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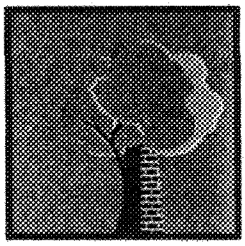

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OF LANDSLIDES IN THE EUROPEAN COMMUNITY
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Part I : Methodology (Reviews) for the Temporal Study of Landslides

REMOTE SENSING AND PHOTOGRAMMETRIC TECHNIQUES FOR LANDSLIDE STUDIES IN EUROPE

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INTRODUCTION

Remote sensing can be defined as comprising the measurement and recording of electromagnetic energy reflected from or emitted by the earth's surface and the relating of such measurements to the nature and properties of objects on the earth surface. The products which are mostly used in earth sciences are aerial photographs, satellite images and radar images.

Up till now the use of remote sensing data in the study of landslides can be considered rather haphazard, due to the limited availability of funds and images, lack of knowledge of the applicability of the different remote sensing, and limited cooperation between various research groups. Generally one works with what is available. Aerial photographs are the most frequently used type of remote sensing data. One could say that airphoto-interpretation has become a standard procedure within most landslide projects, although the extent and detail of the interpretation may vary considerably. Satellite images have been used in landslide studies since the mid-seventies, however only on a scientific level. They have seldom been included within real projects.

In general it can be stated that the full capabilities of remote sensing data, regarding spatial, temporal and spectral resolutions, are not fully exploited in landslide studies. The use of images with different spatial resolutions and scales in a hierarchical analysis, e.g. zooming in on problem areas from smaller scale images to larger scale ones, is not very common. Neither is the use of multispectral images to obtain information outside of the visible part of the spectrum to analyse soil humidity, or vegetation characteristics on landslides, for example. Also the use of multispectral images in the evaluation of the activity of landslides has been applied only in a limited number of cases.

The use of remote sensing data can be differentiated for the various phases within a landslide study: detection and classification of landslides, monitoring the activity of existing landslides, and analysis and prediction in space and time of slope failures.

This paper will give a general overview of the research done in each of these three phases of landslide studies within the EEC countries. Some of the work has been done in the framework of the European Programme on Climatology and Natural Hazard (EPOCH).

We apologize to those researchers, whose valuable contributions are not cited in this paper, for various reasons.

REMOTE SENSING IN LANDSLIDE DETECTION

Detection is a general term used for mapping landslides within a remote sensing image. It includes two aspects: recogniton (is it a landslide ?), and classification (what type of landslide is it ?). Recognition of a landslide, used in a general sense, means whether it is possible to map a landslide, with varying forms and spectral characterist, within a remote sensing image. Import and aspects in the recogniton of landslides are the size of the features, their contrast (the difference in spectral characteristics between the landslides and the surrounding areas) and the morphological expression.

For the recognition of landslide features a number of remote sensing tools are available. The most widely used are show in Table 1, together with some of their technical specifications (after Rengers et al., 1992). The table indicates the minimum sizes needed for features to be recognized for various conditions of contrast with respect to their background

TYPE OF IMAGERY

	LANDSAT MSS	LANDSAT TM	SPOT XS	SPOT PAN	Aerial photos 1:50,000	Aerial photos 1:25,000	Aerial photos 1:10,000
Ground resolution cell size	80	30	20	10	0,5	0,25	0,1
High contrast: features-background	800	300	200	100	5	2,5	1
Low contrast: features-background	3200	1200	800	400	20	10	4

Table 1. Table with the minimum sizes of objects to be recognized for various conditions of contrast with their background in various types of imagery. Values should be used only as an indication of the order of magnitude. All units are in metres.

The use of stereoscopic imagery in slope stability studies is very important in view of the clear and diagnostic morphology, created by mass movements. Features such as scarps, disrupted vegetation cover, and deviations in soil moisture or drainage conditons are generally used in conjunction with morphological features. Considering the size of most landslides, which is on the order of several tens to a few hundreds of metres, the most useful photographic scale is around 1:15,000. At this scale the phenomenon can only be identified as a slope instability feature, but a preliminary analysis of the feature is also possible as the elements of the landslide can be recognized and analyzed. Using smaller scale imagery a slope failure may be recognized as such, if size and contrast are sufficiently large. However, the amount of analytical information, enabling the interpreter to make conclusions on type and causes of the landslide, will be very limited at scales smaller than 1:25,000. It can be concluded from Table 1 that the satellite imagery available today is not suitable for identifying mass movement phenomena, unless they are very large. Nevertheless, several authors have used LANDSAT or SPOT images for identification of mass movements (in the ECC: Stephens, 1988; Vargas, 1992; Scanvic et al, 1992). If landslides have to be identified for differences in vegetation conditions and variations in soil humidity, have been used in landslide studies (Mantovani et al. 1984). Black and white airphotos have been used very extensively in landslide recognition and classification (Flageollet, 1984; Canuti et al, 1985; 1986; Marcolongo et al, 1986; Turrini et al, 1991).

