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Susceptibility mapping of instability related to shallow mining cavities in a built-up environment

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ABSTRACT

Anthropogenic activities and urbanization frequently spread over areas underlain by unstable karst ground or man-made cavities, leading to potential risk situations for buildings, infrastructure and population. The roof of the cavities may rapidly propagate upwards, eventually resulting in progressive ground settlement and/or sudden collapse. These processes are frequently accelerated or triggered by various human activities (e.g., overloading, water recharge, water table decline). In this paper, the susceptibility to instability of artificial cavity networks under an urban area in Apulia Region, Southern Italy, was assessed and evaluated. Here, there is dense network of underground quarries excavated for the extraction of massive calcarenite for building and ornamental stone that are currently affected by severe instability problems. Identifying the zones of the cavities most prone to instability is of great practical importance. Susceptibility models have been developed analyzing the statistical relationships between the cavity sections with evidence of instability and a number of predisposing factors mainly related to the 3D geometry of the voids, roof thickness and the presence of overloads. The models produced by the discriminant analysis and the logistic regression approaches were independently and quantitatively evaluated through the construction of ROC curves. Although the two models are characterized by different input data treatment, as the logistic regression allows using continuous and discrete variables or any combination of both types even if they do not have a normal distribution, the ROC curves highlighted, for both methods, a satisfactory congruence between the model results and the observed data. Consequently, from the model performance analysis, the two models were evaluated comparable in terms of result reliability. The methodology should be considered as a general first-level analysis for near surface underground cavities aimed at identifying critical cave sectors that can be the focus of more detailed analyses, especially those associated with sensitive zone related to the presence of buildings, roads and frequent presence of human activity.

1. Introduction

Over the last decades, the investigations dealing with ground instability problems in urban areas related to natural caves (Ballard et al., 1982; Sarman, 1983; Waltham, 1993; Van Schoor, 2002; Gutiérrez and Cooper, 2002; Alberto et al., 2008; Gutiérrez et al., 2008, 2009; Abu-Shariah, 2009; Gutiérrez, 2010, 2016; Fidelibus et al., 2012; Gómez-Ortiz and Martín-Crespo, 2012; Papadopoulou-Vrynioti et al., 2013; Pueyo Anchuela et al., 2015) and anthropogenic voids (Smith and Rosembaum, 1993; Hawkins and McDonald, 1994; Fasani et al., 2011; Martínez-Pagána et al., 2013; Abbasnejad et al., 2016) have increased substantially. The most common natural cause of subsidence addressed in those contributions is the presence of karst cavities, and in many case histories the instability processes are either accelerated or triggered by human factors. Several procedures have been proposed for assessing and mapping sinkhole susceptibility, as well as for evaluating quantitatively and independently the prediction capability of the models (e.g., Galve et al., 2009a, 2009b, 2011). Moreover, recent papers illustrate the practicality of constructing sinkhole magnitude and frequency relationships (hazard curves) for specific areas (Taheri et al., 2015; Gutiérrez and Lizaga, 2016; Gutiérrez et al., 2016). Currently forming sinkholes in karst areas are not necessarily related to active dissolution. They may be the surface expression of the upward propagation of cavities by roof collapse (stoping) above a relict karst system or anthropogenic voids.

The assessment of the susceptibility to instability processes in areas underlain by artificial underground cavities has been scarcely explored in the literature. The presence of such voids, especially where they are located at shallow depth beneath built-up areas, may constitute a significant threat for the integrity of engineering structures and human safety. Upward propagating cavities and the consequent ground subsidence may severely damage any human-built structure and may even cause life losses by swallowing people or causing the collapse of the structures

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occupied by them. Apulia region (Southern Italy), covering 19,345 km^2, is strongly impacted by sinkholes induced by natural and man-made cavities. The presence of widespread cavity networks is very common on both sides of the Murgia plateau. A total of 3533 underground cavities have been inventoried by the Apulia Speleological Federation, 1112 of which are anthropogenic. The high number of subsurface cavities is related to the geological characteristics of the territory, in combination with the historical, cultural and religious background. Some areas underlain by thick and laterally continuous calcarenite formations have dense networks of mine galleries excavated in the past in order to create spaces for housing, religious places, and shelters for animals, as well as for quarrying rock blocks for construction. The assessment of the short-term and long-term stability of underground quarries can be carried out using data from stable (positive) and unstable (negative) cave sections and applying statistic or even heuristic approaches. Deterministic procedures require the expensive and time-consuming acquisition of a great deal of information on the rock properties and the geometry of the cavities, and generally simplify the complexity of a non-static phenomenon. A recent study by García-Gonzalo et al. (2016) present an approach for designing the span of entry-type mining excavations producing stability graphs on the basis of learning classifiers.

In Apulia region the greater concentrations of man-made cavities are located in the urban areas of Canosa, Cutrofiano, Altamura, Gravina and Ginosa. This investigation is focused in Altamura, due to the presence of a widespread cavity network (ca.18 km), the availability of geometrical surveys of the cavities, and the considerable number of reported instability cases.

This contribution analyses and assesses the ground instability conditions related to networks of underground artificial cavities in the urban area of Altamura (Apulia). Here, since the Middle Ages, extensive underground mining was carried out in the northeastern sector of the city, aimed at extracting calcarenite blocks, thus producing large and irregular cavity systems. The underground mining zone covers an area of approximately 6490 m^2 and the depth of the cavity roofs ranges from 5 m to 25 m. These mine galleries have been progressively abandoned and knowledge on their spatial distribution has vanished through time. Up to the 1960s and 1970s, most of the cavities were overlain by a sparsely populated suburban portion of Altamura. Currently, due to recent urban expansion, the largely unknown cavities underlie a densely developed built-up area. Over the last few years, the occurrence of several damaging collapse sinkholes has triggered the attention towards the hazards associated with mine galleries. The instability of these voids is adversely affected by both the natural degradation of the rock mass (e.g., development of unloading cracks, weathering) and various human activities (e.g., deep foundations, water infiltration).

