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Recommendations for Landslide Hazard and Risk Mapping in Croatia

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Key words: Geohazards, Landslides, Landslide hazard, Landslide risk, Hazard and risk mapping, GIS.

Abstract

The preparation of landslide hazard and risk maps is required as a base for rational land use planning and decision-making, in landslide prone areas. In this paper, an inventory was made of the currently available methods for landslide hazard and risk zonation, in order to produce recommendations for the use of specific methods in relation to the scale of analysis. A hierarchical set of activities aimed at obtaining landslide-related information for all levels of land use planning in the Republic of Croatia is constructed. This set encompasses: the establishment of a national landslide inventory on a regional scale (<1:100,000), statistical landslide hazard analysis of geological-morphological factors at the medium scale (1:25,000) and the geotechnical characterisation of slope movements followed by landslide risk analysis on a detailed scale (>1:5,000).

1. INTRODUCTION

The term landslide denotes the movement of a mass of rock, debris or earth down a slope (CRUDEN, 1991). Most of the terrain in hillside areas has been subjected to landslides at least once under the influence of a variety of causal factors. The number of slope instability is significantly increased due to urbanisation and development in landslide-prone areas. Hence, landslides continue to be one of the most threatening and widespread geohazards.

There is an increasing trend for geohazards to be recognised in planning legislation and guidance, especially in the last decade (the International Decade for Natural Disaster Reduction). Many countries presently have specific planning or development policies aimed to reduce the losses due to natural hazards (SCHUSTER, 1991; McINNES, 1996). Methods vary from guidance documentation alone, through mandatory building codes and finally to insurance or disaster relief schemes (STATHAM et al., 1995). Zoning and subdivision ordinances are used to divert development into areas where the risks are less and to ensure that, where developments are permitted, the appropriate engineering measures are incorporated.

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Risk assessment is a prerequisite for all the methods of hazard prevention and mitigation. It consists of three steps: (1) hazard assessment - identification of past/present landslides as well as the prediction of future occurrences; (2) vulnerability analysis - identification of the location and distribution of population, infrastructure and vital economic activities exposed to a potential or present landslide; and (3) calculation of the expected loss (risk) from the hazard and vulnerability. Hazard analysis requires a detailed knowledge of the geoenvironmental predisposition factors and initiation events that lead to landsliding. This lies within the domain of earth scientists. Vulnerability and risk evaluation also includes other disciplines, such as urban planning, social geography, economy, etc. The end result of hazard and risk analysis should be presented in informative documents, usually in the form of various maps which display the spatial distribution of hazard and risk classes. These documents are used by decision-makers who have to define a general risk prevention policy.

Many methods and techniques have been proposed for landslide hazard and risk mapping over the last 30 years (BRABB, 1984; HANSEN, 1987; MIHALIĆ, 1996). Significant progress has been made by establishing the basic definition of terms related to hazard and risk assessment (VARNES, 1984). Van WESTEN's (1993) overview of the available methods is of great importance for improving the quality, as well as for achieving a uniform approach to landslide hazard mapping on an international level. On the other hand, examples of landslide risk zonations are still rare because of the difficulties in assessing the probability of landsliding and of the vulnerability of elements at risk. However, the evaluation of risk corresponds to a political, economic and social necessity. Therefore, research of operational risk evaluation methods is in progress (RAGOZIN, 1994; REZIG et al., 1996).

The first fundamental step of hazard and risk assessment is the identification and mapping of all landslide phenomena, i.e. compilation of the landslide inventory (FERNÁNDEZ et al., 1996; ROSENBAUM & POPESCU, 1996). Collection and management of spatial data require the utilisation of geographic information systems (GIS). Furthermore, the cartographic landslide data bases should be valid nation-wide in order to enable extrapolation of acquired experience to areas with similar characteristics (LEROI, 1996). In many countries, the development of such databases started in the

1990's. The most important are examples from France (LEROI, 1996), Germany (POSCHINGER, 1994; KRAUTER et al., 1996), the USA (BROWN, 1992) and Canada (CRUDEN, 1996). Moreover, there is a tendency towards establishment of a World Landslide Inventory (BROWN et al., 1992). To ensure the consistency of data recording, the International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory (WP/WLI), initiated in the 1988 at the 5th International Symposium on Landslides, is suggesting a standard terminology for describing landslides (WP/WLI, 1993). GIS technology is also essential for assembling the hazard and risk models, as well as for an efficient and rapid information exchange between scientists, engineers, policy makers, and all the people and institutions dealing with the landslide hazard.