Overviews on the recognition of landslides from imagery are given by Rib and Liang (1978) and Crozier (1984).

Many different systems have been proposed for the classification of slope movements, such as Sharpe (1938), Varnes (1978) and Hutchinson (1988). A good overview of classification systems is given by Hansen (1984). Pratically all of these systems include factors which cannot be identified on the basis of image interpretation alone, such as the speed of movement or the material involved. Therefore, a more simplified classification system should be used, based on the diagnostic features visible in the called photo-checklist, in which the most important features such as type, subtype, activity, depth, vegetation and whether it is a scarp or a body, are noted (see table 2 from Van Westen, 1993).

TYPE	SUBTYPE	ACTIVITY	DEPTH	VEGETATION	SCARP-BODY
Slide	Rotational	Stable	Shallow	Bare	Scarp
Flowslide	Translational	Dormant	Deep	Low vegetation	Body
Flow	Complex	Active	-	High vegetation	-
Derrumbe	-	-	-	-	-
Creep	-	-	-	-	

Table 2. Example checklist used in photo-interpretation of mass movements.

For landslide classification the relation between the size of the objects and the spatial resolution of the imagery should be better than for detection. Every individual element of a landslide (scarp, body, rotated blocks, etc.) should be recognizable. Therefore, large scale stereoscopic imagery have to be used.

REMOTE SENSING IN LANDSLIDE MONITORING

Monitoring means the comparison of landslide conditions, such as areal extent, speed of movement, surface topography, soil humidity etc., from different periods in order to assess the activity of a landslide.

For the monitoring of a landslide a wide range of techniques, providing very detailed measurements of the surface topography can be used (Agostoni et al, 1991). The Global Position System (G.P.S.) is a technique which uses a whole series of satellites to determine the *X,Y,Z* location in the terrain. It has been recently applied in Italy in studies of the monitoring of the Tessina landslide in the region of Veneto by the local Geological Department (1992). The principle advantages of this system are the flexibility and relative easy of operation, still allowing an accuracy in the order of centimetres. Scanvic et al (1993) report the first results of the use of radar-interferometry in the detection of landslide movements. This relatively new method, which is considered to give results within a centimetre accuracy, will most probably be used frequently with the availability of radar data from ERS-1.

More traditional methods of aerial photogrammetry for the monitoring of landslides have been widely applied in Spain (Rispol and Corominas, 1992) and in Italy in the studies of the Ancona landslide (Cunietti et al, 1985): in this study also the uncertainties of photogrammetric measurement of slope movements are discussed. Techniques of terrestrial photogrammetry have been used by Chandler (1989), Kalaugher & Grainer (1990), Rispoli and Tarrida (1988) and by Marcolongo (1974). Bison et al (1989, 1990) report the use of Thermal Infra-Red data obtained from a ground platform in monitoring soil moisture conditions in relation with landslide movements.

REMOTE SENSING IN LANDSLIDE HAZARD ANALYSIS

The term hazard is defined by Varnes (1984) as: the probability of occurrence of a potentially damaging phenomenon within a specified period of time and within a given area. Landslide hazard is commonly shown on maps, which display the spatial distribution of hazard classes (landslide hazard zonation). Zonation refers to "the division of the land in homogeneous areas or domains and their ranking according to degrees of actual/potential hazard caused by mass movement" (Varnes, 1984). Landslide hazard zonation requires a detailed knowledge of the processes that are or have been active in an area, and on the factors leading to the occurrence of the potentially damaging phenomenon. This is considered the task of earth scientists.

The potential and the specific requirements for imput data for a landslide hazard analysis is scale dependent. Generally three scales of analysis are distinguished: a regional scale (<1:100,000), a medium scale (1:50,000-1:25,000) and a large scale (>1:10,000). Table 3 provides a summary of the input data required at each of these three scales, together with a description of the data collection techniques and an indication of the feasibility of obtaining the information (Van Westen, 1993).

