, adverse weather conditions or certain system limitations are additional limiting factors to the acquisition of satellite data at the most appropriate times and serve to restrain the full achievement of the available temporal resolution.

3.6 Applicability of Satellite Remote Sensing

On the basis of the foregoing discussion, it may be concluded that currently available satellite remote sensing has limited application to the *direct mapping* of slope instability features. The spatial resolution of these systems is insufficient to allow the identification of landslide features smaller than about 100 m, even when conditions favor a strong contrast between the landslide and the background areas. If contrast conditions are less favorable, identification may be limited to features greater than 400 m. Such dimensions are greater than those of many economically significant landslides.

The lack of stereoscopic imagery, except in the case of the SPOT satellite, further limits the applicability of much of the currently available satellite imagery. Stereoscopic imaging capability allows for the visualization of the land surface in three dimensions. Such three-dimensional information is necessary for the interpretation of the characteristic and diagnostic morphologic features of slope failures. Therefore, accepting the limitations related to the spatial resolution, stereoscopic SPOT satellite images may sometimes be used for small-scale regional hazard zonation studies. LANDSAT thematic mapper images could also be used for the same purpose, but only when stereomates, which provide a means for stereoscopic viewing, are made with the help of a detailed DEM. Such detailed DEM data are not often available.

In contrast, satellite images are valuable tools for *indirect mapping* methods. These methods require information concerning the spatial distribution of landslide-controlling variables, such as a particular geomorphic condition, a specific lithology, or a particular type of land use. These may be mapped rapidly and reliably over large areas with the use of satellite images. In practice, this mapping process implies the use of a combination of satellite imagery and large-scale photography. Large-scale aerial photography is used for the initial landslide inventory mapping and analytical stages of slope instability assessment. These findings are then extrapolated and used to assist in the interpretation of the smaller-scale satellite imagery. In the interpretation of small-scale images, the local reference level of the interpreter is of great influence. The reference level of the interpreter is greatly improved when local large-scale information is combined with regional small-scale synoptic data. The value of stereoscopic SPOT satellite imagery can hardly be overestimated in these applications, as was demonstrated by Scanvic and Girault (1989) and Scanvic (1990) with a case study of landslide vulnerability mapping near La Paz, Bolivia. The combined use of aerial photographs and satellite imagery in slope instability studies has also been emphasized by Tonnayopas (1988) and especially by van Westen (1992, 1993). The efficiency of integrating satellite images, aerial photographic interpretations, and field data was further improved by van Westen through the application of GIS techniques.

The potential of radar imagery for landslide hazard zonation requires further investigation. The results with radar interferometry are promising, and terrain roughness classification methods appear encouraging (Slaney and Singhroy 1991). Evans (1992) provided an overview of the applicability of synthetic aperture radar (SAR) to the study of geologic processes. However, problems remain with the use of radar imagery for landslide evaluations. Figure 8-13 is an ERS-1 satellite radar image for an area in southern Italy characterized by intensive slope processes and a local topographic relief that does not exceed 100 m. The geometric distortions due to foreshortening, a characteristic of the radar systems, and speckling due to the surface reflection characteristics resulted in a poor image.

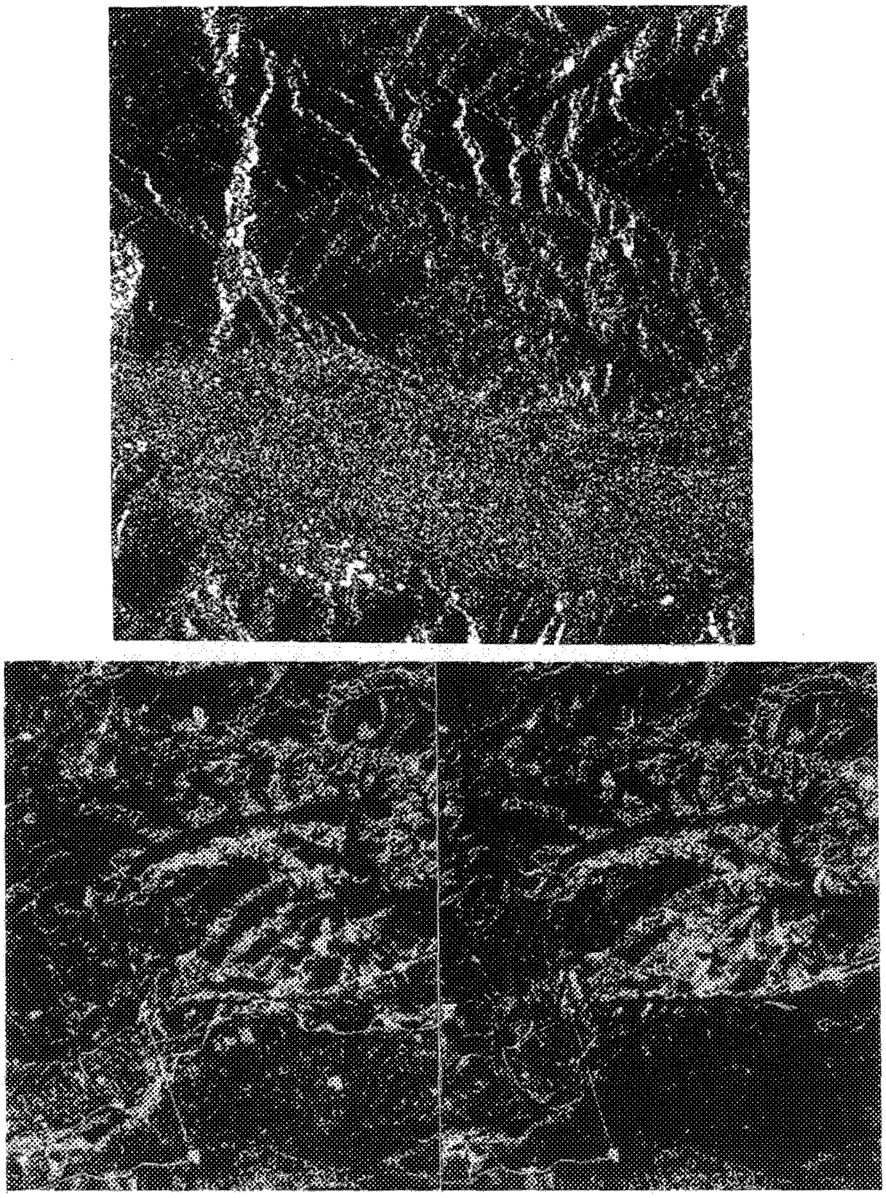


FIGURE 8-13 Comparison of ERS-1 radar image of area in Basilicata, southern Italy, with SPOT image of same zone. Internal topographic relief is less than 100 m; nevertheless, radar image already shows considerable geometric distortion of slopes (foreshortening). Speckling is characteristic of radar images.