Before starting any data collection, a number of interrelated things should be clearly defined, such as the aim of a study, the scale and degree of precision of the presented results, and the available resources in the form of money and manpower. To achieve the optimisation of costs and quality, the application of different data analysis methods at various scales is required.

Accordingly, a concise review of current methods of landslide hazard and risk assessment is presented in this paper. The review is aimed at a comparison of the methods, and proposition of a logical set of activities related to the preparation and implementation of hazard and risk maps, in the field of land use planning in the Republic of Croatia. This set comprises all levels of urban planning, from national to the local scale.

2. LANDSLIDE HAZARD AND RISK

The terminology concerning hazards and risk used in this paper conforms to the definitions proposed by VARNES (1984). Evaluation of various risk components (hazard, vulnerability, cost), and of the landslide risk as a whole, presupposes that answers are available for the questions as shown in Table 1 (LEROI, 1996).

Accordingly, landslide research aimed at hazard and risk mapping comprises the aspects of landslides summarised in the following paragraphs.

Since the term of landsliding encompasses "all movement of a mass of rock, debris or earth down a slope" (CRUDEN, 1991), which types of movement are present in the studied area should be defined. The types of movement are essentially those defined by the International Geotechnical Societies' UNESCO Working Party on World Landslide Inventory: fall, topple, slide, spread and flow (CRUDEN & VARNES, 1996).

Location of the unstable areas should be determined by the engineering geological mapping of the landslides. The objective would be to record identifiable landslide features and their dimensions (IAEG COMMISSION ON LANDSLIDES, 1990).

Evaluation of the probability or timing of the future occurrence is dependent on the probability of occurrence of the triggering factor. A trigger is an external stimulus, such as intense rainfall, that causes a near-immediate response in the form of a landslide by rapidly increasing the stresses or by reducing the strength of slope material (WIECZOREK, 1996). Hence, it is of primary importance to differentiate the conditions that caused slope instability from the processes that triggered the movement (POPESCU, 1994).

Landsliding causes damage both in the areas of instability initiation and in the areas of transport and of the reception of the movements. In order to be able to describe where the landslide is moving, it is necessary to investigate it's activity. The UNESCO WORKING PARTY ON WORLD LANDSLIDE INVENTORY (1993) suggests describing the landslide activity in terms relating to state, distribution and style of activity.

The assessment of losses consists of analysis of the interactions between the phenomenon and goods, i.e. behaviour of structures and people that are exposed to landsliding. Hence, it is fundamental to determine the level of intensity of a potential phenomenon. An important characteristic of the movement comprised in the intensity analysis is the rate of landsliding (IUGS WG/L, 1995).

3. METHODS OF LANDSLIDE HAZARD ZONATION

All the methods proposed are founded upon a single principle "the past and present are keys to the future" which implies that slope-failures in the future will be more likely to occur under those conditions which led

Component	Question
Hazard	1) Which type of movement is involved? 2) Where are the potentially unstable areas? 3) At which moment can the identified phenomenon be triggered? 4) How far can the phenomenon be propagated?
Vulnerability	5) What are the interactions with the environment, natural or modified by Man?
Cost	6) What is the cost of the resulting damage?

