Principles for the assessment and mapping of integrated geological hazard in Bulgaria

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Abstract. The territory of Bulgaria is at risk of a number of unfavorable and destructive geological processes and phenomena constituting the geological hazard. The generally high hazard degree necessitates analyzing, evaluation and mapping of the geological hazard and risk processes. Evaluation and mapping of geological risk is the final stage of a long-lasting gathering of information for each destructive geological process. The purpose of the present study is to analyze the principles and order in assessing and mapping the overall geological hazard. Typical hazardous geological processes for the territory of our country are taken into account (active faults, abrasion/sea erosion, erosion, landslides, rockfalls, collapse, swelling, liquefaction of dispersed soils, etc.). A methodological approach is presented to combine all hazardous geological processes into an integrated hazard map. The study presents the results obtained during the implementation of the project “*Elaboration of analysis, evaluation and mapping of geological risk*” realized in 2016 by a large research team and supported by the Ministry of Regional Development and Public Works in Bulgaria.

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INTRODUCTION

The need for modern methods of assessing natural destructive processes has recently increased because of their high activity. Such processes cause human victims, increased social tensions and severe consequences for the social-economic environment, expressed in demolition of buildings, infrastructure, historical monuments, disruption of land use and destruction of areas, interruption of communications, and environmental degradation. This necessitates the development of a national methodology for assessing the geological risk as a final stage to provide for the economic and sustainable development of our country. The compilation of the methodology requires competent knowledge of the geological hazards; recognition of the most dangerous geological processes and phenomena; provision of guidance on their description; and assessment of the emergence potential for hazards and the resulting risk.

Recently, more modern methods of assessing natural destructive processes have been introduced in the world practice (Schmidt-Thomé and Jarva, 2004; United Nations 2009, 2015, 2016), thus requiring their introduction and application on the territory of our country. For this reason, it is necessary to clarify the engineer-geological concepts that are internationally accepted or in the process of validation, as well as to comply with our current geological reality. The evaluation of geological risk itself is preceded by a number of other geological assessments: susceptibility, vulnerability and hazard (Dobrev *et al.*, 2014; Ivanov *et al.*, 2017b).

The methodology described herein aims to clarify the above-mentioned sequence until the final estimates of geological risk are reached. This is important because the risk is commonly a combination of several destructive geological processes or a succession of interconnected geological events. This fact requires the assessments of both single geological hazard and

hazard of multivalent character (multi-hazard) (Greiving, 2006; Olfert, 2006). The methodology clearly outlines the direction and significance of geological risk zoning.

Considerable experience has been gained after the usage of GIS in land-use planning, which commenced at the end of the 1980s. There are already many approved (partially or completely) GIS-based methods in the mapping of landslides and other destructive geological processes (Chacon *et al.*, 2006; Thapa and Esaki, 2007; Soms and Laizāns, 2011; Corominas *et al.*, 2014).

At the beginning of the 1990s, the approach proposed by Brabb (1993) to illustrate the starting point for the International Decade of Natural Disaster Reduction (1991–2000) showed a lack or low coverage of landslide mapping in Europe. Ten years later, GIS-based landslide mapping projects were implemented in many countries by national geological, environmental and other public agencies. At the same time, a map of the geological hazards, with explanatory text, was published in Bulgaria (Iliev-Broutchev, 1994).

The methodology for the assessment of geological risk (Dobrev *et al.*, 2014) and the mapping of geological risk in Bulgaria (Ivanov *et al.*, 2017b) have been compiled in accordance with the requirements of the “*Ordinance on the terms, orders and authorities for performing analysis, evaluation and cartographing the risk of disasters*” (State Gazette, 2012). These projects were implemented in 2014–2016 by request of the Ministry of Regional Development and Public Works. According to the ordinance the list of geological hazards and risks includes tectonic movements, abrasion, erosion, landslides, rockfalls, collapse, swelling, liquefaction of soils and other geological processes. Seismic and flood risks are detached from the geological risk and are not considered in the present study.

PRINCIPLES AND SEQUENCE IN THE ASSESSMENT AND MAPPING OF GEOLOGICAL HAZARDS

The basic principles for geological hazard and risk investigations and zoning applied in the current study are suggested by Varnes (1984) and supplemented by Chacon *et al.* (2006) as follows:

- 1) The past and present are the key to understand the future;
- 2) Basic conditions causing landslides and other destructive geological processes can be identified;
- 3) The degree of hazard can be assessed;
- 4) The risks arising from geological destructive processes can also be quantified.

The main types of maps linked with geological hazard and geological risk management programs are: inventory maps (or descriptive maps, distribution maps); maps of susceptibility; maps of geological hazard; maps of geological risk.

Inventory maps (Maps of distribution of destructive geological processes)

These maps contain locations and outlines of the destructive geological processes, as well as data for single or multiple events. Small-scale maps show only the locations of processes/phenomena, while large-scale maps can be much more detailed as other relevant data can be presented, such as activity, time of appearance, dimensions, etc.