The application of thermal infrared (TIR) remote-sensing imagery for slope instability studies is still in an early research phase. The spatial resolution of the thermal band of the LANDSAT thematic mapper is far too coarse for landslide investigations. Yet a higher spatial resolution apparently would markedly degrade the thermal resolution of the detectors from their current sensitivity of 0.1°C. A number of materials identification experiments have been performed with airborne TIR sensors (Lasky 1980; Bison et al. 1990). The lower altitudes of these airborne sensors compared with the LANDSAT TM thermal sensor allow them to achieve increased spatial resolution while maintaining the thermal resolution.

Bison et al. (1990) conducted some promising thermal inertia mapping research on a small area in Italy that is subject to landsliding. Thermal inertia provides a measure of the ease with which an object changes temperature. In natural soil materials the presence of water greatly reduces the rate at which the soil changes temperature in response to diurnal heating and cooling cycles. Thus, comparison of thermal images taken at different times within the daily cycle allows the determination of relative thermal inertia values. If other factors are the same, wetter soils will show greater relative thermal inertia values. Bison et al. evaluated TIR images collected immediately before and after sunrise in the autumn to produce maps of relative thermal inertia. Effects of vegetation and shadowing were identified and removed. Detectors installed in the ground registered variations in temperature of the soils on a slope. These variations could be correlated with variations in the soil moisture content and with patterns visible in the thermal imagery. However, no threshold values were established for the soil moisture content in relation to the occurrence of slope failures.

The term *small-format aerial photographs* refers to all photographs taken from airborne platforms and that have a negative size smaller than the conventional 23- by 23-cm aerial photographs. Useful images have been collected at a variety of negative sizes, including the common 35-mm film size. Small-format oblique aerial photographs may be obtained with a hand-held camera from helicopters, light aircraft, and even ultralight aircraft. These methods allow for almost real-time synoptic information on landslides to be obtained. Such information is extremely useful for the evaluation of large, complex slope failures. To make precise measurements of objects from these photographs, techniques of nonconventional photogrammetry must be employed. These techniques are becoming more promising because software programs have been developed that allow for detailed quantitative work with a minimum of ground control points (V. Kaufmann, personal communication, 1993, Technical University, Graz, Austria).

4. GEOGRAPHIC INFORMATION SYSTEMS IN HAZARD ZONATION

The occurrence of slope failures depends generally on complex interactions among a large number of partially interrelated factors. Analysis of landslide hazard requires evaluation of the relationships between various terrain conditions and landslide occurrences. An experienced earth scientist has the capability to mentally assess the overall slope conditions and to extract the critical parameters. However, an objective procedure is often desired to quantitatively support the slope instability assessment. This procedure requires evaluation of the spatially varying terrain conditions as well as the spatial representation of the landslides. A geographic information system (GIS) allows for the storage and manipulation of information concerning the different terrain factors as distinct data layers and thus provides an excellent tool for slope instability hazard zonation.

4.1 Geographic Information Systems

A GIS is defined as a "powerful set of tools for collecting, storing, retrieving at will, transforming, and displaying spatial data from the real world for a particular set of purposes" (Burrough 1986). The first experimental computerized GIS was developed as early as the 1960s, but the real boom came in the 1980s with the increasing availability of inexpensive personal computers (PCs). For an introduction to GIS, the reader is referred to textbooks such as those by Burrough (1986) or Aronoff (1989). Generally a GIS consists of the following components:

1. Data input and verification,
2. Data storage and data-base manipulation,
3. Data transformation and analysis, and
4. Data output and presentation.

Currently there are many different systems on the market, ranging from public domain software for PCs to very expensive systems for mainframe computers. In general, the systems differ with respect to

- Type of data structure (vector versus raster);
- Data compression technique (Quadtrees, run-length coding);
- Dimension (two-dimensional versus three-dimensional);
- Mainframe, minicomputer, and microcomputer hardware; and
- User interface (pop-up menus, mouse-driven, help options, etc.).

The advantages of the use of GIS as compared with conventional spatial analysis techniques are treated extensively by Burrough (1986) and Aronoff (1989). An ideal GIS for landslide hazard zonation combines conventional GIS procedures with image-processing capabilities and a relational data base. Since frequent map overlaying, modeling, and integration with remote-sensing images (scanned aerial photographs and satellite images) are required, a raster system is preferred. The system should be able to perform spatial analysis on multiple-input maps and connected attribute data tables. Necessary GIS functions include map overlay, reclassification, and a variety of other spatial functions incorporating logical, arithmetic, conditional, and neighborhood operations. In many cases landslide modeling requires the iterative application of similar analyses using different parameters. Therefore, the GIS should allow for the use of batch files and macros to assist in performing these iterations. Since most data sets required for landslide hazard zonation projects are still relatively small, mostly less than 100 megabytes, they can be readily accommodated by inexpensive PC-based GIS applications.

The advantages of GIS for assessing landslide hazard include the following:

1. A much larger variety of hazard analysis techniques becomes attainable. Because of the speed of calculation, complex techniques requiring a large number of map overlays and table calculations become feasible.
2. It is possible to improve models by evaluating their results and adjusting the input variables. Users can achieve the optimum results by a process of trial and error, running the models several times, whereas it is difficult to use these models even once in the conventional manner. Therefore, more accurate results can be expected.
3. In the course of a landslide hazard assessment project, the input maps derived from field observations can be updated rapidly when new data are collected. Also, after completion of the project, the data can be used by others in an effective manner.