Table 1 Risk components with questions connected to landslide risk assessment.

van WESTEN, 1996	LEROI, 1996
Heuristic approach	Expert evaluation
Statistical approach	Statistical return analysis
Deterministic approach	Mechanical models

Table 2 Methods of landslide hazard zonation.

to past and present instability (CARRARA et al., 1995). Application of the above principle requires mapping both the landslides and a set of geological-morphological causal factors, and establishment of a hazard model. There are three main approaches for the developing of hazard models: heuristic, statistical and deterministic approach. Each of them is based on different elements as shown in Table 2.

3.1. HEURISTIC APPROACH

In heuristic methods the expert opinion of the engineering geologist and/or geomorphologist is used to classify the hazard. Two types of heuristic analysis can be distinguished: geomorphic analysis and qualitative map combination.

The geomorphic method is also known as the direct mapping method (HANSEN, 1987). It consists of geomorphological and/or engineering geological mapping through which the surveyor identifies past and present landslides and makes assumptions on those sites where failures are likely to occur in the future. Direct hazard determination is based on individual experience. The decision rules vary from place to place and are difficult to formulate. In addition, the resulting documents generally are "paper" ones (KIENHOLZ, 1978).

To overcome the problem of the "hidden rules" in direct mapping, indirect mapping methods have been developed. Qualitative map combination is based on *a priori* knowledge of the causes of landsliding in the investigated area. Hence, instability factors are ranked and weighted according to their assumed or expected importance in causing a mass-movement. In this method the expert's knowledge can be formalised into rules, but the result essentially depends on the experience of the surveyor. At present, maps obtained by this method cannot readily be evaluated in terms of reliability or certainty.

3.2. STATISTICAL APPROACH

In the statistical approach, causal factors are defined *a posteriori*, through back analysis of historical events. Therefore, the role of each factor (that led to landslides in the past) is determined on the basis of the observed relations with the past/present landslide distribution. The statistical approach can be applied following different techniques which essentially differ on the statistical procedure used: bivariate or multivariate analysis.

In bivariate statistical analysis each instability factor map is combined with a landslide distribution map, and weighting values based on landslide densities are calculated (SIDDLE et al., 1991; van WESTEN, 1993; YIN, 1994).

Multivariate statistical analysis of the important factors related to landslide occurrence, give the relative contribution of each of these factors to the total hazard within a defined land unit. For each sampling unit, the presence or absence of landslides is also determined. The model is conceptually fairly simple, but large data sets are needed to obtain enough cases to produce reliable results (CARRARA et al., 1995).

3.3. DETERMINISTIC APPROACH

There are some examples of landslide hazard assessment by calculating safety factors over large areas (van WESTEN, 1993; LEROI, 1996). The resulting safety factors are only indicative and are used to test multiple scenarios based on variable triggering hypotheses. The most frequently considered are hydraulic and seismic triggers. The main problem with these methods lies in the choice of the representative input parameters and the slope stability model.

For the rational consideration of the natural variability and uncertainty of each input variable in slope stability analyses, a probabilistic approach is essential (HAMMOND et al., 1992; TERLIEN et al., 1995). The objective is to obtain the probability distribution of the factor of safety and hence probability of failure. The most important limitation to the application of probabilistic methods in landslide hazard assessment may be the lack of statistical data on soil properties, pore water pressures and on loads (CHOWDHURY, 1984).

4. LANDSLIDE RISK ASSESSMENT

Landslide risk assessment requires the understanding, analysis and control of damage which are the consequences of the interaction between slope movements and exposed elements (property, people and various activities). However, due to the complexity of the phenomena and partly to an absence of conceptual knowledge of certain risk components, a unified approach to the problem does not exist. As a result of technical and sociological advances several researchers and organisations started to develop a methodology for landslide risk evaluation in the last decade (FELL, 1994; RAGOZIN, 1994; LEONE et al., 1996; LEROUEIL et al., 1996).