Maps of the susceptibility of the terrain to destructive geological processes

Susceptibility maps point the probable occurrence place of various destructive geological processes. The basic approach of land susceptibility includes simple distribution of factors associated with instability processes, aiming to identify hazardous areas without reflecting the time factor. This approach is useful for areas where it is difficult to provide sufficient historical data on the destructive processes. These are not only factual material maps, but they may additionally contain elements of a well-known geological and geotechnical interpretations based on geomorphological features, aerospace analysis, engineering geological field mapping, etc. For example, zoning susceptibility usually includes a description of the actual situation (*e.g.*, old landslides or collapses), along with an assessment of areas with potential for occurrence of such phenomena in the future. However, an estimation of the occurrence frequency is not included.

Such mapping does not predict the exact time of occurrence of a given hazardous geological process, but only outlines the areas where these processes is likely to occur.

On these maps, the susceptibility of the terrain is graded in categories (or classes) from stable (very low) to unstable (very high). Color schemes are used to represent susceptibility, with unstable areas shown in “warm” colors (red, orange and yellow), while “cool” colors (green and/or blue) represent more stable regions (Spiker and Gori, 2000).

Maps of the geological hazard

The geological hazard of landslides is defined as “probability of occurrence at a given time and within a given area of a potentially destructive phenomenon” (Varnes, 1984). This is also valid for other hazards.

Hazard zoning uses the results of susceptibility zoning (*e.g.*, terrain prone to sliding), and approximately allocates the frequency (annual probability) to the potential phenomena. All dangerous processes that may affect an area, including those away from it but still able to affect it, have to be taken into account. Hazard can be expressed by the frequency of a certain type of phenomenon with a certain type, volume and speed of the manifestation of dangerous high-intensity

processes. For example, the definition of a hazard map includes zoning indicating the annual probability of occurrence of landslides in the entire area.

Hazard maps show only the location and intensity of the individual hazards without information on the vulnerability of the area. Thus, these maps are maps of geological hazard, but they are not risk maps.

Maps of geological risk

Geological risk maps indicate the expected annual damage value across the affected area by combining the probability information from the geological hazard map with an analysis of all possible consequences (victims, property damage, accidents and loss of service) (Varnes, 1984; Spiker and Gori, 2000).

ASSESSMENT AND MAPPING OF INTEGRATED GEOLOGICAL HAZARD

Methodological approach

The so-called multi-hazard approach (Greiving, 2006; Olfert, 2006) has been chosen for the assessment of the integral geological hazard for the territory of Bulgaria (Fig. 1). We have taken into account all relevant geological hazards for a particular area, as well as its vulnerability. Thus, we assessed the level of disaster

risk for the research area (State Gazette, 2012; Dobrev *et al.*, 2014; Ivanov *et al.*, 2017b).

The integrated multi-hazard risk assessment of a given territory starts with a compilation of separate maps for each hazard (Fig. 1). Thus-produced maps show the areas of highest danger, as well as the intensity of the relevant processes (Nakov, 2005; Hamova *et al.*, 2015; Babukova and Zlatunova, 2016; Berov *et al.*, 2017; Ivanov and Berov, 2017; Ivanov *et al.*, 2017a).

Integrated map of hazard

Data of all individual hazards are integrated into a map, showing the overall potential of hazards in the studied area. The resulting integrated hazard map shows the areas (actual or potential) with high level of geological hazards.

The geological hazard for a given area can be represented as a sum of the individual values for the individual processes (as shown in Fig. 1), and it is necessary to take into account the intensity of these processes.

$$\text{SUM}_{\text{hazard}} = \text{AF} + \text{ER} + \text{AB} + \text{RF} + \text{LS} + \text{DF} + \text{CL} + \text{LQ} + \text{SW}$$

Integration of geological processes into a single map is a possible and easy process when using GIS. A more problematic issue is whether all the hazards

Fig. 1. Model of assessment of the Integrated Geological Hazard Index.

Table 1
Sequence for assessing each hazard

HAZARD	
Weighting estimation of the hazard	Hazard ratio (intensity)
<p>Weighted Hazard Assessment</p> $\text{Weighted Hazard Result} = \text{Individual Weight of Hazard} \times \text{Hazard ratio}$	

should be aggregated with equal or different weights (*i.e.*, whether certain hazards are more important than the others). Such weighing requires expert assessment and has a significant impact on the results of integrated hazard values (Greiving, 2006; Olfert, 2006). In order to provide a variety of weighting hazard assessments, the relevant researchers and scientists often use the so-called Delphi process. The Delphi method (Helmer, 1966), is widely accepted by many institutions, ministries and research organizations. Each of the hazards carries a certain weight, a percentage of the total hazard we take for 1 (or 100%). On this basis, the integration of all types of hazard and the development of an Integrated Hazard Map can be carried out. For this purpose, the whole range of the class for each hazard (I–V), respectively the hazard ratio, is multiplied by the individual weight of a given hazard in percentages. Thus, the maximum rating of all processes (H_{SUM}) is also 1 or 100%. The used algorithm is summarized in Table 1.

Determination of the hazard ratio

The hazard ratio is determined according to the intensity of the relevant hazard for the studied area. It is used as a multiplier to create a weighted hazard assessment.

