SLOPE INSTABILITY: THE ROLE OF REMOTE SENSING AND GIS IN RECOGNITION, ANALYSIS AND ZONATION

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Abstract

Slope instability processes are the product of local geomorphological, hydrological and geological conditions, the modifications of these conditions induced by geodynamic processes and human activity, the vegetation and landuse practices and the frequency and intensity of precipitation and seismicity. The paper describes the integrated use of remote sensing and GIS in the process of recognizing slope movements and in the analysis and zonation of landslide hazard. After a short introduction on some methodological aspects of slope instability hazard mapping, emphasis is given to the unique role of remote sensing in the hazard mapping. An evaluation is made of the applicability of different remote sensing data, considering spatial, spectral and temporal resolution. The capabilities of GIS in the data integration and the analysis of terrain variables in relation to slope instability are highlighted. A methodology for different scales of analysis is given. Some observations are made on aspects of objectivity and accuracy in landslide hazard assessments. Finally, a training package for the use of GIS in slope instability zonation (GISSIZ) is presented.

1. Introduction

Although the occurrence of natural hazards, such as earthquakes, volcanic eruptions, floods or hurricanes, can be considered as unpreventable, the disastrous impact they have on society can largely be controlled through the appropriate mitigation of their effects. Examples of this are found in the comparison of the great floods in Bangladesh (1988), causing the death of 1410 people, with the Mississippi flood in the USA in 1993 (30 fatalities), or the disaster caused by hurricanes in Bangladesh in 1990, with the successful mitigation of hurricane Andrew in 1992. Even more striking is the comparison between the Armenian earthquake of 1988 which, having a magnitude of 6.9, had an estimated death toll of 25,000 to 100,000, with the recent earthquake in Los Angeles (M=6.8), causing only 40 fatalities.

Mitigation of hazards can only be successful when detailed knowledge is available on the expected type, frequency and magnitude of the process, while the impact on the environment depends on the violence of the process, and the vulnerability of the elements at risk. Effective relief operations is largely dependent on the damages expected to the existing infrastructure in the area.

For hazard zonation, as well as the risk assessment and the planning of relief operations the use of remote sensing and geographic information systems is playing an important role. The basic questions related to the understanding of a hazardous process (what, why and where) depends on the spatial distribution of the endogene and exogene parameters controlling the process. While the impact of the process on society depends on the distribution of elements at risk, taking into account their vulnerability for a specific type of hazard. Finally, the success of a relief operation depends largely on a well founded expectation of what will happen and where that will occur and the derived planning and protection of strategic elements for relief operations (infrastructure, hospitals, and the provision of primary elements, such as water, food and medicines).

Evaluating the role of remote sensing in hazard mitigation, it becomes clear that an effective application has to be built upon an integrated system, constituted by data derived from several sources varying in sensor type, scale and time. Sequential aerial photography is essential in the inventory of type and assessment of activity of processes. Environmental parameters and their (gradual) changes are often best assessed and monitored by the, stereoscopic study of satellite data. Images with a high temporal resolution (NOAA and METEOSAT) are profitably used for the evaluation of rapid environmental changes, while real time imagery for direct damage assessment and relief operations is depending on the availability of all-weather radar satellite systems (if technically feasible in a set of geostationary stations).

The present paper is based on an international research programme, with the ITC, the Colombian Geographical Institute (IGAC) and the French Geological Service (BRGM) as operating agents and financially sponsored by UNESCO, the European Union and the Dutch Ministry of Education and Science A methodology for hazard zonation at three different scales of approximation has been developed, following the scales of analysis presented to the IAEG in a monograph on engineering geological mapping (IAEG, 1976). Subsequent research has been directed towards the validation of the extrapolation of decision rules for hazard zonation through the use of training areas, the quality of a hazard assessment as a function of the reliability of the input data, the application of deterministic models for large scale hazard predictions and the possibility to formalise expert opinions to be used in the elaboration of decision rules. Although this research is showing promising results, much investigations are still needed to optimise the methodologies for the prevention of natural disasters and the for the organisation of emergency relief programmes, making use of remote sensing and geographic information systems. However, clear methodological lines have been established with the successful developments in hazard zonation.