ANDERSON's et al. (1996) proposal of a risk-based method for selecting alternatives for landslide risk mitigation is presented as follows. The proposal is interesting because it comprises the whole procedure: the identification of risk, the estimation of risk, and the evaluation of risk through either aversion or acceptance (Fig. 1). Risk identification involves development of

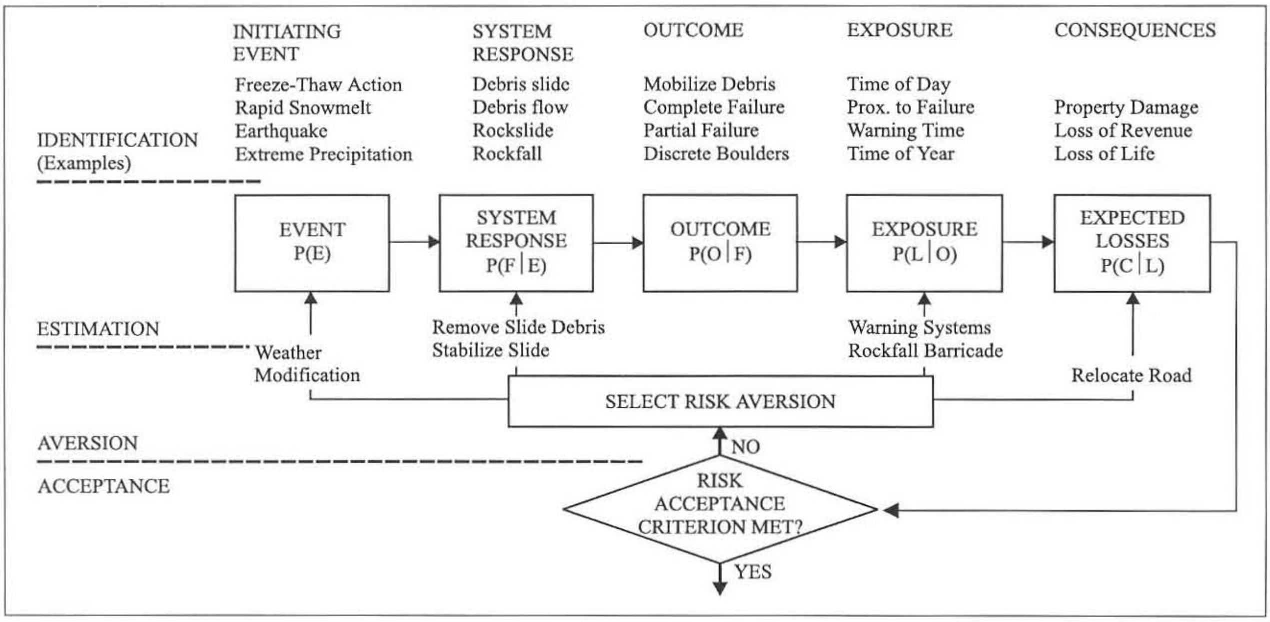

Fig. 1 Framework model for risk-based method to mitigate landslides (ANDERSON et al., 1996).

the risk model for the evaluation of an existing landslide risk. In order to achieve this it is necessary to recognise and list the various factors which could contribute to the landslide failure risk, and then to organise these into logical event sequences. The model is organised in the form of an event tree, which commences with events that can initiate failure, and ends with the consequences of a failure (Fig. 2). In the later phase the risk model serves for evaluation of the effectiveness of proposed rehabilitation alternatives. The second step involves risk estimation, i.e. assigning the probabilities and consequences to the occurrence of each failure mode. If these risks are unacceptable, the assessment proceeds to the third step - risk aversion. This involves the formulation and evaluation of remedial action (rehabilitation) alternatives. The final step in the risk assessment process is the decision on what degree of safety is acceptable.

A crucial stage for a good understanding of slope movements and the risk associated with them, is the characterisation of movement through factors having a mechanical significance. It requires establishing a relationship between the characteristics of a given movement, existence of definite predisposition factors, occurrence of triggering or aggravating factors, existence of definite revealing factors, and of the consequences of the movement. For this purpose, VAUNAT et al. (1994) are developing geotechnical characterisation of slope movements, taking into account slope movement type, involved material and movement stages. Such a characterisation constitutes an essential step for the development of expert systems on slope engineering, for the selection of numerical models for the simulation of specific aspects of slope behaviour, as well as for the design of remedial measures for stabilising a slope.

