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A three-dimensional back-analysis of the collapse of an underground cavity in soft rocks

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ABSTRACT

The assessment of stability of man-made underground caves, excavated in the past and later on abandoned, represents a serious challenge for land and urban planning operations, especially for the areas of possible interaction of the caves with overlying structures and infrastructures. Several areas of Southern Italy are characterized by the presence of abandoned underground quarries for the extraction of soft calcarenite rocks, which now threatens the overlying environment due to the risk of collapse and the consequent generation of sinkholes. This work presents a back-analysis of a sinkhole occurred in 2011 in the town of Marsala, caused by the collapse of an underground quarry, as a representative case study of these phenomena. Based on the available geometrical and geological dataset as well as the field observations of the phenomenon, in this article the assumptions and the results about the genesis of the 2011 sinkhole, as derived from a three-dimensional finite element back-analysis aimed at reconstructing the stress-strain evolution that brought to the ground failure collapse, is discussed. In particular, the 3-D numerical analyses have been performed in order to identify the factors responsible of the genetic mechanism of the sinkhole. The finite element analysis has been carried out by accounting for the geotechnical characterization of the Marsala calcarenites derived from both specific laboratory tests performed on samples taken from the site and literature data available on the same rock material; the numerical results have been then validated by means of the comparison with field observations and also compared with those achieved through a 2-D model of the same case study.

1. Introduction

The assessment of stability of man-made underground caves, which were excavated in the past and then abandoned afterwards, and the consequent evaluation of possible sinkholes, represent a serious challenge for land and urban planning purposes. The importance of assessing the stability conditions of a specific cave system is also related to the eventual interaction of the cave with overlying structures and infrastructures at the ground surface (Waltham et al., 2005; Parise and Gunn, 2007; Gutierrez et al., 2014). Recent case studies of the collapse of man-made underground caves affecting urban areas have been proposed in the literature, as for example those involving the calcarenite caves in Southern Italy (Delle Rose et al., 2004; Parise, 2015; Parise and Lollino, 2011; Lollino et al., 2013; Pepe et al., 2013; Vattano et al., 2013, 2015), the bell-shaped caverns in Israel (Bètournay, 2009), the metal mining caves in Canada (Hatzor et al., 2002), the siltstone Longyou caverns in China (Li et al., 2009;), an abandoned limestone mine in Korea (Sunwoo et al., 2010), and the limestone mines in the Netherlands and Belgium (Bekendam, 1998). In particular, it is well documented that underground quarries and mines definitely represent the most dangerous categories of artificial cavities (Galeazzi, 2013; Parise and Vennari, 2013), highly prone to produce subsidence and sinkhole effects at the surface.

Underground cavities within soft rock masses are frequently involved in failure processes in the long term, i.e. many years/decades after the end of excavation, due to environmental weathering processes involving the soft rock. For example, as regards soft calcarenite rocks belonging to the Calcarenite di Gravina Formation cropping out in Apulia (Southern Italy), Ciantia et al. (2015a, 2015b) indicate two main types of degradation processes of the calcarenites due to environmental weathering: 1) a short-term debonding, occurring during the material saturation, when depositional bonds are destroyed by simple contact with water and fall into suspension; 2) a long-term debonding, occurring when calcarenite remains in contact with water for a long period of time, during which diagenetic bonds are chemically dissoluted until becoming a calcareous soil. The assessment of stability of underground

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caves becomes really complicated for the case of room-and-pillar cave systems, for which the existence of a complex problem geometry, the occurrence of complex boundary and loading conditions for the cave system as well as the change of the same boundary conditions with time, which brings about the degradation of the rock material properties, do not allow for the use of simplified approaches, while requiring, on the other hand, more sophisticated methods to cope with. The assessment of cave stability is traditionally faced by means of simplified empirical, phenomenological or analytical approaches, which require significant assumptions regarding the failure mechanism of the cave, and therefore can be adopted with a certain degree of confidence only in the case of the assessment of local stability, as the stability analysis of single pillars, or of single rock beams representing the local portion of a roof. This becomes even more complicated in the case of heterogeneous, and/or karstified, rock masses (Andriani and Parise, 2015). However, these methods are generally not adequate to account for all the main factors governing the problem and therefore their use should be limited only to specific cases for which the schematization is acceptable, since they cannot account for variable geometries or heterogeneous deposits, as well as they cannot provide any information regarding the stress state, the strain level or the potential failure mechanism of the involved rock mass (Tharp, 1995; Diederichs and Kaiser, 1999a, 1999b; Liu et al., 2000; Hutchinson et al., 2002; Lollino et al., 2004; Suchowerksa et al., 2012). In recent years, numerical modeling has provided a powerful tool to explore the stress-strain state within the rock mass around the cave and the corresponding displacement field induced by a specific loading condition or a change in the boundary conditions, also adopting non-linear constitutive models for the rock material. Moreover, nowadays the availability of three-dimensional numerical codes, due to the empowered capacity of the computing machines, allows for the development of three-dimensional models that can simulate properly the evolution of the stress-strain state of the rock mass to the failure conditions (Canakci, 2007; Fraldi and Guarracino, 2009; Ferrero et al., 2010; Ciantia et al., 2015c; Luisi et al., 2015).