2. Principles of slope instability hazard mapping

Slope instability processes are the product of the local geomorphological, geological and hydrological conditions, the modification of these conditions induced by geodynamic processes and human activity, the vegetation and landuse practices and the frequency and intensity of precipitation and seismicity. The evaluation of the natural environmental conditions, which led to slope failures in the past, are the key for the hazard assessment of a slope, which has not yet failed. Therefore a careful study of the natural conditions of an area has to be made in the light of the landslides occurring in the area. It is the task of the earth scientist to evaluate the causes of slope failures and he is professionally the best trained expert in modelling (mapping) the spatial variability of the causative factors involved in the instability process. Essential steps to come to a prediction are:

- a landslide inventory, giving the types of landslides, their spatial distribution and their development through time,
- the analysis of the terrain conditions leading to slope failures.
- the determination of the spatial variability of the causative factors, and
- the assignment of the degree of likelihood that a slope failure will occur.

The availability of a reliable landslide inventory is essential to enable an analysis of the occurrence of slope failures in relation to environmental conditions. Landslide inventories are generally obtained by direct mapping.

In relation to the terrain conditions leading to slope instability, basically two philosophies can be recognised. One is based on the professional judgement of the earth scientist, who makes a correlation between slope failure and causative factors directly in the field. The opposite of this experience-driven approach, consists of the mapping of a (large) number of parameters and the (statistical) analysis of the possible contributing factors in relation to the occurrence of slope instability phenomena. Based on the results of the analysis statements are made regarding the conditions under which slope failures occur.

Once the causal relationship between landslides and terrain conditions has been established by heuristic reasoning or by factor analysis, it is necessary to extrapolate the findings over the area. In the experience-driven, qualitative analysis this is done by an evaluation of comparison, while in the statistical analysis the presence or absence of contributing factors is checked off on the factor maps or in the database and on that basis statements are made in respect to the stability.

In our applied geomorphological methodology the following problems arise:

- the difficulty of applying the direct geomorphological mapping methodology at small scales in the early phases of projects, as an analytical landslide oriented survey is necessarily executed at larger scales,
- the degree of subjectivity in the analysis of the causative factors of a slope movement and the extrapolation of a set of conditions.

In order to solve these problems an integrated methodology for landslide hazard analysis at different scales had to be developed.

3. Remote sensing applied to slope instability zonation

Considering that landslides directly affect the ground surface, makes the application of remote sensing techniques very suited to slope instability studies. The use of remote sensing is particular useful when stereo images are used, depicting in the stereomodel the characteristic morphological features of landslides. Also the overall terrain conditions (lithology, soil, relief, drainage, landuse), determining the susceptibility of the area for sliding, can profitably be assessed from remote sensing data. However, the practical applicability of remote sensing in landslide hazard zonation depends largely on the methodology applied, which is closely related to the scale of the survey and the requirements to the accuracy and objectivity of the assessment.

The applicability of remote sensing data to landslide inventory depends on the spatial resolution of the images in relation to the size of the features characterising slope failures. Comparison of the ground resolution cell of remotely sensed images with the average values for different types of slope movements means that the scale of 1:25 000 should be considered as the smallest scale to analyse slope instability features (Rengers et al.,1992) Using smaller scales, a slope failure may be recognised as such, when size and contrast with the surroundings are sufficiently large, but the analytical information obtained from the image will not allow for conclusions in relation to type and possible causes of the landslide Furthermore smaller or older slope failures would pass unnoticed. In this respect the use of sequential imagery is always recommendable, also when large scale imagery is used. Sequential data furnish a much more complete inventory, on the activity of slope failures. The necessity for large scale images was confirmed by Dunoyer and van Westen (1994). This study compared, for an area west of the city Manizales (Colombia), the degree of uncertainty in the interpretation of large scale (1.10 000) photographs. Interpretation depends, even at this large scale, strongly on the experience of the interpreter, the establishment of clear classification rules, local knowledge, the interpretation of sequential imagery and particularly fieldwork.