5. SCALE-RELATED RECOMMENDATIONS

Not all the methods of landslide hazard zonation are equally applicable at each scale of analysis, because of the difference in required input data and degree of precision of the obtained results. Table 3 provides an overview of the various methods of landslide hazard analy-

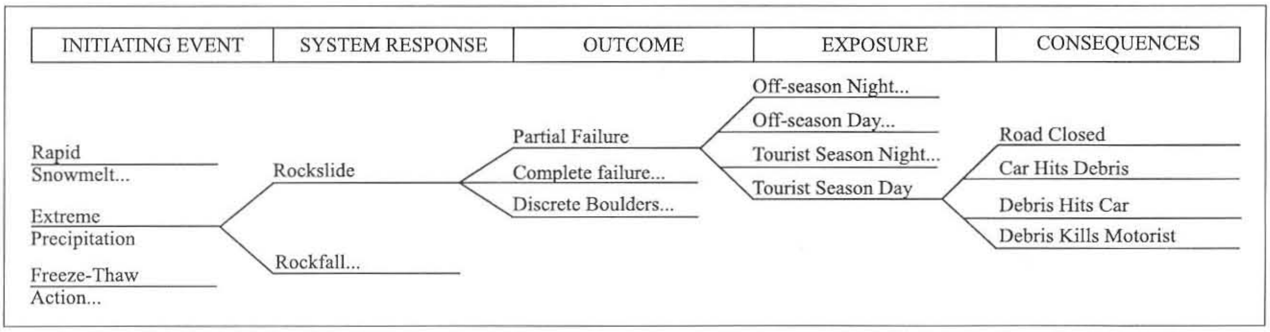

Fig. 2 Hypothetical event tree branch for evaluating outcome probability for landslide risk assessment (ANDERSON et al., 1996).

Type of analysis	Technique	Scale of use recommended Regional (<1:100,000)	 Medium (1:25,000-1:50,000)	 Large (1:5000-1:10,000)
Heuristic analysis	Geomorphological analysis	Yes	Yes*	Yes*
	Qualitative map combination	Yes**	Yes*	No
Statistical analysis	Bivariate statistical analysis	No	Yes	No
	Multivariate statistical analysis	No	Yes	No
Deterministic analysis	Safety factor analysis	No	No	Yes***

* But strongly supported by other more quantitative techniques to obtain an acceptable level of objectivity.
** But only if sufficient reliable data exist on the spatial distribution of the landslide controlling factors.
*** But only under homogeneous terrain conditions, considering the variability of the geotechnical parameters.

Table 3. Hazard analysis techniques in relation to mapping scales (SOETERS & van WESTEN, 1996).

sis and recommendations for their use at the three most relevant scales. From consideration of the advantages and pitfalls of landslide hazard zonation techniques, it follows that the best scale for landslide hazard mapping is the medium scale, i.e. 1:25,000. At this scale it is possible to obtain an overview of the hazard in its entirety, at a reasonable cost.

Regardless of the scale at which the hazard is evaluated, the risk maps should be drawn at scales above 1:5,000. This is due to the impossibility of acquisition of required input data at smaller scales.

The main field of application for landslide hazard and risk maps concerns land use planning, development and regulations. Hence, hazard and risk zonation has to comprise all levels of land use planning. To obtain an acceptable cost/benefit ratio and to ensure the practical applicability of the zonation, the development of a clear hierarchical methodology for the structuring and analysis of data is necessary.

5.1. APPLICATION TO CROATIA

Regional and medium scale landslide hazard mapping has never been undertaken in the Republic of Croatia. There are some examples of landslide hazard analyses at large and detailed scales, aimed at urban planning of particular areas. There is no experience of landslide risk assessment in Croatia.

