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Managing expert-information uncertainties for assessing collapse susceptibility of abandoned underground structures

Aude Nachbaur *, Jérémy Rohmer

BRGM, 3 avenue C. Guillemin, 45060 Orleans Cedex 2, France

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ABSTRACT

Assessing the collapse susceptibility of abandoned cavities at a regional scale is associated with large uncertainties that are mainly related to the very nature of the phenomena, but also to the difficulty in collecting exhaustive information at such a scale on often "forgotten" structures. In this context, the expert's role is essential, because he is able to synthesize the information resulting from the inventory and from the commonly imprecise, if not vague, criteria on the basis of his experience and his knowledge of the geological, historical, economic regional context.

In this article, we propose mathematical tools for representing and processing this information in order to give flexibility to this step and manage the uncertainty inherent in the expert's information. The first tool, based on the weight of evidence theory, is for managing the uncertainty due to the heterogeneous spatial distribution of the data, whereas the second tool, based on the fuzzy set theory, is for managing the imprecision and incompleteness of available data, which hinder the definition of the class boundaries of the quantitative decision criteria. Based on an appropriate representation of the uncertainty sources (related to the input data and to the expert diagnostic), we then propose a methodology that integrates the uncertainty in the final output of the collapse susceptibility assessment and provides a confidence indicator useful within the decision-making process. The proposed methodology is applied to the Arras territory in the North of France, where abandoned chalk pits (dating back to the Roman ages) and war saps located in the vicinity of the First World War front lines (i.e. covered trenches), raise both difficulties for urban planning.

1. Introduction

The Earth's subsurface has, throughout history, been intensively worked not only for extracting material, as testified by the vast number of quarries and marl pits, but also for various other reasons resulting in underground structures as varied as war saps (covered frontline trenches), underground shelters, troglodyte dwellings, etc. (LCPC, 2002). In addition to these anthropogenic structures are the "natural" cavities such as the karsts in limestone environments. The existence of most of these underground cavities, classified as "abandoned", is unknown whereas voids can extend several tens of meters.

It is estimated that France contains more than 500,000 of such underground structures whose partial or total ruin can have considerable socio-economic consequences for the community (Van Den Eeckhaut et al., 2007; Gutiérrez et al., 2008). For example, in the French region of Picardy more than 300 constructions were damaged through cavity collapse following the winter rains of 2000–2001 (Bouchut and Vincent, 2002). These events can be sufficiently violent to cause human loss. Thus, in 1961, the collapse of an underground chalk quarry in the Paris suburb of Clamart caused the destruction of 20 buildings with the death of 21 people (Josien, 1995).

In France, cartographic tools known as Risk Prevention Plans (RPP), have been developed at municipal scale for determining cavity-associated risks (MATE, 1999). However, faced with both the number and the diversity of such abandoned cavities, the authorities require decision-aid tools to be able to rank the risks at spatially larger scales (such as grouped-municipality, if not regional scale) and manage the resultant uncertainties (Waltham et al., 2005). The present study puts forward a methodology in answer to these expectations.

Contrary to other natural phenomena, no single random variable can be identified for the overall measurement of the dreaded event, i.e. cavity collapse. In most cases, the studied underground structures are not accessible, which eliminates the use of a systematic deterministic approach. The particularity of mining cavities is the precision often provided by the existence and knowledge of mine plans and geometric parameters, even when incomplete. In the general case, we are concerned with limited and non-exhaustive input data, seldom supported by geometric and mechanical parameters. Being given the specificity of the studied natural phenomenon, the only predictive models that can be established consist in expressing the spatial probability of a surface instabilities appearance, known as "susceptibility". Two approaches can

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* Corresponding author. Tel.: +33 2 38 64 39 65.
E-mail address: a.nachbaur@brgm.fr (A. Nachbaur).

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be commonly proposed in the view to assess the level of susceptibility: the first one being based on empirical methods and the second one based on the quantification of this level by means of mathematical and statistical tools. In both cases, we have to deal with multiple and locally highly variable, controlling factors mainly based on the judgment and information of an expert panel.

Where purely empirical methods are concerned, in France, methodological guides have been produced for assessing underground-cavity susceptibility in general (LCPC, 2002) or dedicated, for example, for the marl-pits of Upper Normandy (LCPC, 2008) or for mining cavities (INERIS, 2004). These guides develop a phenomenological approach based on analyzing the rupture mechanisms and generally resulting in a qualitative spatial ranking of the susceptibility based on a weighting adjusted by experts. The application of a scoring and classification procedure has been commonly applied for ranking the collapse susceptibility of karstic cavities (Forth et al., 1999; Kaufmann and Quinif, 2002; Zhou et al., 2003; Cooper, 2008; Guerrero et al., 2008). One major limitation of such an approach is the choice of the weightings, which is highly dependent on expert judgments (i.e. subjectivity), hence widely varying from one expert to another.