The disadvantages of GIS for assessing landslide hazard include the following:

1. A large amount of time is needed for data entry. Digitizing is especially time-consuming.
2. There is a danger in placing too much emphasis on data analysis as such at the expense of data collection and manipulation based on professional experience. A large number of different techniques of analysis are theoretically possible, but often the necessary data are missing. In other words, the tools are available but cannot be used because of the lack or uncertainty of input data.

4.2 Examples from the Literature

The first applications of a simple, self-programmed, prototype GIS for analyzing landslide hazard zonation date from the late 1970s. Newman et al. (1978) reported on the feasibility of producing landslide susceptibility maps using computers. Carrara et al. (1978) reported results of multivariate analysis applied on grid cells with a ground resolution of 200 by 200 m and using approximately 25 variables. Huma and Radulescu (1978) reported an example from Romania that provided a qualitative hazard analysis by including the factors of mass movement occurrence, geology, structural geologic conditions, hydrologic conditions, vegetation, slope angle, and slope aspect. Radbruch-Hall et al. (1979) wrote their own software to produce small-scale (1:7,500,000) maps of the United States. Each map contained about 6 million pixels, which showed hazards, unfavorable geologic conditions, and areas in which construction or land development may exacerbate existing hazards. These maps were made by qualitative overlay of several input maps.

During the 1980s the use of GIS for slope instability mapping increased sharply because of the development of a great variety of commercial systems, such as Arc/Info (Environmental Systems Research Institute 1992) and Intergraph Corporation's MGE (Intergraph Corporation 1993). The increasing power and availability of PCs led to the development of several GIS applications that would work on these computers, including Tydac Corporation's SPANS and IDRISI (Eastman 1992a, 1992b).

The majority of case studies presented in the literature concerning the use of GIS methods for slope instability investigations deal with qualitative hazard zonation. The importance of geomorphic input data is stressed in the methods of Kienholz et al. (1988), who used detailed aerial photointerpretation in conjunction with a GIS for qualitative mountain hazard analysis. They state that because of the lack of good models and geotechnical input data, the use of a relatively simple model based on geomorphology seemed to be the most realistic method. Most examples of qualitative hazard analysis with GIS are recent (Stakenborg 1986; Bertozzi et al. 1992; Kingsbury et al. 1992; Mani and Gerber 1992; van Westen and Alzate-Bonilla 1990). Many examples are presented in the proceedings of specialty conferences, such as those edited by Alzate (1992) and by Goodchild et al. (1993).

Examples of landslide susceptibility analysis utilizing GIS techniques have been reported by U.S. Geological Survey (USGS) personnel in Menlo Park, California (Brabb 1984, 1987; Brabb et al. 1989). These studies extended earlier studies and took into account additional factors besides landslide activity, geology, and slope. Other examples of quantitative statistical analysis of landslide cause or potential with GIS are rather scarce (Choubey and Litoria 1990; Lopez and Zinck 1991; van Westen 1993). This lack of examples is strange, since one of the strong advantages of using a GIS is the capability to test the importance of each factor, or combination of factors, and assign quantitative weighting values.

Recent examples of multivariate statistical analysis using GIS have been presented by Carrara and his team from Italy. Their work initially used large rectangular grid cells as the basis for analysis (Carrara et al. 1978; Carrara 1983, 1988). Later studies evolved toward the use of morphometric units (Carrara et al. 1990, 1991, 1992). The method itself has not undergone major changes. The statistical model is built up in a "training area" where the spatial distribution of landslides is (or should be) well known (Carrara 1988). In the next step the model is extended to the entire study area, or "target area," on the basis of the assumption that the factors that cause slope failure in the target area are the same as those in the training area.

Another example of multivariate analysis of landsliding using a GIS was presented by Bernknopf et al. (1988), who applied multiple regression analysis to a data set using presence or absence of landslides as the dependent variable and the factors used in a slope stability model (soil depth, soil strength, slope angle) as independent variables. Water table and cohesion data were not considered, however. The resulting regression function allows the computation of landslide probability for each pixel.

Deterministic modeling of landslide hazard using GIS has become popular. Most examples deal with infinite slope models, since they are simple to use for each pixel separately (Brass et al. 1989; Murphy and Vita-Finzi 1991; van Westen 1993). Hammond et al. (1992) presented methods in which the variability of the factor of safety is calculated from selected input variables utilizing Monte Carlo techniques. This implies a large number of repeated calculations, which are readily supported by use of a GIS.

Another useful application of GIS has been the prediction of rock slides. The prediction is made for a series of pixels by comparing discontinuity measurements within structurally homogeneous regions with slope and aspect values for each pixel (Wentworth et al. 1987; Wagner et al. 1988). The method is feasible only in structurally simple areas, however.

A relatively new development in the use of GIS for slope instability assessment is the application of so-called "neighborhood analysis." Most of the conventional GIS techniques are based on map overlaying, which allows only for the spatial comparison of different maps at common pixel locations. In contrast, neighborhood operations permit evaluation of the neighboring pixels surrounding a central pixel. The process is repeated for a sequence of central pixels, the analysis neighborhood, or window, moving around the map. Neighborhood functions are used to compute, or determine, such morphometric and hydrologic features as slope angle, slope aspect, downslope and cross-slope convexity, ridge and valley lines, catchment areas, stream ordering, and the contributing areas for each pixel in the map area by evaluating the data contained in a gridded DEM. Zevenbergen and Thorne (1987) presented a method for the automatic extraction of slope angle, slope aspect, and downslope and cross-slope convexity. An overview of the algorithms applied in the extraction of morphometric parameters from DEMs was given by Gardner et al. (1990).