Data types	Summary of data collection techniques	Feasibility of data collection		
		Regional scale	Medium scale	Large scale
GEOMORPHOLOGY				
Terrain Mapping Units(TMU)	Satellite stereo image interpretation+ walk over study+ radar (limited)	high	moderate	low
Geomorphological units	Aerial photointerpretation+ field check	moderate	high	high
Geomorphological subunits	Aerial photointerpretation+ field check	low	high	high
Landslide (recent)	Aerial photointerpretation+ field description+ termal IR	low	high	high
Landslide (older period)	Aerial photointerpretation+ collection of landslide records from newspapers, fire brigades, or church archives	low	high	high

TOPOGRAPHY				
Digital Terrain Model (DTM)	Collection of existing contour maps+ photogrammetrical techniques with air-photos or SPOT	moderate	high	high
Slope map (degree or %)	Made from a DTM	moderate	high	high
Slope direction map	Made from a DTM, no extra data collection required	moderate	high	high
Breaks of slope	Aerial photointerpretation	low	moderate	high
Concavities/ convexities	Made from a DTM, or detailed photointerpretation	low	low	high
ENGINEERING GEOLOGY				
Lithologies	Checking of existing geological maps, or by mapping if no data are available using airphotos, satellite images and/or radar+ fieldwork	moderate	high	high
Material sequences	Made by a combination of other maps (geomorphological, geology, slope and DTM)	low	moderate	high
Sampling points	Field descriptions of soil and rock outcrops, and laboratory analysis of selected samples to caracterize material types	moderate	high	high
Faults & lineaments	Satellite image, aerial photo, radar interpretation, and fieldwork	high	high	high
Seismic events	Collection of existing seismic records	high	high	high
Isolines of seismic intensity	Questionnaires on the observed damage from earthquakes	low	moderate	high
LAND USE				
Infrastructure (recent)	Aerial photo and satellite image interpretation+ topographic map. Termal IR limited extent	moderate	high	high
Infrastructure (older)	Aerial photointerpretation+ topographic map	high	high	high
Land-use map (recent)	Aerial photointerpretation+ classification of satellite images+ field check+field description	moderate	high	high
Land-use map (older)	Aerial photointerpretation	moderate	high	high

HYDROLOGY				
Drainage	Aerial photo interpretation+ topographic map	high	high	high
Catchment areas	Aerial photo interpretation+ topographic map or modelling from a DTM	moderate	high	high
Meteorological stations	Collection of existing meteorological data	high	high	high
Water table	Field measurements + modeling	low	low	moderate

Table 3. Overview of imput data needed for landslide hazard analysis

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). 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 area. The determination of actual probabilities required analysis of triggering factors, such as earthquakes or rainfall, or the application of complex models. In most cases, however, there is no clear relationship between these factors and the occurrence of landslides (the legend classes used in most hazard maps do not give more information than relative indications, such as high, medium, and low hazard).

A large amount of research on hazard zonation has been done over the last 30 years as the consequence of an urgent demand for slope instability hazard mapping. Overviews of the various slope instability hazard zonation techniques can be found in Cotecchia (1978), Brabb (1984), Hansen (1984), Varnes (1984), and Hartlén and Viberg (1988). Initially the investigations were oriented mainly toward problem solving at the scale of site investigation and development of deterministic models. A wide variety of deterministic slope stability methods is now available to the engineer. Good reviews of these can be found in Lambe and Whitman (1969), Chowdury (1978,1984), Hoek and Bray (1981), Graham (1984), Bromhead (1986), and Anderson and Richards (1987).

The large regional variability of geotechnical variables such as cohesion, angle of internal friction, thickness of layers, or depth to groundwater, is inconsistent with the homogeneity of data required in deterministic models. The site investigation approach provides an unacceptable cost/benefit ratio for engineering projects over larger areas during the planning and decision-making phases due to the high cost and time requirements of data collection. Several types of landslide hazard zonation techniques have been developed to tackle such problems encountered in the application of deterministic modelling. A summary of the various trends in the development of techniques is given in Table 4.

Type of landslide hazard analysis	Main characteristic	Regional scale 1:100,000	Medium scale 1:25,000	Large scale 1:1,000
A. Distribution analysis	Direct mapping of mass movement features resulting in a map which gives information only for those sites where landslides have occurred in the past	2-3	3-3	3-3
B. Qualitative analysis	Direct, or semi-direct, methods in which the geomorphological map is renumbered to a hazard map, or in which several maps are combined into one using subjective decision rules, based on the experience of the earth scientist	3-3	3-2	3-1
C. Statistical analysis	Indirect methods in wich statistical analysis are used to obtain predictions of the mass-movement hazard from a number of parameter maps	1-1	3-3	3-2
D. Deterministic analysis	Indirect methods in which parameter maps are combined in slope stability calculations	1-1	1-2	2-3
E. Landslide analysis	Indirect methods in which earthquakes and/or rainfall records or hydrological models are used for correlation with known landslide dates, to obtain thereshold values with a certain frequency	2-2	3-3	3-2