Slope stability categorisations for the Zagreb City area have been undertaken twice. In 1979 the lithological classification and slope stability categorisation was produced, and in 1988 categorisation were made in the framework of The Seismic Microzonation of Zagreb City. In both cases the methods of direct mapping were applied, and the derived maps are at the 1:10,000 scale. Both of these maps are still relevant for urban development in Zagreb. Moreover, the Map of lithological classification and slope stability categorisation of the Mt. Medvednica hillsides is part of the legislative document - The Physical Plan of the Zagreb City. The drawback of these maps is the outdated data, as well as in the applied assessment method, because the criteria of evaluation are not clearly defined.

At the level of detailed physical development plans (i.e. on a large scale) it is common to perform the geotechnical slope stability analysis with the definition of construction conditions according to the planned land use. This could prove rational only for small areas, i.e. <100 ha (STANIĆ & MIHALIĆ, 1995).

In respect of the fact that consideration of instability in the planning processes in Croatia is only partial, and thus unsatisfactory (MIHALIĆ & STANIĆ, 1995), the proposal of a logical set of activities connected to the hazard and risk mapping was constructed which comprises all the levels of urban planning. The proposal is presented in the framework of recommendation for the application to urban planning documents currently valid in the Republic of Croatia with special emphasis to the territory of Zagreb City. These recommendations are applicable at three levels (Fig. 3):

1) At the regional scale (1:100,000 or smaller) the national landslide inventory should be made. The objective of the inventory is to provide an insight into the spatial distribution of landslides in Croatia. It is also possible to analyse landslide density. Although the method does not enable the production of a landslide hazard map, the quantitative presentation of landslide density would indicate areas in Croatia where mass movements can be a constraint to development. The information obtained should serve for physical planning at the national and county level. Overlaying of a landslide distribution map with the maps which display elements at risk (i.e. land use map) should also indicate areas where landslide hazard mapping is necessary. Additionally, the records of the most significant land-

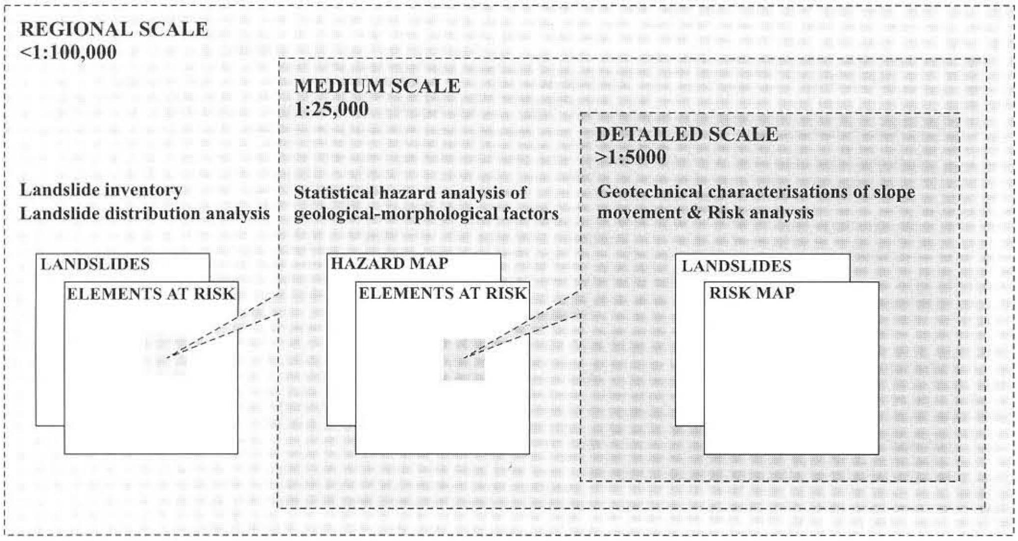

Fig. 3 Hierarchical model for landslide hazard and risk mapping.

slides in Croatia could also serve as input for the World Landslide Inventory.