The potential value of DEMs for dynamic slope stability analysis was stressed by Pike (1988) and Wadge (1988). Carrara automatically identified from a detailed DEM the homogeneous units he used as the basis for a multivariate analysis. The morphometric and hydrologic parameters used in that analysis were also extracted automatically (Carrara et al. 1990; Carrara 1988). Niemann and Howes (1991) performed a statistical analysis based on automatically extracted morphometric parameters (slope angle, slope aspect, downslope and cross-slope convexity, and drainage area), which they grouped into homogeneous units using cluster analysis. Various authors (Okimura and Kawatani 1986; Brass et al. 1989) have used neighborhood analysis in the modeling of groundwater tables over time, and used these values as one of the input factors in infinite slope modeling. A simple type of neighborhood analysis was applied by van Dijke and van Westen (1990) to model the runout distances for rock-fall blocks. Ellen et al. (1993) developed a dynamic model for simulating the runout distance of debris flows with a GIS.

A recent development in the use of GIS for slope instability zonation is the application of expert systems. Pearson et al. (1991) developed an expert system in connection with a GIS in order to remove the constraint that users should have considerable experience with GIS. A prototype interface between a GIS (Arc/Info) and an expert system (Nexpert Object) was developed and applied for translational landslide hazard zonation in an area in Cyprus. The question remains, however, as to whether the rules used in this expert system apply only to this specific area or are universally applicable.

4.3 GIS-Based Landslide Hazard Zonation Techniques

The most useful techniques for the application of GIS landslide hazard zonation are presented in the following discussion. A brief description of the various landslide hazard analysis techniques was given in Section 2.4. Each technique described here is shown schematically in a simplified flowchart. An overview is given of the required input data (as discussed in Section 2.3), and the various steps required in using GIS techniques are mentioned briefly. A recommendation is also provided regarding the most appropriate working scale (see also Section 2.2).

4.3.1 Landslide Inventory

The input consists of a field-checked photointerpretation map of landslides for which recent, relatively large-scale aerial photographs have been used combined with a table containing landslide parameters obtained from a checklist. GIS can perform an important task in transferring the digitized photointerpretation to the topographic base map projection using a series of control points and camera information.

The GIS procedure is as follows:

- Digitize the mass movement phenomena, each with its own unique label and a six-digit code containing information on the landslide type, subtype, activity, depth, and site vegetation and whether the unit is a landslide scarp or body;
- Recode the landslide map showing the parameters for landslide type or subtype into maps that display only a single type or process.

In this technique, the GIS is used only to store the information and to display maps in different forms (e.g., only the scarps, only the slides, or only the active slides). Although the actual analysis is very simple, the use of GIS provides a great advantage for this method. The user can select specific combinations of mass movement parameters and obtain better insight into the spatial distribution of the various landslide types. The method is represented schematically in Figure 8-14.

The code for mass movement activity given to each mass movement phenomenon can also be used in combination with mass movement distribution maps from earlier dates to analyze mass movement activity. Depending on the type of terrain being studied, time intervals of 5 to 20 years may be selected. This method of interval analysis provides estimates of the numbers or percentages of reactivated, new, or stabilized landslides.

Mass movement information can also be presented as a percentage cover within mapping

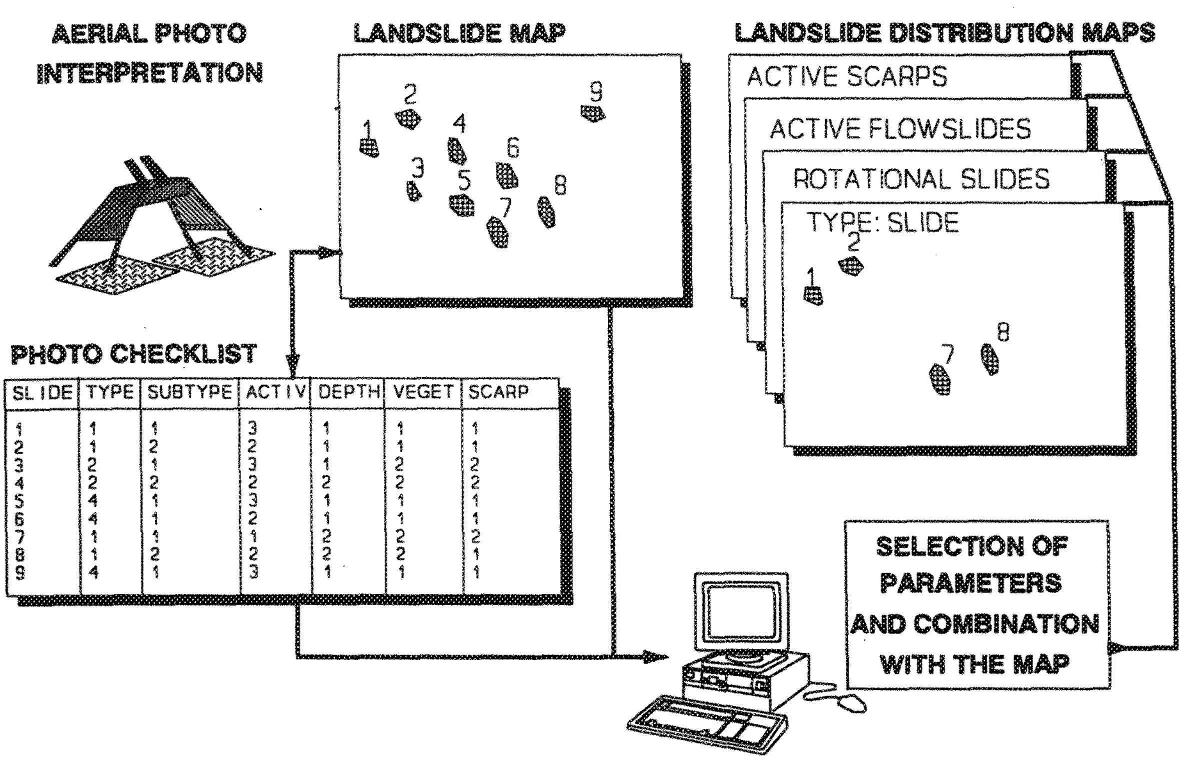


FIGURE 8-14
Use of GIS for analysis of landslide distribution. See Table 8-4 for code numbers in photo checklist.

units. These mapping units may be TMUs, geomorphic units, geologic units, or any other appropriate map unit. This method may also be used to test the importance of each individual parameter for predicting the occurrence of mass movements. The required input data consist of a mass movement distribution map and a land-unit map. If the method is used to test the importance of specific parameter classes, the user decides, on the basis of his or her field experience, which individual parameter maps, or combination of parameter maps, will be used.