Table 4. Summary of the feasibility and usefulness of applying techniques for landslide hazard zonation on three working scales. The first number indicates the feasibility of obtaining the information using remote sensing techniques (1 = low: it would take too much time an money to gather sufficient information in relation to the expected output; 2 = moderate: a considerable investment would be needed, which only moderately justifies the output; 3 = good: the necessary input data can be gathered with a reasonable investment related to the expected output). The second number indicates the usefulness (1 = of no use: the method does not result in very useful maps at the particular scale; 2 = of limited use: other techniques would be better, 3 = useful).

The most straightforward approach to landslide hazard mapping is a *landslide inventory map*, based on aerial photo interpretation, ground survey, and/or a data base of historical occurrence of landslides in an area. The final product gives the spatial distribution of mass movements, represented either at scale or as points (Wieczorec, 1984). Mass movements inventory map are the basis for most of the other landslide hazard zonation techniques. They can, however, also be used as an elementary form of hazard map, because they display where in an area a particular type of slope movement has occurred. They provide information only for the period shortly preceding the date the aerial photos were taken or the fieldwork was conducted. They provide no insight into the temporal changes in mass movement distribution.

Many landslide that occurred some time before the photographs were taken may have became undetectable. Therefore a refinement is the construction of *landslide activity maps*, based on multitemporal aerial photo interpretation (Canuti et al., 1979; 1985; 1986).

A new field in landslide prediction which still has to be explored is the use of METEOSAT/NOAA images, which allow rainfall estimations every half hour (METEOSAT) to every half day (NOAA) (see Hielkema, 1989). This data could be used in combination with a statistical analysis of rainfall threshold values, or with a dynamic slope stability model. At present, however, the only applications in Europe concern previsional models for evaluation of river floods (Lanza and Siccardi, 1992a -b).

UNCERTAINTY

One of the important aspects which should be taken into account with respect to the use of remote sensing techniques in landslide study is an assessment of the error and uncertainty. Errors and uncertainty related to the use of existing data, to data collection, data analysis and production of final hazard maps, can be distinguished. An extensive treatment of the various error sources in landslide hazard analysis is given by Carrara et al. (1992).

The occurrence of landslide is governed by complex interrelationships between factors, some of which cannot be determined in detail and others only with a large degree of uncertainty. It is important at this point to distinguish *error* and *uncertainty*. The error in a map can be assessed only if another map, or field information is available which is error-free, and with which it can be verified. Slope angles, for examples, can be measured at several points in the terrain, and these point values can be compared with a slope map to assess the degree of error. This evaluation is different for maps which are not based on factual, measured data, but on interpretation, such as the genetic elements for a geomorphological map. Such a map can also be checked in the field, but it is still possible that different geomorphologists will not agree on the specific origin of a certain landform. In other words, there is no absolute way to verify the map. Only the uncertainty of the map can be assessed, by comparison of different maps by different observer. If the area identically mapped in several maps is small, the map is considered to contain a high degree of uncertainty. This method will only render reliable result if the field experience of the observers, and the mapping method is identical. Usually this is not the case, and it may be that one of the observers has made a lot of errors in mapping, and that the other observer has mapped more reliably. For this reason, although it is possible to express the difference between the various maps in a quantitative way, the actual uncertainty of such maps is difficult to determine in a absolute manner.

The amount of uncertainty is strongly related to the degree of subjectivity of a map. The terms *objective* and *subjective* are used mostly to indicate whether the various steps taken in the determination of the degree of hazard are verifiable and reproducible by other researchers, or whether they depend upon the personal judgement of the researcher. The larger the subjectivity will be, the larger also the uncertainty, as the possibility increases that different individuals will came to different conclusions.

Many of the imput maps used in landslide hazard analysis are based on aerial photograph interpretation and will therefore contain a large degree of uncertainty. Table 5 gives a list of factors that are considered to be important in controlling slope instability and a qualitative description of uncertainty (partly after Carrara &al.,1992).