The photoscale necessary for the elaboration of a landslide inventory map implies that this technique can only be applied at a profitable cost/benefit ratio in medium scale hazard zonations covering not too large areas. Applications over larger areas would be possible, if experiences obtained in detailed studies could be extrapolated successfully. In this respect the use of training areas in landslide mapping, with the objective of extrapolating decision rules, has been investigated in the Caldas area of Colombia (Naranjo et al., in press). Results from this study show that the use of training areas is possible, although there are serious limitations to its use in hazard mapping, even when the geological and geomorphological conditions in the training and prediction area are the same. The classification into hazard classes of the summed weight values was crucial, as the landslide pattern in the training and prediction area were somewhat different

A large variety of remote sensing images can be used for the mapping of the factors controlling the occurrence of slope failures Stereo SPOT has been successfully applied to terrain classification; creating terrain units homogeneous in geomorphic origin, lithology and distribution of soils Those terrain units form the spatial database to which landslide controlling factors are coupled in an attribute database. Information on those attributes can be obtained by more detailed photointerpretation or by fieldwork. At the medium scale of hazard analysis, the terrain classification is generally replaced by the mapping of the individual factors controlling landslides. Information on the lithology, geological structures and soils, including their genetic origin can successfully be interpreted from medium to small scale aerial photography or even on satellite images, particularly on Stereo SPOT.

The spectral information obtained by the multispectral sensors of earth observation satellites is particularly useful in the mapping of the overall drainage conditions, the vegetation, landuse and the human activity. McKean *et al.* (1991) demonstrated the successful application of vegetation indices as indicators of slope instability and van Westen (1993) classifies landuse and landuse changes, resulting in the increase of slope instability, from multispectral data. Multitemporal data, coupled to an acceptable spatial resolution (SPOT), opens also the possibilities for the monitoring of human activity and the impact changes on the stability of slopes.

Investigations are underway to evaluate the applicability of radar (ERS, JERS and the planned Radarsat), with its all-weather capability, for the monitoring of slopes and damage assessment. Although geometric distortions related with the imaging system, such as foreshortening and layover, which are particularly present in areas of relief, seem to be a major disadvantage to radar applications in landslide studies. On the other hand, radar interferometry seems a most promising development, enabling the monitoring of very small movements over large periods of time.

4. Geographic information systems in landslide hazard zonation

Methodologies based on the joint analysis of a large number of parameters have profited strongly from the development of Geographic Information System (GIS), which are computerized systems for storing, retrieving, transforming and displaying geographically referenced data (Aronoff, 1989; Burrough, 1986).

The main advantage of the use of GIS in slope instability mapping relies on the possibility to superimpose a set of factor maps and to analyse them in combination with a landslide occurrence map. Certain GIS systems allow also for a smooth combination of digital geocoded remote sensing data with maps and other layers of data, which implies that small scale thematic information available in remote sensing images can be related directly to the landslide occurrence in the area obtained from large scale images or from the field. The scanning of aerial photographs and their geometric correction enables the direct entering of photo interpretations into GIS and on-screen interpretation is becoming a practical technique

The other advantage of GIS is that complex computation techniques, necessary in the crossing of several factor maps and for table calculations, are feasible. This brings a much larger potential of objective hazard analysis techniques within reach, particularly the possibility to test the importance of each factor, or combination of factors, and assign quantitative weighting values based on mass movement density. The obtained hazard prediction can be evaluated and when necessary the decision rules (relative weights) related to the input parameters are adjusted in accordance and the final results are extrapolated over the whole area. Based on the final classification new output maps are generated, presenting the hazard classification based on the calculated decision rules and the stored geodata.

One danger in the use of GIS is that too much emphasis is given to the mathematical or statistical data analysis at the expense of the analysis by the expert during the data collection in the field and geared by local knowledge and professional experience. Decision rules used for hazard classifications work much better if they are based on a professional reasoning instead of a pure statistical analysis.