Knowledge on the distribution of potentially unstable zones within the mines is of paramount importance for preventing damage and managing potential risk situations. The susceptibility to instability processes within the mine galleries (e.g. relative spatial probability of cave instability) is assessed and mapped by means of two statistical multivariate methods: discriminant analysis and logistic regression. These approaches allow assessing and mapping susceptibility to cavity instability by analyzing the statistical relationships between the known instability phenomena (cavity sections with evidence of instability) and a number of environmental and anthropogenic factors that control their distribution. These two multivariate statistical methods have been widely applied to various hazardous ground instability processes, notably landslides (Carrara, 1983; Ercanoglu et al., 2004; Suzen and Doyuran, 2004; Carrara et al., 2008; Nandi and Shakoor, 2009; Pellicani et al., 2014). However, the application of those statistical methods for producing spatially-distributed susceptibility models, largely based on the distribution of objective evidence of instability, has been barely explored in the scientific literature. The most common approach is to focus the stability analyses to specific sites applying deterministic methods and mechanical simulations. Furthermore, the use of multiple methods allows to compare their performance in terms of reliability of the predictions. That allows the identification of the method with the best quality/effort ratio. In this work, the susceptibility assessments were carried out using a portion of the known cavity sections with evidence of instability (training set). Subsequently, model performance has been evaluated by comparing the distribution of the remaining unstable sections (test set) with the resulting susceptibility maps. ROC curves were generated to estimate quantitatively and graphically the prediction capability of the models (Metz, 1978; Fielding and Bell, 1997; Drummond and Holte, 2004; Brenning, 2005; Gorsevski et al., 2006).

2. Material and methods

2.1. Geological setting

The city of Altamura is located in Apulia region, southern Italy, at around 485 m a.s.l. Form the geological perspective, it is situated in

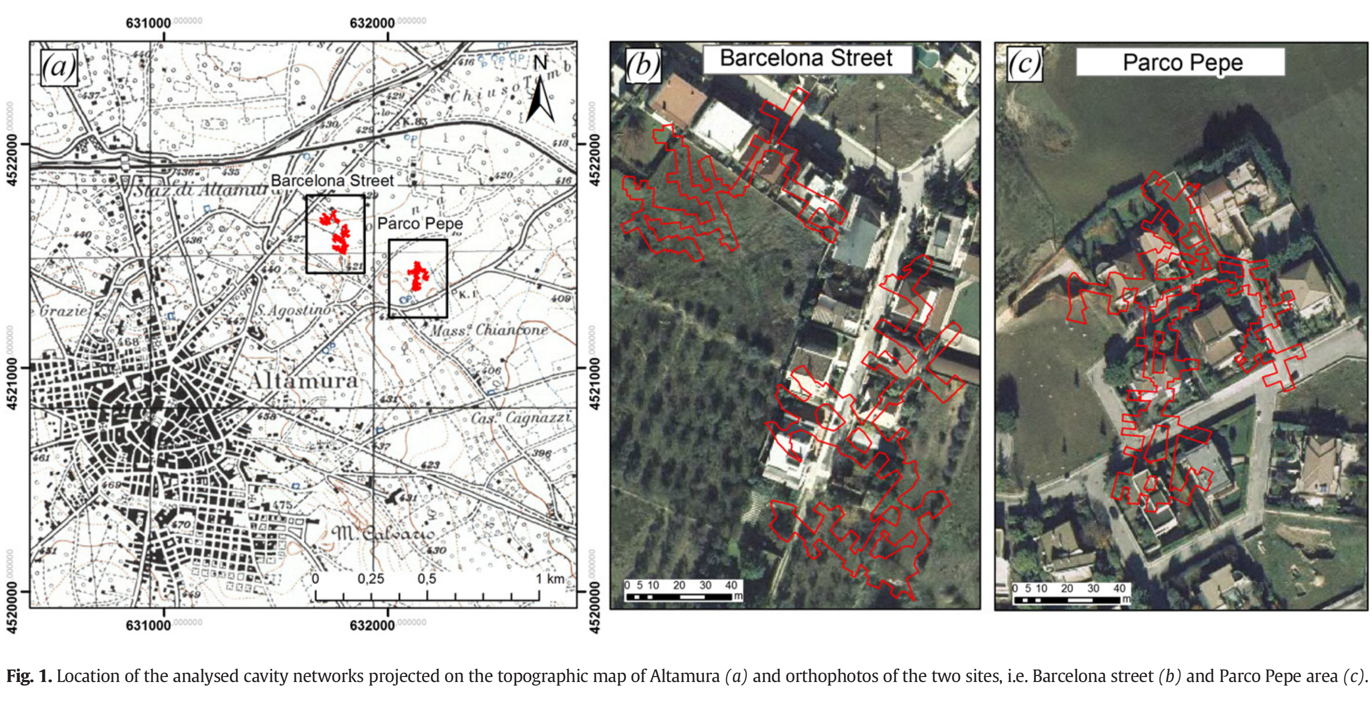

Fig. 1. Location of the analysed cavity networks projected on the topographic map of Altamura *(a)* and orthophotos of the two sites, i.e. Barcelona street *(b)* and Parco Pepe area *(c)*.