OVERVIEW OF INPUT DATA FOR QUANTITATIVE RISK ANALYSIS FROM THE CONSEQUENCES OF GEOHAZARD

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Abstract: The aim of landslide risk assessment is to determine the spatial and temporal probability of landslides in a particular area, together with their mode of spread, size and intensity. Risk analysis must take into account possible breakdown mechanisms. Regardless of the work scale, the hazard assessment must define the time frame for the occurrence of potential types of landslides and their intensities at the considered location. The time occurrence of a landslide is normally expressed in terms of frequency, return period or probability overrun. The return period is the inverse annual probability return and refers to the average time interval in which an event of a certain magnitude is expected to occur. This paper provides an overview of the input data required for the assessment and quantitative risk analysis related to the occurrence of the most common geohazards in practice (landslides, shallow landslides, debris flows and large slow landslides). For a clearer overview, their importance in the assessment of sensitivity and hazards for different landslide mechanisms is given. At the same time, methods for quantitative risk analysis of landslide have been proposed.

Keywords: landslide, hazard, risk analysis, risk assessment, quantitative risk analysis, input parameters.

INTRODUCTION

This paper provides an overview of the input data required for adequate risk analysis of the consequences of geohazards. Risk is a combination of the consequences of activities and the associated uncertainties of the outcome of those activities. At the same time, it represents the expected degree of damage in the occurrence of some form of geohazard in relation to the loss of human lives, property and the harmful impact on the environment. Risk involves quantifying the probability of occurrence of some form of geohazard that may have adverse consequences. In practice, the acceptable level of risk is assessed (Benac, 2013), as well as measures of the probability and severity of adverse effects on human life and health, property or the environment. Landslide risk is often defined as the probability of a landslide event multiplied by the consequences.

The risk assessment involves the process of making recommendations on whether existing acceptable risks and current risk control measures are adequate. If not, the question is whether alternative risk control measures are justified and whether they will be implemented. Risk assessment includes phases of risk analysis and risk assessment. Risk assessment also encompasses the entire process of risk analysis and evaluation. Risk analysis applies the use of available data to calculate the risks to individuals, the population, property and the environment from the consequences of hazards. They typically contain the following steps: scope definition, hazard identification, vulnerability assessment and risk assessment. Risk analysis includes the systematic use of information to determine the initial event, the causes and consequences of the initial event and to express risk (Table 1). The main data needed to define risk analysis can be divided into four groups: landslide inventory data, environmental factors, driving factors and risk elements (Soeters and Van Westen, 1996; Van Westen et al., 2008). The inventory of landslides is the most important because it provides insight into the locations of past landslides, as well as their breakdown mechanisms, causal factors, frequency of occurrences, quantities and damage they caused.

There are relatively few papers that provide an overview of the original input data for quantitative hazard and risk analysis (Van Westen et al., 2008). Corominas and Moya (2008) provide an overview of the data methods used in slide description studies and Cepeda et al. (2012) provide an overview of methods for using meteorological data in analyzing precipitation thresholds for quantitative hazard assessment. Pitilakis et al. (2011) present in their paper a comprehensive overview of the data to be collected for the characterization and physical assessment of hazard vulnerability elements, such as buildings, roads, pipelines and the like. A good overview of the use of remote sensing for landslide hazard analysis and risk analysis can be found in the papers of Soeters and van Westen (1996), Singhroy (2005), Michoud et al. (2010) and Stumpf et al. (2011). In order to develop a reliable hazard and landslide risk map in a given area, which is crucial for insight into the spatial and temporal frequency of landslides, each hazard and/or risk study should begin with the most complete inventory of landslides in space and time according to Table 1.

Table 1. Overview of input data sources and their relevance for quantitative risk analysis for different landslide mechanisms (F = fall, SL = shallow landslides and debris flows, LSL = large slow landslides), (modified according to Corominas et al., 2013).

Basic source	**Data group**	**Examples**	**M**	**Scale**				**Relevance**		
				N	**R**	**L**	**LS**	**F**	**SL**	**LSL**
Laboratory analyzes	Soil properties	Grain size distribution, saturated and unsaturated shear strength of soil, soil water retention curves, hydraulic conductivity of saturated soil, clay minerals, sensitivity, viscosity, density.	Ps	x	x	o	•	L	C	V
	Rock properties	Unlimited compressive strength, shear strength, mineralogy.	Ps	x	x	o	•	C	L	C
	Vegetation properties	Tensile strength of roots, strength of pulling of roots, evapotranspiration.	Ps	x	x	o	•	L	V	M
	Age assessment	Radiocarbon C-14 test, pollen analysis.	Pl	o	o	o	•	L	L	V
Terrain measurements	Landslide age	Dendrochronology, lichen method for estimating landslide age, tephrochronology, archaeolog. artifacts.	Pl	o	o	o	•	M	M	V
	Depth of soil	Wells, trenches, pits, material outcrops, material sampling drills.	Ps	x	x	o	•	L	C	M
	Geophysics	Seismic wave refraction, microseismic observation, electromagnetic method, magnetic method, ground-penetration radar, geophysical drilling methods.	Ps	x	x	o	•	L	M	V
	Soil characteristics	Standard penetration tests, field drilling.	Ps	x	x	o	•	L	C	M
	Rock characteristics	Lithology, discontinuities (types, spacing, orientation, openings, fillings), rock mass ranking.	Ps	x	x	o	•	C	L	V
	Hydrological characteristics	Infiltration capacity, water face fluctuation, soil absorption, pore pressure.	Ps	x	x	o	•	V	C	C
	Characteristic of vegetation	Root depth, root density, vegetation species, crop factor, ratio of rock cover material.	Ps	x	x	o	•	M	V	L
Observation networks	Landslide shifts	Electronic distance measuring devices, GPS systems, theodolite, terrestrial laser scanner, interferometry.	Pl	x	x	o	•	V	V	V
	Groundwater	Piezometers, strain gauges, water flow measuring stations.	Pn	x	x	o	•	V	C	C
	Meteorological data	Precipitation, temperature, humidity, wind speed.	Pn	•	•	•	•	V	V	V
	Seismic data	Stations for measuring seismic activity, stations for strong displacement, microseismic studies.	Pn	•	•	•	•	V	V	V