The Croatian Institute of Geology is currently developing a landslide inventory as part of the preparation of the Basic Engineering Geological Map of the Republic of Croatia scale 1: 100,000. Figure 4 is a cartographic representation of a landslide inventory in the central part of the Zagreb section.

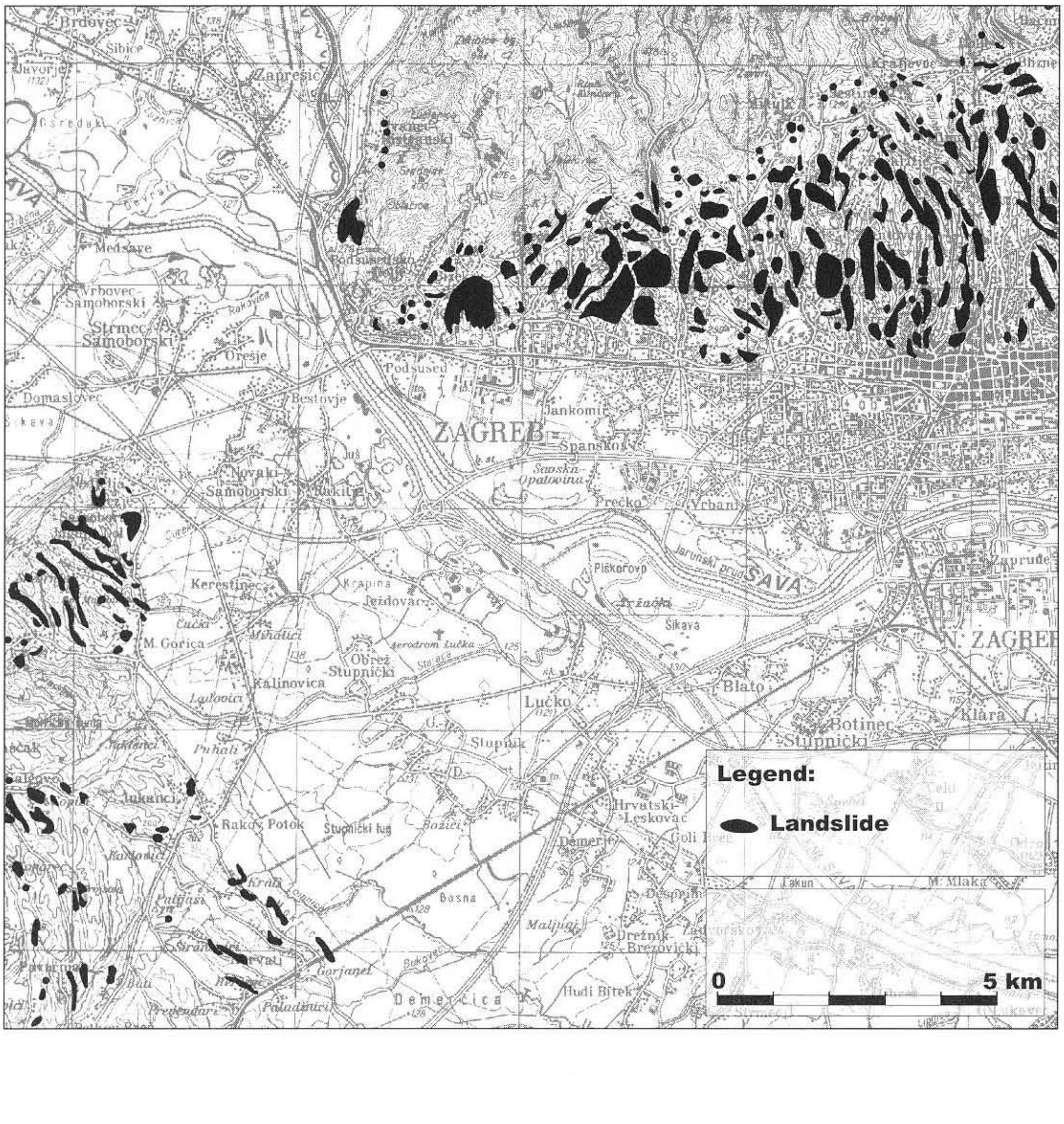

Fig. 4 Landslide inventory map of the central part of Zagreb section (Engineering Geological Data Base - Institute of Geology, Zagreb).