The use of GIS implies on the other hand a more systematic data gathering, instead of experience-based selective data collection. The power of the computer lies in computing and therefore the user is forced to work more on a quantitative data input. Typical qualitative data, such as type of lithology, soil or landuse has to be classed and rated according to their contribution to slope instability. Finally all data have to be digitised, which turns out to be one of the most time consuming and tiring jobs in the process of making a landslide hazard zonation.

5. Scale related techniques in hazard zonation

The development of a clear hierarchical methodology in hazard mapping is a necessary condition to obtain an acceptable cost/benefit ratio and to ensure the practical applicability of hazard mapping (Table 1). The working scale for a slope instability analysis is determined by the requirements of the user for whom the survey is executed. Considering that planners and engineers form the most important user community, the following scales of analysis, which were presented to the International Association of Engineering Geologists (IAEG, 1976) have been differentiated for landslide hazard zonation:

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

The national scale
A general inventory of problem areas for the entire country,which can be used to inform national policy makers and the general public. The detail will be low, as the assessment is mostly done on the basis of generally applicable rules. Inventory maps based on existing recordings in data banks can be used, preferably in combination with lithological maps and maps delineating areas with more or less relief. A broad relief classification, if not available from maps, can be obtained from almost any type of satellite image.

The regional mapping scale
This is meant for planners in the early phases of regional development projects or for engineers, when evaluating possible constraints for large engineering works. The areas to be investigated are large, in the order of 1000 square kilometres or more, and the required detail of the map is low. The map indicates areas where mass movements can be a constraint on the development of rural, urban or infrastructural projects. Terrain units with an areal extent of several tens of hectares are outlined and classified according to their susceptibility for occurrence of mass movements. The mapping methodology is mostly based on terrain classification. Homogeneous terrain units, defined by geomorphological and geological criteria, are outlined on stereo satellite images or small scale aerial photographs. Within these, so called Terrain Mapping Units (TMUs), the degree of hazard is assumed to be uniform. The terrain conditions (lithology, geomorphology, distribution of soils, drainage and dominant landuse) pertaining to each TMU are established by sampling procedures on larger scale photographs and during short fieldtrips (walk-over surveys). At the same time information is gathered on the occurrence of slope failures. Mostly qualitative, experience-driven, methods are used to determine the contribution of the various parameters in landsliding. The crossing of these parameters with the attributes belonging to the TMU's creates the possibility to come to a qualitative rating of the hazard for every TMU.

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

Table 1. Methodologies for landslide hazard analysis in relation to mapping scales.

Type of analysis	GIS techniques	Characteristics	Recommended to use at scale:		
			Regional 100.000	Medium 25 000	Large 10 000
Inventory	Landslide distribution analysis	Analyse distribution and classification of landslides	Yes, but... (*)	Yes	Yes
	Landslide activity analysis	Analyse temporal changes in landslide pattern	No	Yes	Yes
	Landslide density analysis	Calculate landslide density in terrain units or as isopleth map	Yes, but (*)	No	No
Heuristic analysis	Geomorphological analysis	Use in-field expert opinion in zonation	Yes	Yes, but. (**)	Yes, but (**)
	Qualitative map combination	Use expert-based weight values of parameter maps	Yes, but (***)	Yes, but . (**)	No
Statistical analysis	Bivariate statistical analysis	Calculate importance of contributing factor combination	No	Yes	No
	Multivariate statistical analysis	Calculate prediction formula from data matrix	No	Yes	No
Deterministic analysis	Safety factor analysis	Apply hydrological and slope stability models	NO	No	Yes, but.. (****)