Note: Importance is marked as C (crucial), V (very important), M (moderately important) and L (less important). The potential for this information is collected at different levels and is presented as: • = possible, o = difficult possible, x = not possible. The scales are: N (national level), R (regional level), L (local level) and LS (local specific level). M denotes the method used for spatial data collection where: Pl = point (local) data related to individual specifics (eg landslides), Ps = sample of points that characterize spatial units (eg soil types, vegetation types), Pn = points in the network to be interpolated, Sc = data based on surface characteristics (eg landslide polygons, buildings), Cs = complete surface coverage, L = line data.

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Area mapping	Landslides	Type, relative age, speed of movement, state of activity, initiations, transport of materials, zones of deviation, area, depth, volume, consequences.	Sc	o	•	•	•	C	C	C
	Geomorphology	Characterization of landslide shapes, processes, surface material.	Cs	o	o	•	•	L	V	V
	Soil types	Textures, soil classification, boundary area mapping, conversion to engineering soil types.	Cs	o	o	•	•	L	C	V
	Lithology	Lithological mapping, meteorological zones, border area mapping, formations.	Cs	o	o	•	•	C	V	V
	Structural geology	Depth measurements of cover plane and discontinuity, stratigraphic reconstructions, mapping curve, structural reconstruction.	Cs	o	o	•	•	V	L	V
	Vegetation	Vegetation type, density, leaf growth area index.	Cs	o	o	•	•	L	V	M
	Land use	Types of land use, characterization of vegetation by land use.	Cs	o	o	•	•	V	V	V
	Elements of risk	Typology of construction, structural system, foundation systems, classification of roads and pipelines.	Sc L	o	o	•	•	V	V	V
Archival studies and data from the past	Landslides in the past	Historical data on location, date of origin, trigger mechanisms, size, volume, range length.	Sc Pl	o	o	•	•	V	V	C
	Damage data	Historical data on economic losses and affected population with dates, location and characterization.	Pl	o	o	o	o	V	V	V
	Meteorological data	Precipitation (continuous or daily), temperature, wind speed, humidity.	Pl	•	•	•	•	V	V	V
	Land use change	Historical maps of land/cover use for different periods.	Pn	•	•	•	•	M	V	V
	Elements of risk	Historical maps of buildings, transport infrastructure, economic activities and population characteristics.	Cs	•	•	•	•	V	V	V
	Digital height values	Topographic maps with isohypses, digital relief models.	Sc L	•	•	•	•	V	V	V
	Thematic maps	Geological, geomorphological, channel networks and other existing thematic maps.	Cs	•	•	•	•	V	V	V

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Remote sensing	Aerial photography and high resolution satellite imagery	Interpretation of images for mapping and characterization of landslide locations, geomorphology, land/cover use, mapping of risk elements.	Sc Cs	○	•	•	•	C	C	C
	Multispectral images	Image classification methods for landslide mapping, land/cover use, normalized vegetation difference index, leaf growth index for a specific area.	Sc Cs	•	•	•	•	M	V	M
	Digital elevation data	Aerial stereophotogrammetry, space stereophotogrammetry, LIDAR, InSAR.	Cs	•	•	•	•	C	C	C

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QUANTITATIVE RISK ANALYSIS METHODS FOR LANDSLIDES

For the purposes of quantitative risk analysis (QRA) it is necessary to have an accurate input of geological and geomechanical data and a quality digital terrain model for a particular observation area in order to perform a good assessment of possible scenarios, event calculation and relevant return period (Lee and Jones, 2004). The risk for a landslide scenario can be expressed analytically based on the formulation $R=P(M_i)P(X_j|M_i)P(T|X_j)V_{ij}C$, where R is the risk due to the occurrence of a landslide of strength M_i on the risk element located at a distance X from the source of the landslide, $P(M_i)$ is the probability of landslides of a certain strength Mi, $P(X_j|M_i)$ is the probability of the landslide to a point located at a distance X from the source of the landslide with intensity j, $P(T|X_j)$ is the probability element at site X at the time of landslide, V_{ij} is the vulnerability of the landslide element of strength and intensity, while C is the value of the hazard element. Elements of risk are population, buildings, economic activities, including public services or any other persons directly exposed to hazard in a particular area (UN-ISDR, 2004).