To compensate for this shortcoming, a large variety of rigorous mathematical and statistical tools has been introduced enabling one to quantify the probability between empirically established relationships without introducing expert subjectivity. Thus, White (1988) used the nearest neighbor analysis to interpret the spatial distribution of sinkholes, Mancini et al. (2009) tested a multicriteria decision analysis to combine several quantitative factors controlling the subsidence of a salt mine in order to score the hazard. Gao and Alexander (2003) and Bruno et al. (2008) used a decision tree, Lamelas et al. (2008) chose logistic regression. Applying several karst susceptibility assessment methodologies to the Ebro Valley, Galve et al. (2009) noted that models derived from the nearest neighbor distance and sinkhole density were more reliable than the probabilistic or heuristic methods. These tool types, however, are only based on the initial collection of data and thus favor the best informed sectors so that the susceptibility assessment might result in outlining the sectors where information on the cavities is available. Thus, a major limitation of these approaches is that they are unsuited to an inventory that is known to be scarce and incomplete. The quality and precision of these approaches rest in fact on the exhaustiveness of the inventory, the realization of which is limited notably by the size of the study area. Introduction of the expert's subjectivity because of his knowledge of the regional context is thus essential in order to fill the gaps of the data-gathering phase.

Overlapping these methodological approaches and in the view to overcome the usual limitations encountered within commonly-used collapse susceptibility assessments of underground structures, an alternative is proposed in this article fulfilling the following requirements: (1) providing a useful tool for decision-makers and regional planning managers; (2) being flexible and adaptable to all kinds of cavity and specific local conditions; (3) enabling to take into account expert judgments of all types (geological, geographical, historical, engineering, etc.) while introducing analytical tools that control the weight of expert's subjectivity; (4) enabling to use existing punctual data collection while, at the same time, overcome any deficiency or lack of this collection.

The present article is organized as follows. In the first section, the general principles adopted for collapse susceptibility assessment of abandoned underground structures are described. In the second section, we shall see the adopted mathematical tools developed to manage the multiple uncertainty sources associated with the assessment. We shall also see that these tools depend on the nature of the criteria used. They are adapted either from the "weight-of-evidence" approach, which has been widely used in the field of mineral exploration (Bonham-Carter, 1994) and further applied for geohazard assessment, or from the "fuzzy set" theory (Zadeh, 1965) to deal with imprecision and incompleteness of available data. Based on an appropriate representation of the uncertainty sources, we then propose a methodology that integrates the uncertainty in the final output of the collapse susceptibility assessment and synthesizes a confidence indicator useful within the decision-making process to assess the sensitivity of the results to the inputs. Finally, the use of the proposed methodology is illustrated for the Arras region of northern France (Section 4).

2. Methodology for assessing collapse susceptibility

2.1. Definition of susceptibility

The susceptibility of a surface disturbance (i.e. ground instability) measures the spatial probability of its appearance at the surface, without any reference to a temporal frequency associated with the hazard (Galve et al., 2009). This susceptibility level is an indicator for the decision maker, and is here assessed quantitatively as an "index".

From a practical point of view, the Collapse Susceptibility (CS), i.e. the susceptibility of a collapse appearing at the surface, is commonly estimated as the crossing of two separate susceptibility values, i.e. the Presence Susceptibility (PS) and the Rupture Susceptibility (RS), because regarding the large spatial scale considered, each of these susceptibility values can be assessed from independent controlling factors. The first term PS corresponds to the susceptibility of cavities being present, whereas the second term RS corresponds to the susceptibility of the overlying ground (overburden) rupturing provided that a cavity is actually present. Thus, the latter susceptibility of the rupture process of the overburden is assessed in a "worst-case" situation because the presence of a cavity, i.e. the presence of void, is an additional factor increasing the ground rupture tendency.

From a mathematical point of view, the operation consisting in merely multiplying both susceptibilities to obtain the final collapse susceptibility implies that the two considered events are independent. This can be justified by the application of the Bayes theorem (see Eq. (1)) considering that the presence of a cavity given the occurrence of a collapse event can be considered "certain" (i.e. the susceptibility is one).

As an illustration, a voluminous cavity below a massive resistant granitic overburden will present no surface risk. Conversely, a thin fractured and weathered limestone cover will not contain the propagation of instability, provided that a cavity can exist at the same place. Notice that although we focused here on brittle deformations that are the more damaging for the surface, such an approach could also be applied to plastic deformations that control ground instabilities such as settlement or subsidence.

2.2. Principles of the methodology

The study area is divided into homogeneous sectors for each of which one calculates a susceptibility index. The desired susceptibility index (here, that of the collapse susceptibility, CS) derives from two susceptibility values (here PS and RS) assessed in parallel as outlined in Fig. 1. The calculation of each value is a three-step process involving:

- Step 1: an inventory of existing data and a collection of information (geological and historico-economic) on the local context. This step is described in Section 2.2.1;
- Step 2: a list of relevant controlling factors (i.e. criteria) identified by experts from Step 1, the expertise being the central aspect of the method. This step is described in Section 2.2.2 and the key role of expertise is further discussed in Section 2.3;
- Step 3: a specific susceptibility map for each identified criterion starting from a quantitative index (for which the calculation method is described in Section 3 and illustrated in Section 4.3).

Such an approach is easily integrated into a GIS (Geographic Information System) and the final collapse susceptibility map is then