The hazard intensity is determined on the basis of data such as the frequency and degree of occurrence of a hazardous process. They differ due to the specific characteristics of each hazard, so it is impossible to compile a uniform classification that is valid for all types of hazards. The intensity of each hazard is classified into five classes (Table 2) and can be mapped for the respective process with the corresponding attribute table (Berov *et al.*, 2017; Ivanov and Berov, 2017). This relative scale allows the comparison of several spatially relevant hazards and overcomes, to a certain extent, the difficulties in assessing the hazards and risks. This should be considered as one of the main problems that interfere with complex or integrated risk assessment.

Determination of the weighting estimation for each hazard

The hazards of each process are also weighted, *i.e.*, the weight of a probability of the hazard in the studied ter-

Table 2
Intensity Hazard Classes and their corresponding Hazard ratio

Intensity Hazard Classes		Hazard ratio
I	very high	0.2
II	high	0.4
III	medium	0.6
IV	low	0.8
V	very low	1.0

ritory is estimated in advance. Hazard weights (weight scores) are obtained, using expert opinion (the Delphi method).

The estimation of hazard starts with separate assessments for each hazardous process. The next step is to combine the hazards according to the accepted individual weighting criteria (G') with the hazard ratio according to its intensity class. The last step is the weight hazard estimation, *i.e.*, H is calculated for all processes (Table 3). The result is presented in an integrated map of hazard, showing the total potential of hazards (0 to 1, or 0% to 100%) for each area, where 0 is the lack of geological hazard (*i.e.*, processes are not developed) and 1 means the occurrence of processes with very high intensity (very high degree of geological hazard).

The individual relative value of each factor generating the geological hazard and risk is evaluated according to a methodology, ranking the risk factors pursuant to potential losses and the probability of a particular hazardous event. This allows the classification of geological hazards by risk factors and their relative contribution to the overall risk. For this purpose, an individual relative value or weight is determined for each hazard. The class of intensity is also defined as very high, high, medium, low or very low (with Hazard ratio from 1 to 0). Calculated hazard values for some processes are shown in Table 4 and Fig. 2.

CONCLUSION

The present study provides a summary of the principles, assessment and mapping of general geological hazards in Bulgaria. The necessary steps for geological hazard assessment and mapping and their order

Table 3
Calculation of the combined (weighted) H'_{SUM} result for each hazard and for each area

№	Geological Hazards – Process	Intensity class (I)	Weight (G)	Weight (G'), %	Total Hazard (H'_{SUM})
1	Active faults (AF)	I – V	1	4.4	$I_{AF} \times G_{AF}$
2	Erosion (ER)	I – V	2	8.9	$I_{ER} \times G_{ER}$
3	Abrasion (Sea erosion) (AB)	I – V	2	8.9	$I_{AB} \times G_{AB}$
4	Rock falls (RF)	I – V	5	22.2	$I_{RF} \times G_{RF}$
5	Landslides (LS)	I – V	4	17.8	$I_{LS} \times G_{LS}$
6	Debris Flows (DF)	I – V	5	22.2	$I_{DF} \times G_{DF}$
7	Collapsibility of loess (CL)	I – V	2	8.9	$I_{CL} \times G_{CL}$
8	Liquefaction of weak soils (LQ)	I – V	1	4.4	$I_{AF} \times G_{AF}$
9	Swelling of soils (SW)	I – V	0.5	2.2	$I_{SW} \times G_{SW}$
Total:			22.5	100%	H'_{SUM}

Table 4
Calculated Hazard Values for some processes (example)

Geological Hazards – Process	Intensity class (I)		Hazard ratio	Weight (G')		Total (H)
Landslides (LS)	V	very high	1	4	17.8%	0.178
	IV	high	0.8			0.142
	III	medium	0.6			0.107
	II	low	0.4			0.071
	I	very low	0.2			0.036
Liquefaction of weak soils (LQ)	V	very high	1	1	4.4%	0.044
	IV	high	0.8			0.036
	III	medium	0.6			0.027
	II	low	0.4			0.018
	I	very low	0.2			0.009
Swelling of soils (SW)	V	very high	1	0.5	2.2%	0.022
	IV	high	0.8			0.018
	III	medium	0.6			0.013
	II	low	0.4			0.009
	I	very low	0.2			0.004

Fig. 2. A sketch of an integrated hazard map: a) single hazards; b) integrated hazard.

are outlined. The approach we apply is consistent with the peculiarities of the territory of Bulgaria, including specific geological features and geomorphology. The most widespread geological hazards, which pose a threat to the population as well as to the infrastructure, have also been taken into account. Each process is assessed with the appropriate weight in its participation in the integral assessment of the overall geological hazard. The sequence is evaluated by assessing each hazard according to the following algorithm: *weighted result of hazard* = *individual weight of hazard* × *hazard ratio*. The possibility to present

the overall geological hazard for a given territory, such as municipality, district or state, is estimated through this approach. It is useful to decision-makers for finding essential solutions during construction of important infrastructure objects, and for mitigation of a natural disaster impact.

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