To perform a quantitative risk analysis, it is necessary to know all the parameters for calculating the parameter R for a particular type of landslide, because each landslide has a specific probability of occurrence, intensity and probability of impact. Global hazard areas can be determined by collecting a specific risk for different types of geohazards and their intensities. Two alternative types of analysis are used to determine risk: deterministic and probabilistic analysis. Deterministic risk analysis uses average or at least favorable values of risk components (worst case scenario) which gives a univariate result expressed by average or maximum risk. On the other hand, for probabilistic risk analysis, all or only some of the risk components are assumed to be consistent with the probability distribution so that the results are presented under probabilistic conditions, using representations of (cumulative) probabilities and consequences (Corominas et al., 2013; Pine, 2008).

DISCUSSION

Risk analysis can relate to a single building, feature or area. Area analysis is a very demanding process in terms of collecting the data needed to determine risk. Spatial analysis is usually performed at the regional level and conducted on a GIS platform with maps used to illustrate risk. The analysis does not necessarily require an estimate of the frequency in the source area, but the list of events reaching the infrastructure should be as complete as possible. Geohazard analysis is usually performed using analytical and/or numerical models and includes the calculation of spatial parameters that affect the probability of occurrence of a certain size or reached speed of the exposed geohazard element. The calculation of the exposure depends on the scale of the analyzed area and the type of potentially exposed hazard elements. When exhibiting, there is an important difference between static (buildings, roads, other infrastructure, etc.) and moving elements (vehicles, people, etc.). With specific spatial and local scales, and when the trajectory is included in the analysis, such a process is limited only to the risk elements located on the potential trajectory of the rock mass landslide. Debris flows can affect larger areas in relation to rock mass landslides, due to their increased mobility, ie the influence of fluids as an integral part. Spatial surface exposure can be calculated as the ratio of the affected area to the total area. Spatial exposure can also be seen as a function of flow kinematics, ie the hydrodynamic impact that affects an individual structure during the debris flow propagation. To analyze the risk of landslides and adopt spatial planning, it is necessary to understand the mechanisms of landslides that may occur in the area under consideration. Several geohazard scenarios are considered, together with their potential consequences, so that the relevant components of direct and indirect risk can be assessed quantitatively.

CONCLUSIONS

The risk of the consequences of geohazard can be described through three basic components: hazard, exposure of at-risk elements and their vulnerability. They can be characterized by spatial or non-spatial attributes. In determining the risk analysis of geohazard consequences, the procedure is performed through the following steps: (i) geohazard analysis which includes analysis of intensity, probability of rock mass slip and its potential reach, (iii) identification of risk elements including number of occurrence, value and degree of exposure, (iv) vulnerability analysis and (iv) risk assessment. The susceptibility to the occurrence of possible geohazards in a given area can be determined on the basis of geomorphological mapping, empirical or semi-empirical evaluation systems, as well as deterministic and statistical methods.

Methods for determining the propagation of debris flow and mudflow can be divided into two main categories, namely empirical methods and physical methods. Empirical methods are relatively simple methods that allow a rapid assessment of the propagation of debris flow and mudflow based on the relationship of topographic slope factors and the length of the flow range. On the other hand, physically based methods are complex methods that use numerical (kinematic) simulations of motion and propagation of debris flow and mudflow. The intensity of such phenomena in nature with a significant initiated volume of rock mass is a necessary factor in hazard assessment and is expressed by the kinetic energy of hydrodynamic impact that such phenomena cause through the process of downstream propagation on slopes or within channels.

Due to the growing consequences of climate change in the world, more and more frequent occurrences of rock material propagation resulting from longer periods of precipitation and drought can be expected. In this regard, in the future it will be necessary to develop relevant maps of hazards and risks of debris flows and mudflows, and thus to make an adequate selection of an appropriate method for assessing geohazards and risks of such possible occurrences. Considering the methods of geohazard and risk assessment that are applicable in the world, the size of the area of application and an adequate scale should be considered. Geohazard zoning at national, regional and local scales is carried out using simple methods based on heuristic or empirical procedures (adopting only a few parameters for assessment), unfortunately neglecting the time component. When assessing hazard on a large scale, it is proposed to adopt a quantitative method over a qualitative one, which separates the assessment of hazard and risk. Today, high-resolution 3D images of terrain (aerial and terrestrial images using LiDAR technology) or photogrammetric images using SfM technology (Structure from Motion Technology) are available for conducting highly sophisticated deterministic spatial simulations of the movement and propagation of debris flow and mudflows for the purpose of risk determination. For this reason, appropriate methods of geohazard assessment for these phenomena should be adopted by introducing modern deterministic methods, while heuristic methods can serve as an auxiliary tool for verification and validation the terrain results.

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