FACTORS	UNCERTAINTY
Slope angle	Low
Slope direction	Low
Slope convexity	Low
General lithological zonation	Low
Detailed lithological composition	High
General tectonic framework	Low
Detailed rock structure	High
Earthquake acceleration	High
Rainfall distribution	Intermediate
Geomorphological setting	Low
Detailed geomorphological situation	Intermediate
Present mass movement distribution	Intermediate
Present mass movement typology	Intermediate
Present mass movement activity	Intermediate/high
Present mass movement distribution	High
Soil type distribution	Low/intermediate
Soil characteristics	Intermediate/high
Soil thickness	High
Groundwater conditions	High
Land use	Low
Past climatological conditions	High

Table 5. Main factors in landslide hazard zonation and their estimated degree of uncertainty.

The degree of uncertainty is related to many factors, such as the scale of the analysis, the time and the money allocated for data collection, the size of the study area, the experience of the researchers, and the availability and reliability of existing maps. From this list it can be seen that many factors contain an inter-mediate or high degree of uncertainty, either because they are based on a limited amount of factual data (such as soil characteristics) or they are made by subjective interpretation.

The landslide occurrence map is by far the most important map in a landslide hazard survey, since it gives the locations where landslides have occurred in the recent past. Furthermore, the resulting hazard maps are compared with the actual distribution of landslides in order to check its accuracy. Therefore a landslide occurrence map should be as accurate as possible.

Photo-interpretation plays a very important role in the creation of a mass movement inventory map, although it should always be followed by an extensive field check. It has been recognized in the literature that creation of mass movement occurrence maps contains a large subjective element. Various authors (Fookes et al., 1991; Carrara, 1992; Carrara et al., 1992; Van Westen, 1993) discuss the results of a comparison of different photo-interpretation maps of landslide areas in Papua, New Guinea, Italy and Colombia. The area which is equally interpreted by different authors may be as small as 7% of all landslide area.

From these examples it is obvious that identification of landslides can contain a very high degree of uncertainty. Several factors play a role in this degree of uncertainty, such as the researcher's experience in photo-interpretation and field knowledge; the aim of the study; the characteristics of the study area; the age and type of mass movements; the scale, quality, and type of photo used; and the conversion of the information from the aerial photos to the base map. When working with the Geographical Information Systems (GIS), digitizing error will aggravate the situation.

Another input map for landslide hazard analysis which is considered to be very subjective is the geomorphological map. Maps made by different geomorphologists will contain large differences, especially if the maps are made by photo-interpretation, with limited field checks. The differences will be greatest when the geomorphologists design their own legend.

To assess the variability in outlining geomorphological units a test can be made by comparing photo-interpretations done by several persons. A useful method of comparing various geomorphological photo-interpretations is given by Middelkoop (1990). In a test given by Van Westen (1993) only 10% of the area was assigned the same legend unit by all (4) interpreters. About 17% was mapped identically by three and 53% by two interpreters. The remaining 20% of the area was mapped differently by each person. When a simplified legend was used better results were obtained: 36% identically mapped by all four, 32% mapped by three, and 31% by two.
From this example it can be concluded that a geomorphological map has a high degree of subjectivity, and depends strongly on the experience of the person that is making the map, as well as on the amount of time spent in the field for checking the interpretation.

CONCLUSIONS

It can be concluded that aerial photos are the most important remote sensing tools in landslide studies. The application of presently available satellite remote sensing is limited as far it refers to the direct mapping of slope instability features. The spatial resolution does not allow for the identification of landslide features smaller than 100 m. in conditions of a favourable strong contrast between the landslide and the background. If contrast conditions are less favourable then identification is even limited to features up to 400 m.. The need for stereo imagery, necessary for the interpretation of the characteristic and diagnostic morphological features of slope failures, is another limiting point in the applicability of an important part of the presently available remote sensing imagery. It is expected however, that within the next decade there will be satellite imagery available with spatial resolution below 10 m. and with stereo capabilities (ADEOS, JAPAN/US system planned for 1995).

Currently the available satellite imagery (SPOT, LANDSAT TM, JERS-1) are mostly useful in indirect mapping methods, when the spatial distribution of landslide controlling variables, such as a particular geomorphological condition, a specific lithology or a kind of land-use are identified and outlined on the satellite images. In practice it implies a combined use of satellite imagery and large scale photography. For the inventory mapping and the analytical part of slope instability assessment, large scale aerial photography is used in representative sample areas, while the extrapolation of the findings is executed on smaller scale imagery.

The potentials of the use of radar imagery for landslide hazard mapping still need further investigations. Within the coming decade a large increase in the availability of radar satellite imagery is foreseen (ERS-1, ERS-2, JERS-1, Almaz, Radarsat). Although the results on terrain roughness classification, and radar interferometry seem very promising (Evans, 1992) the geometric distortion due to foreshortening and the speckling will generally give rather poor quality images in mountains.

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