The following GIS procedures are used for mass movement density analysis:

- Calculation of a bit map (presence or absence) for the specific movement type for which the analysis is carried out;
- Combination of the selected parameter map with the bit map through a process called "map crossing," which spatially correlates the conditions on the two maps; and
- Calculation of the area percentage per parameter class occupied by landslides.

With a small modification, the number of landslides can be calculated instead of the areal density. In this case a bit map is not made, and the mass movement map itself, in which each polygon has a unique code, is overlaid by the parameter map. The method is represented schematically in Figure 8-15.

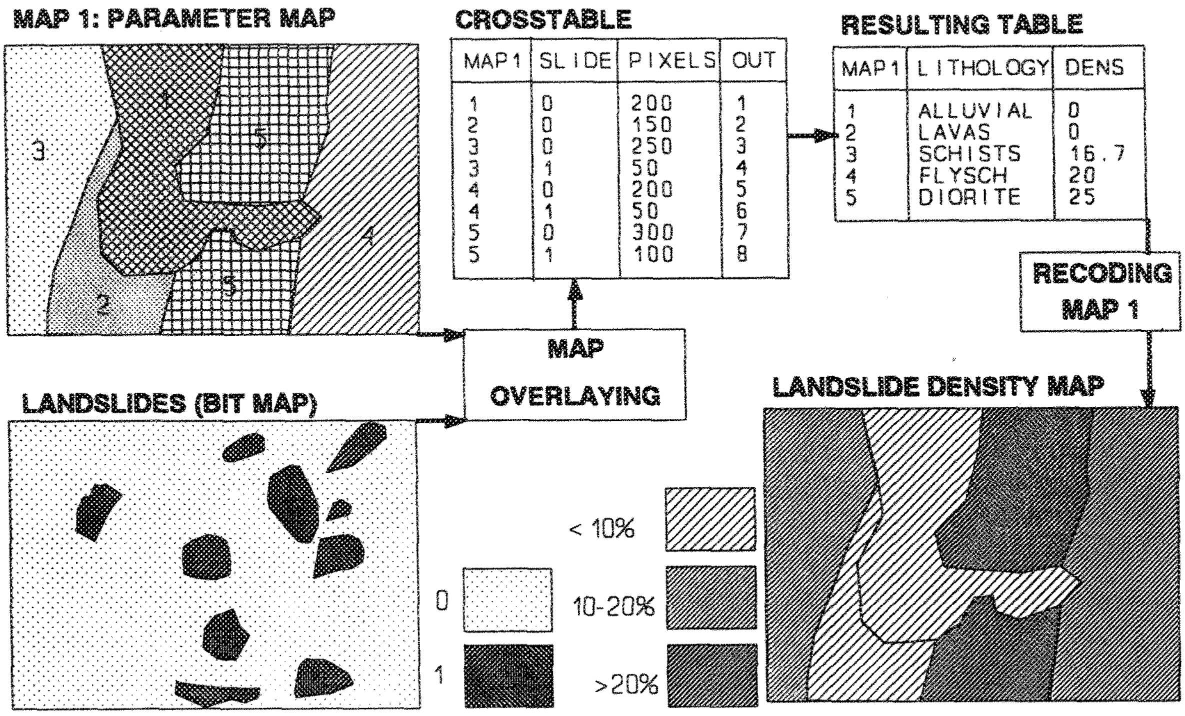
Isopleth mapping is a special form of mass movement density mapping. The method uses a large circular counting filter that calculates the landslide density for each circle center automatically. The resulting values for the circle centers are interpolated and contours of equal density are drawn. The scale of the pixels and the size of the filter used define the values in the resulting density map.

The method is most appropriate at medium or large scales. At the regional scale the construction of a mass movement distribution map is very time-consuming and too detailed for procedures of general regional zoning. Nevertheless, when possible, it is advisable to prepare such a map also for the regional scale, although with less detail.

4.3.2 Heuristic Analysis

As explained in Section 2.4.2, when a heuristic approach is used, the hazard map is made by the mapping geomorphologist using site-specific knowledge obtained through photointerpretation and fieldwork. The map can be made either directly in the field or by recoding a geomorphic map. The criteria on which hazard class designa-

IGURE 8-15
se of GIS for
nalysis of landslide
ensity.



tions are based are not formalized in generally applicable rules and may vary from polygon to polygon. GIS can be used in this type of work as a drawing tool, allowing rapid recoding of units and correction of units that were coded erroneously. GIS is not used as a tool for the analysis of the important parameters related to the occurrence of mass movements. The method can be applied at regional, medium, or large scales in a relatively short time period. It does not require the digitizing of many different maps. However, the detailed fieldwork requires a considerable amount of time.

If the analysis is done by combining several parameter maps, qualitative weighting values are assigned to each class of parameter map, and each parameter map receives a different weight. The earth scientist decides which maps will be utilized and which weighting values will be assigned on the basis of field knowledge of the causal factors (see Figure 8-16).

The following GIS procedures are used:

- Classification of each parameter map into a number of relevant classes;
- Assignment of weighting values to each of the parameter classes (e.g., on a scale of 1 to 10);
- Assignment of weighting values to each of the parameter maps; and
- Calculation of weights for each pixel and classification in a few hazard classes.

The method is applicable on all three scales. Each scale has its own requirements as to the required detail of the input maps.

4.3.3 Statistical Analysis

In statistical methods, overlaying of parameter maps and calculation of landslide densities form the core of the analysis. If bivariate techniques are chosen, the importance of each parameter or specific combinations of parameters can be analyzed individually. Several methods exist for calculating weighting values (see Section 2.4.3). Most are based on the relationship between the landslide density per parameter class compared with the landslide density over the entire area. Each method has its specific rules for data integration required to produce the total hazard map.