(*) only with reliable data on landslide distribution, as mapping will be out of an acceptable cost/benefit ratio.
(**) strongly supported by other more quantitative techniques, to obtain an acceptable level of objectivity
(***) only if sufficient reliable data exist on the spatial distribution of the landslide controlling factors.
(****) only under homogeneous terrain conditions, considering the variability of the geotechnical parameters

slope, when appropriate. It is necessary to make a good landslide distribution map. The interpretation of aerial photographs, possibly of several dates, is the main source of information. The parameter mapping can be done on small scale photographs, as well as satellite images. Multitemporal data can demonstrate the occurrence of slope movements with changes in landcover. Fieldwork emphasizes quantitative description of slope failures and the terrain conditions associated with the landslides. The landslide hazard is established by the statistical analysis of the conditions which led to slope failures in the past. When using bivariate statistical techniques, the scientist has the possibility to determine the influence of single parameters or specific combination of parameters. The final definition of the decision rules will be experience-driven, which improves the accuracy of the assessment. Multivariate techniques establish a final hazard classification without identifying which factor or factor combinations are determining the potential instability of a particular slope.

Large scale hazard mapping

This can be used at the level of site investigations previous to the design phase of engineering works. This scale is also meant to evaluate the variability of a slope safety factor as function of variable slope conditions or under influence of triggering factors, such as rainfall and seismicity The size of an area under study is in the order of several square kilometres and the hazard classes on such maps should be absolute, indicating the probability of failure for each grid cell or mapping unit, with areas down to one hectare or less. The methodology is based on detailed engineering geological zoning, delineating homogeneous zones in the geotechnical sense. Large scale aerial photographs are reliable sources of information at such a scale of mapping, although the mapping has to be combined with detailed fieldwork, sampling, geotechnical testing and when possible the monitoring of variations in groundwater level. Detailed fieldwork in unstable zones should provide, through back analysis, the adequate deterministic slope stability model, which is representative for the slopes in the area. Knowing the spatial variability of the geotechnical parameters and the porewater pressures, the safety factors for a selected number of slope profiles are calculated with the aid of the deterministic model. The calculated values are imported in the spatial model, giving the spatial variability of the safety factor. The display of scenarios in relation to variations in triggering factors is possible by introducing other geotechnical slope conditions, simulating a period of rainfall or a horizontal seismic acceleration, resulting in the change of the safety factors. Critical areas can be identified in this way.

6. Objectivity and accuracy

Besides the considerations about techniques to be applied at several levels of approximation, attention has to be paid to the objectivity and the accuracy of the survey. Objectivity refers in this respect to the clarity with which the criteria for the analysis of the stability are established and the assumptions made for the assessment. Objectivity in the assessment does not directly resulting in a high accuracy of the prediction, as very subjective statements on the stability of slopes, based on an expert opinion, can be very accurate. However, such a good, but subjective assessment has a relative value, as the reproducibility will be low. This means that the same evaluation made by another expert will probably yield other results, which can have clearly undesirable legal effects.

As a result of the demand for a high level of objectivity, several researchers have been replacing the subjective expert's opinion on the causative factors related to slope failure, by the statistical analysis of all the terrain conditions observed in areas with slope failures. Although the objectivity of such an approach is guaranteed, doubts may exist on the accuracy of the assessment, certainly considering the experience and skill required in the data collection, when filling in extensive data sheets.

Few studies have been made on the degree of accuracy in slope instability zonations. The study on the degree of uncertainty in photointerpretation, mentioned before, considered the results of a group of twelve photointerpreters, several of them with considerable experience and some with local knowledge. From this research it became clear that the errors made in the interpretation can be large (Dunoyer and van Westen, 1994). These findings coincide with similar investigations on the accuracy of photointerpretation in slope instability mapping (Fookes et al., 1991; Carrara et al., 1992). indicating that inventory mapping is the crucial step in reliable hazard prediction.

The determination of the reliability in a hazard assessment is more difficult, considering that hazard is defined as the probability that a hazard will occur in a certain period of time. In reality a hazard assessment can only be verified by comparing the prediction with the field situation over a lapse of time preferably by making an assessment on an inventory mapping from old photographs and comparing this with an inventory of landslides in the present situation. The probability of the degree of accuracy can also be proved when different assessment methods give similar results.