Fig. 5 Aerial photograph of Kostanjek landslide area taken in 1985 with inscribed landslide boundary (STANIĆ & NONVEILLER, 1996).

2) At the medium scale (1:25,000) statistical hazard analysis of geological-morphological causal factors is required. The detail on the hazard map should be such, that adjacent slopes of the same lithology are evaluated separately, and may obtain different hazard scores, depending on other characteristics, such as slope angle and slope segments. This map should represent a base for rational land-use planning, in order to locate developments on stable ground. The field of application would be the physical planning at the municipal and city level. Accordingly, a landslide hazard map for the territory of Zagreb City should also become a component of the Physical Plan of Zagreb City, by replacing the existing Map of lithological classification and the slope stability categorisation of the Mt. Medvednica hillsides. On the basis of a landslide hazard map, the legislation restricting development in the areas most susceptible to landslides could be enacted.

Enlargement of the landslide hazard map to the 1:10,000 scale could also serve as the basis for construction of the Physical Development Master Plan of Zagreb City. Overlaying of the hazard map with the map which displays elements at risk could indicate the level of risk. In the areas where risk is low, landslide hazard analysis will suffice.

3) At the large scale (>1:5,000) the information of landslide risk is required. To achieve the expected degree of precision it is necessary to undertake complementary investigation, followed by geotechnical characterisation of slope movements, and thus the risk assessment. The application of risk maps lies in the construction of urban plans and of the detailed physical development plans for the areas characterised by high risks.

An example of the area where the landslide risk assessment could be undertaken is the large Kostanjek landslide on the western outskirts of Zagreb, on the southern slopes of the Mt. Medvednica (Fig. 5). The first movement of this active landslide occurred in 1963. It is estimated that a sliding mass of some 32×10^6 m^3 is involved, with a maximum depth of 90 m. The displacements on the surface are 3 - 6 m (STANIĆ & NONVEILLER, 1996). The necessity for landslide risk assessment is conditioned by the presence of numerous houses in the area, as well as by the high level of exploration including continuous ground-displacement measurements.

6. CONCLUSIONS

Predictive models of landslide hazard and risk assessment constitute a major research field which may well take advantage of the potential of new technological advancements - GIS-driven data acquisition, manipulation and analysis. Consequently, the development of the methods of producing landslide hazard and risk maps is still in progress, and no uniform approach is as yet accepted.

By evaluation of the methodological approaches to landslide hazard zonation practices, the statistical analysis of geological-morphological causal factors is suggested, aimed at the prediction of the spatial probability of landslides (i.e. where failures are most likely to occur). This method allows production of landslide hazard maps at the scale of 1:25,000 at an acceptable cost.

Due to the variety of geological situations, the diversity of materials, the complexity of acting mechanisms and the variability of controlling parameters, the indication of the temporal probability of landsliding (i.e. when failures are likely to occur) can only be obtained by risk analysis at the detailed scale (>1:5,000). Hence, of crucial importance for risk analysis is VAUNAT's et al. (1994) geotechnical characterisation of slope movements. To be of value, in terms of the evaluation and presentation of landslide mitigation alternatives, risk analysis should encompass risk identification, estimation, aversion and acceptance, as proposed by ANDERSON et al. (1996).

The priority areas for the construction of risk maps are to be delimited on the basis of the hazard maps. The areas that are to be covered by hazard maps should be determined on the basis of data from a national landslide inventory.

The development of a general methodology for landslide hazard and risk mapping would require definition of the conceptual models, and extraction of simplified operational models from the conceptual models. The choice of the models should also serve as a guide for the development of appropriate data bases, taking into account that the availability of adequate data (both in quantity and quality) is crucial issue enabling the task to be accomplished.

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