The weighting values can also be used to design decision rules, which are based on the experience of the earth scientist. It is possible to combine various parameter maps into a map of homogeneous units, which is then combined or overlaid with the

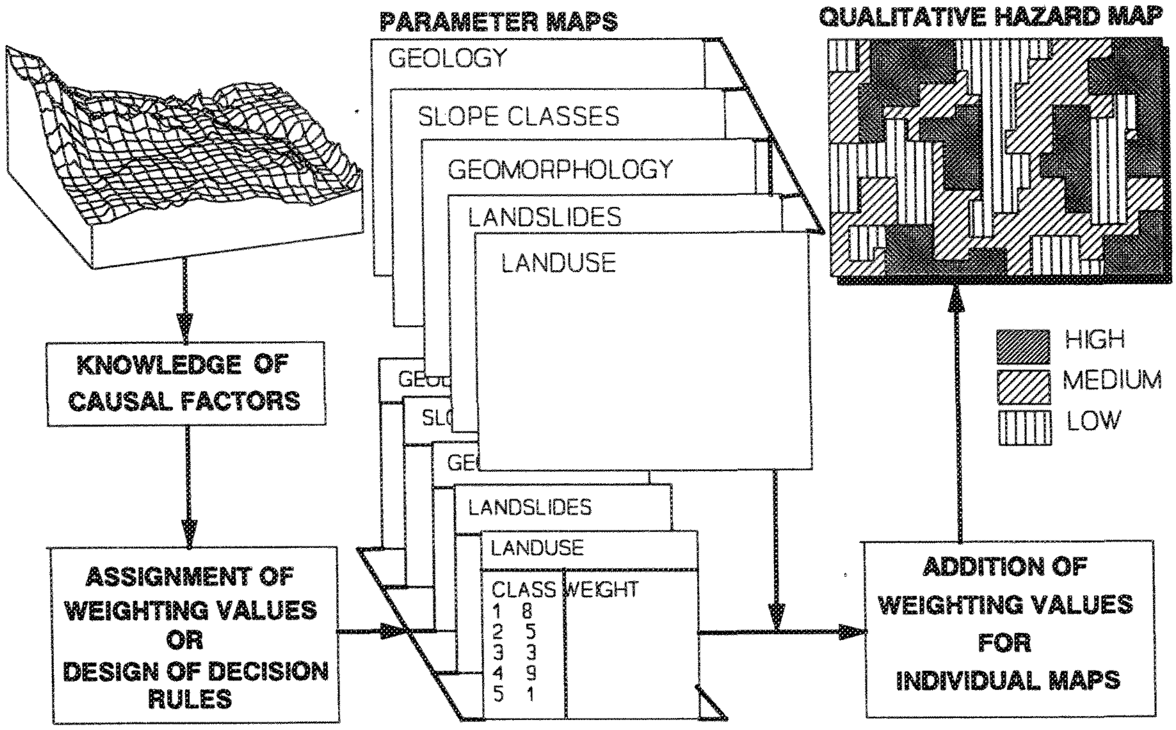


FIGURE 8-16
Use of GIS for qualitative map combination.

landslide map to produce a landslide density for each unique combination of input parameters.

GIS is very suitable for use with this method, especially with macro commands for repetitive calculations involving a large number of map combinations and manipulation of attribute data. It should be stressed that the selection of parameters also has an important subjective element in this method. However, the user can test the importance of individual parameter maps and decide on the final input maps in an iterative manner. The following GIS procedures are used (see Figure 8-17):

- Classification of each parameter map into a number of relevant classes;
- Combination of the selected parameter maps with the landslide map by the process known as map crossing to produce cross-tabulations defining the spatial correlations between the parameter maps and the landslide map;
- Calculation of weighting values based on the cross-tabulation data; and
- Assignment of weighting values to the various parameter maps or design of decision rules to be applied to the maps and classification of the resulting scores in a few hazard classes.

Multivariate statistical analyses of important factors related to landslide occurrence give the relative contribution of each of these factors to the total hazard within a defined land unit. The analyses are based on the presence or absence of mass movement phenomena within these land units, which may be catchment areas, interpreted geomorphic units, or other kinds of terrain units.

Several multivariate methods have been proposed in the literature. Most of these, such as discriminant analysis or multiple regression, require the use of external statistical packages. GIS techniques are used to sample parameters for each land unit. However, with a PC-based GIS, the large volume of data may become a problem. The method requires a landslide distribution map and a land-unit map. A large number of parameters are used, sometimes up to 50. The following GIS procedures are used (see Figure 8-18):

- Determination of the list of factors that will be included in the analysis. Because many input maps (such as geology) are of an alphanumerical type, they must be converted to numerical maps. These maps can be converted to presence or absence values for each land unit or presented as percentage cover, or the parameter

FIGURE 8-17
Use of GIS for bivariate statistical analysis.