Many built-up areas of Sicily (southern Italy) are characterized by underground caves potentially affected by the risk of failure. In particular, the urban area of Marsala (western end of Sicily, Fig. 1A) was affected in the past decades by several collapse phenomena that caused extensive damages to people and infrastructures (Bonamini et al., 2013; Parise and Vennari, 2013; Vattano et al., 2013, 2015). These phenomena are related to the presence of underground quarries for the extraction of calcarenites to be used as building materials. The cavities are carved at depth varying from 10 to about 25 m below ground surface, and are distributed on a single or superimposed layers, following the well-known excavation technique of "room-and-pillar", i.e. chambers and passages separated by rock pillars (Hutchinson et al., 2002; Aydan et al., 2005). However, excavation typically occurred without any planning. With time, the underground quarries were progressively abandoned for several reasons (i.e., interaction with percolating water, decay of the physical-mechanical properties of the rock, high costs, problems and risks related to the excavation operations). Nowadays, signs of instability can be clearly recognized along ceilings, walls and pillars within many cavities. These instabilities easily propagate upward, causing sinkhole and subsidence phenomena according to the mechanisms described in Parise and Lollino (2011), thus creating consistent damages to buildings and infrastructures.

In particular, a sinkhole that occurred in June 2011, affecting an area characterized by an underground quarry system in the eastern sector of Marsala, is described in this paper as a representative case study (Figs. 1B and 2A–D). The site was selected for the availability of geometric data of the underground quarry as resulting from a topographic survey carried out in 2000, prior to the occurrence of the sinkhole, which were useful to define the genetic mechanisms of the instability process. During the 2000 survey, various signs of instability, such as open fractures and detachment of large blocks, had been already observed on the cavity roofs and along the pillars. After the sinkhole, new surveys were conducted inside the quarry aimed at collecting additional data to reconstruct the whole failure mechanism and improve the understanding of the factors that had played a role in the generation of the sinkhole. Since the collapse occluded many of the remaining rooms (Fig. 2D), the post-sinkhole 2011 surveys were limited to the western sector of the quarry. Detailed surface topographic surveys were conducted in the following months to detect new signs of collapse or movements of the topographic surface.

Based on the available dataset acquired for the specific case study, in this article we intend to describe the geological and structural features of the site, and discuss both the assumptions and the results about the genesis of the 2011 sinkhole as derived from a three-dimensional finite element back-analysis aimed at reconstructing the stress-strain evolution that brought to the ground failure collapse. The finite element analysis has been carried out by accounting for the geotechnical characterization of the Marsala calcarenites derived from both specific laboratory tests performed on samples taken from the site and literature data available on the same rock material (Arces et al., 2000; Zimbardo, 2016; Zimbardo, 2016); the numerical results have been then validated by means of the comparison with field observations. The numerical modeling was implemented following a similar procedure applied in other site studies in southern Italy (Parise and Lollino, 2011; Parise, 2012; Lollino et al., 2013) and the results of the 3-D model have been also compared with those achieved through a 2-D model of the same case study (Vattano et al., 2015).

2. Case study: the collapse of the Marsala Panatletico cavity in 2011

From a geological point of view, the Marsala area is characterized by outcropping of the Lower Pleistocene Formation called "Calcarenite di Marsala", referred to the Marsala syntheme.

The formation consists of three main lithofacies, showing both

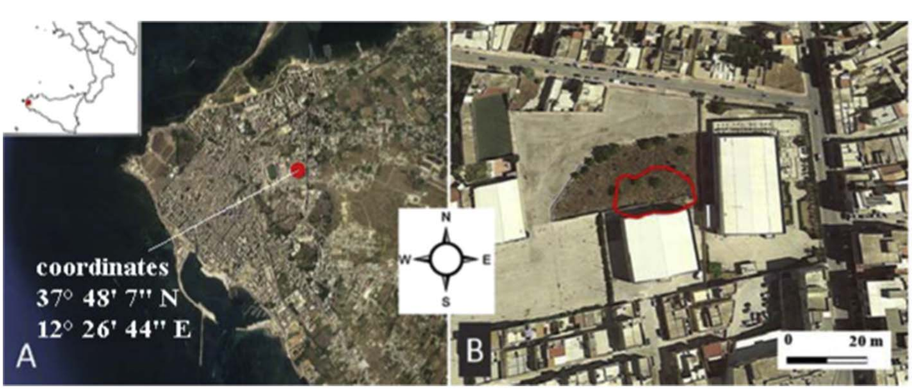

Fig. 1. A) Google earth view of the Marsala city, with indication of the 2011 sinkhole area (in red); in the inset, location of the Marsala area; B) detail of the sinkhole area with indication of the sinkhole perimeter and the buildings nearby. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)