The scale related methodologies, as defined above, can now be evaluated on the objectivity of the assessment. At the regional scale, the causal relationship between terrain conditions and slope failure is basically obtained by a heuristic analysis and therefore the subjectivity of the assessment is high. As observed before, the degree of reproducibility can be increased by defining as precisely as possible the criteria used for the assessment and assigning weights to the factors considered. In very homogeneous terrain, more quantitative methods for the determination of weights can be used in training areas for a posterior extrapolation (Naranjo et al., 1994). Statistical analysis, applied at medium scale, yields highly objective results. Comparison of the assessments obtained with different methods shows rather large differences in results, indicating at least a variability in accuracy between the methods. Multivariate techniques are easier to apply, as they do not ask for an iterative analytical process. The charm of the bivariate statistical analysis is that professional experience can be included in the analysis, which results probably in more reliable statements. Studies are planned to investigate how far professional experiences can be formalised, to be used in the elaboration of decision rules. The large scale mapping gives by far the best and most reliable results, as they are based on the application of physical models. However, even here the selection of the models is based on certain assumptions, introducing a certain degree of subjectivity

7. The training package GISSIZ

A training package has been developed, allowing earth scientists to gain experience with GIS and landslide hazard zonation. The training package for Geographic Information Systems in Slope Instability Zonation (GISSIZ) consists of a textbook, an exercise manual and 10 diskettes with a training data set, a tutorial version of a GIS and a demonstration.

The textbook contains the theoretical aspects of the use of GIS in landslide hazard zonation. It gives an overview of useful techniques and how they are adapted for the application in GIS. Procedures for data capturing, data entry, data base design and data analysis are treated. Results of various methods of analysis are compared, using the basic data set of a research area in Colombia. Evaluation of the potential error sources is given as well as recommendations for the most useful techniques on different scales of analysis.

The exercise manual contains GIS exercises at four different scales and three levels of complexity: basic exercises, for users that are unfamiliar with GIS, exercises on the use of GIS in relatively simple hazard analysis methods, and advanced exercises, including the use of macros and batch files for complex calculations. All exercises can be carried out independently, using a training data set provided on diskettes. Intermediate result maps are also supplied, as well as examples on the resulting hazard maps. Every step in the sequence of commands or menu selections is described in detail. The exercise manual of GISSIZ only provides exercises on data analysis.

The other phases, such as data entry and database design are only described in the textbook. The exercises make use of GIS files from a large data set, compressed on 10 floppy disks, and ordered according to the scale of analysis. One of the diskettes contains a demonstration, explaining the most important aspects of the methodology This demonstration can also be displayed outside of GISSIZ on any PC with a VGA colour screen. GISSIZ costs US$200 and can be ordered from the ITC-Bookshop, PO Box 6, 7500 AA Enschede, The Netherlands.

8. Conclusions

Remote sensing is an extremely useful tool in hazard assessment, risk analysis and disaster management including relief operations. However, the applicability of remote sensing data depends strongly on their availability. Although we have a large variety of remote sensing systems potentially at our disposal, we are still frequently confronted with a scarcity of adequate data. Once data are available, an optimal benefit will only be made from them if use can be made of a GIS, which forms the vital link in the matching of different types of remote sensing data with different scales as well as in geometric properties, with other sources of information.

The results from the hazard assessment study in Colombia, have been published in the form of a training package. With this training package, earth scientists can learn the various aspects of working with GIS in landslide hazard zonation.

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Discussion

Prof. Wadge (NUTIS) asked what was the appropriate methodology for landslide hazard assessment in shanty town developments bordering cities and what role did stereo-SPOT have to play. The answer was that only statistical/deterministic techniques (or even site investigation scale work) was appropriate. BRGM have done some useful work with stereo-SPOT in La Paz, Bolivia; though it cannot identify small slips individually, it can give a good general indication of conditions. Dr. Wu (King's College, London) asked about the prospects for deterministic numerical modelling within GIS, to which Dr. Soeters replied that the principal limitation was useful quantitative constraints on triggers from past events.