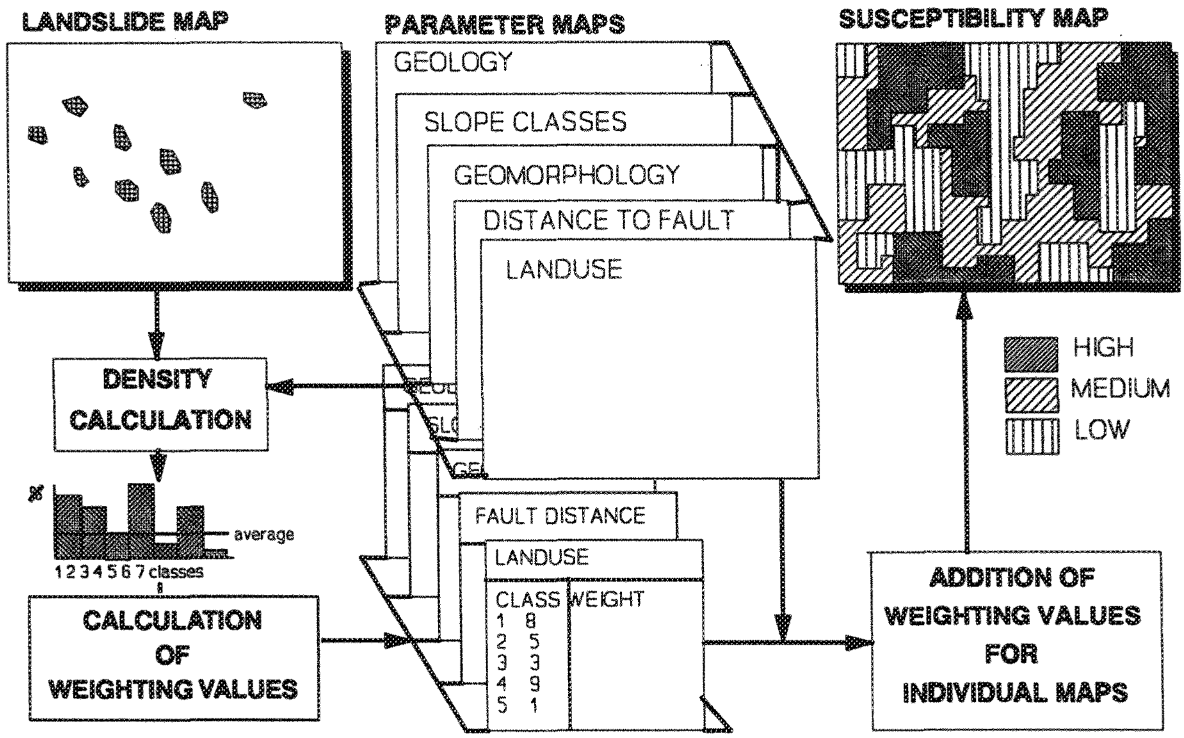
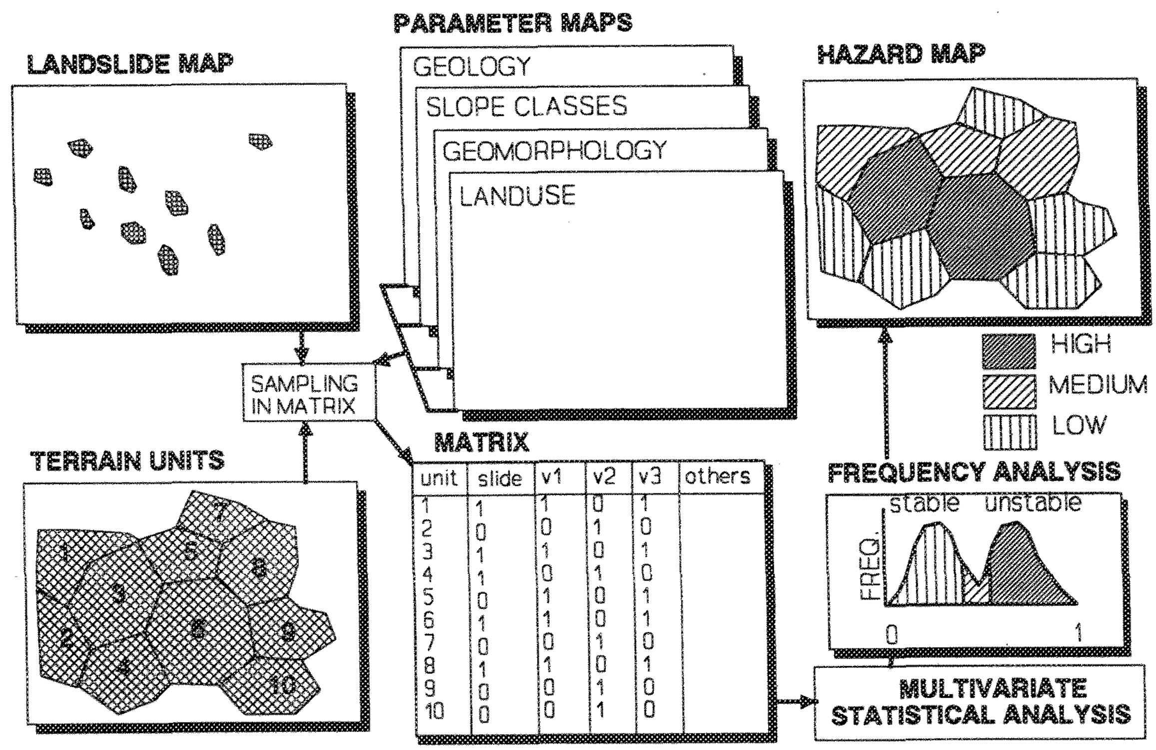


FIGURE 8-18
Use of GIS for multivariate statistical analysis.



classes can be ranked according to increasing mass movement density. By combining the parameter maps with the land-unit map, a large matrix is created.

- Combination of the land-unit map with the mass movement map by map overlaying and dividing the stable and the unstable units into two groups.
- Exportation of the matrix to a statistical package for subsequent analysis.
- Importation of the results for each land unit into the GIS and recoding of the land units. The frequency distribution of stable and unstable classified units is checked to see whether the two groups are separated correctly.
- Classification of the map into a few hazard classes.

Although the statistical techniques can be applied at different scales, their use becomes quite restricted at the regional scale, where an accurate input map of landslide occurrences may not be available and where most of the important parameters cannot be collected with appropriate accuracy. At large scales different factors will have to be used, such as water-table depth, soil layer sequences, and thicknesses. These data are very difficult to obtain even for relatively small areas. Therefore the medium scale is considered most appropriate for this technique.

4.3.4 Deterministic Analysis

The methods described thus far give no information on the stability of a slope as expressed in terms of its factor of safety. For such information, slope stability models are necessary. These models require input data on soil layer thickness, soil strength, depth below the terrain surface to the potential sliding surfaces, slope angle, and pore pressure conditions to be expected on the slip surfaces. The following parameter maps must be available in order to use such models:

- A material map showing the distribution both at ground surface and in the vertical profile with accompanying data on soil characteristics,
- A groundwater level map based on a groundwater model or on field measurements, and
- A detailed slope-angle map derived from a very detailed DEM.

Several approaches allow for the application of GIS in deterministic modeling (see Figure 8-19):

- The use of an infinite slope model, which calculates the safety factor for each pixel;
- Selection of a number of profiles from the DEM and the other parameter maps, which are exported to external slope stability models; and
- Sampling of data at predefined grid points and exportation of these data to a three-dimensional slope stability model.

The result is a map showing the average safety factor for a given magnitude of groundwater depth and seismic acceleration. The variability of the input data can be used to calculate the probability of failure in connection with the return period of triggering events. Generally the resulting safety factors and probabilities should not be used as absolute values unless the analysis is done in a small area where all parameters are well known. Normally they are only indicative and can be used to test different scenarios of slip surfaces and groundwater depths. The method is applicable only at large scales and over small areas. At regional and medium scales, the required detailed input data, especially concerning groundwater levels, soil profile, and geotechnical descriptions, usually cannot be provided.

4.4 Phases of Landslide Hazard Analysis Using GIS

A GIS-supported landslide hazard analysis project requires a number of unique phases, which are distinctly different from those required by a conventional landslide hazard analysis project. An overview of the 12 phases is given in Table 8-10. There is a logical order to these phases, although some may overlap considerably. Phases 7 to 11 are carried out using the computer. Data-base design (Phase 4) occurs before the computer work starts and even before the fieldwork because it determines the way in which the input data are collected in the field.

Table 8-10 also indicates the relative amount of time spent on each phase at each of the three scales of analysis. The time amounts are expressed as a percentage of the time spent on the entire process and are estimated on the basis of experience. Absolute time estimates are not given, since

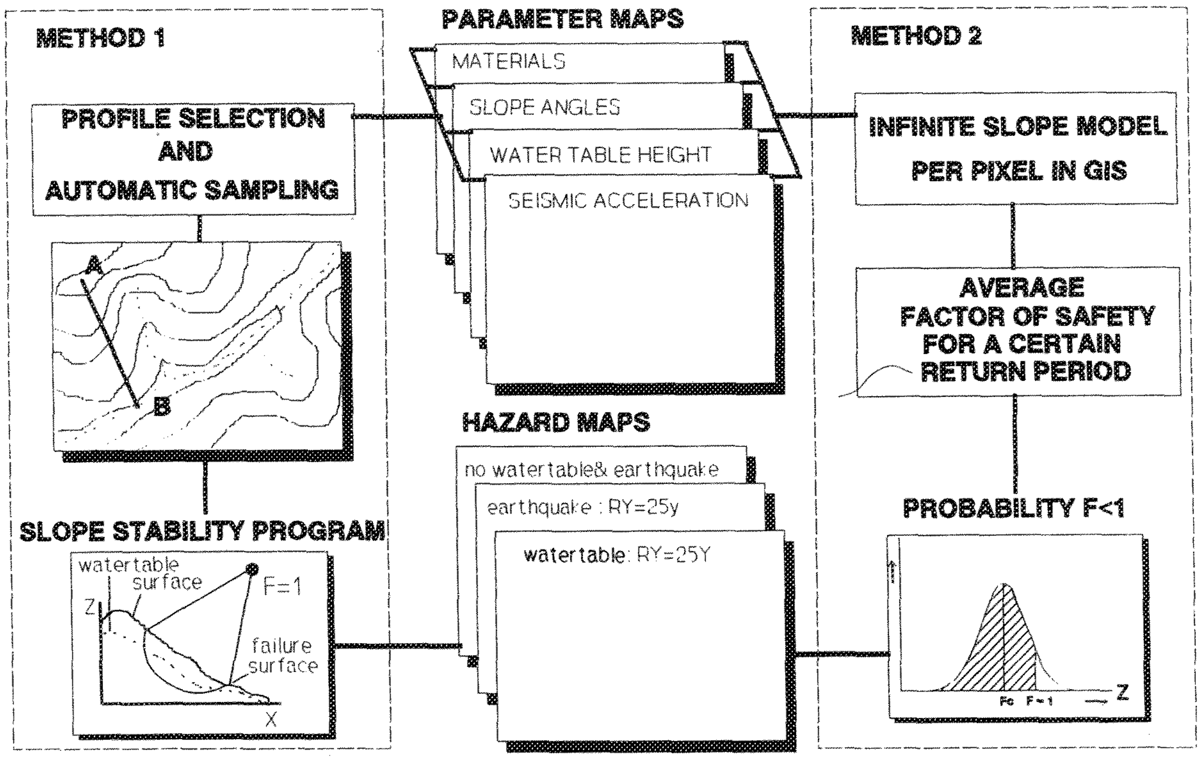


FIGURE 8-19
Use of GIS in deterministic analysis.

Table 8-10
Percentage of Time Spent in Various Phases of Landslide Hazard Assessment Projects at Different Scales Using GIS and Conventional Methods

Phase	Regional Scale		Medium Scale		Large Scale	
	Conventional Methods	GIS-Based Methods	Conventional Methods	GIS-Based Methods	Conventional Methods	GIS-Based Methods
1 Choice of scale and methods	<5	<5	<5	<5	<1	<5
2 Collection of existing data	<5	<5	<5	<5	8	8
3 Image interpretation	50	50	30	30	10	20
4 Data-base design	0	<5	0	<5	0	<5
5 Fieldwork	<5	<5	7	7	10	20
6 Laboratory analysis	0	0	0	<5	0	10
7 Data entry	0	20	0	30	0	15
8 Data validation	0	<5	0	5	0	5
9 Data manipulation	0	<5	0	5	0	5
10 Data analysis	30	10	48	10	61	10
11 Error analysis	0	<5	0	<5	0	<5
12 Final map production	10	<5	10	<5	10	<5

these depend on too many variable factors, such as the amount of available input data, the size of the study area, and the experience of the investigator or investigators.

The percentage of time needed for image interpretation using the GIS approach decreases from the regional scale to the large scale, and fieldwork and laboratory analysis tasks become more important. Data entry requires the most time at the medium scale because of the large number of parameter maps that have to be digitized. Because analysis is based on only one basic data layer of TMUs, the time needed for data entry on the regional scale is much lower.

Working with a GIS considerably increases the time needed for the preanalysis phases, mainly because of the tedious job of hand-digitizing input maps. Time needed for data analysis, however, is not more than 10 percent in the GIS approach versus almost 50 percent using conventional techniques. Many of the analysis techniques are almost impossible to execute without a GIS. Working with GIS considerably reduces the time needed to produce the final maps, which are no longer drawn by hand.

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