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Michal Filippi

Pavel Bosák

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KATALOGIZACE V KNIZE - NÁRODNÍ KNIHOVNA ČR

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Cover photos (some photos were adjusted/cropped)
Top left – A gallery along the "Rio de los Venezuelanos" in the Imawarì Yeuta Cave system in quartz sandstones, Auyan Tepui, Venezuela. Photo V. Crobu. For details see the paper by Sauro et al.
Top right – The 15th siphon of Ramo Nord in the Grotta del Bue Marino, Sardinia. Photo by R. Husák. For details see the paper by D. Hutňan.
Bottom left – Using an Xbox Kinect equipment to survey a cave. Photo by J. Gulley. For details see the paper by Covington et al.
Bottom right – Inclined workings of the Voskresenskyi Mine, Ural Mountains, Russia. Photo by A. Gunko. For details see the paper by A. Gunko.

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RECOGNITION OF INSTABILITY FEATURES IN ARTIFICIAL CAVITIES

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Instability features may be observed in underground settings, including both natural and artificial caves. Recognition, mapping and documentation of such elements is of crucial importance to understand the likely evolution of the caves in terms of instability, and to evaluate the possibility of a direct involvement of the built-up areas above. Many towns and important communication routes are located in Italy above caves, which makes knowledge of the instability conditions an absolute priority for civil protection issues and land management. The role of cavers in the identification of instability features has been rarely taken into account, and always considered as a minor, often unnecessary, element in the stability assessment. Nevertheless, cavers are the only "eyes" underground, and have the opportunity to document what is really occurring. The present article aims at pointing out this crucial role of cavers, and illustrates some of the most common instability features in underground settings, both related to already occurred failures and to incipient signs of deformations. The issue is dealt with focusing on artificial caves, since these have been in the last decades at the origin of several problems in many towns and rural areas of southern Italy.

1. Introduction

Cavers carry out an activity that is often lowly considered, or thought of in negative terms because of the breaking news reporting accidents involving difficult and high-cost rescue operations. Nevertheless, caving has a very important value: cavers are the only people having the possibility, due to their technical skills and ability to move in a subterranean environment, to explore and document the underground world in safety. Documentation, in particular, is extremely important, since it provides all those people that are in charge of decisions (local authorities, land use planners, etc.) but never will directly enter a cave, the necessary material (maps, photographs, videos) to make their own choices.

Even more than for natural caves, the matter becomes of extreme importance for artificial cavities, since these are more frequently located below or in the proximities of inhabited areas or infrastructures. As a consequence, any problem occurring within the underground setting may have direct, sometimes catastrophic, consequences, on the built-up areas above (Waltham and Swift 2004; Parise and Gunn 2007; De Waele et al. 2011; Parise 2012).

Starting from these considerations, the present article intends to point out the importance of cave surveying, mapping and documentation, with particular regard to all those elements related to instability processes that can be observed in natural and artificial caves (Andrejchuk and Klimchouk 2002; Palmer 2007). Being well aware that instability phenomena are rarely sudden, but in most of the cases they are preceded by deformations, it comes out that having the possibility to collect direct observations about the precursory signs of failures may result in the possibility to understand what is going on underground, predict the likely evolution toward the ground surface, and plan interventions to reduce the hazard, or at least to mitigate the risk to people and society.

The present article will illustrate both features related to already occurred instability, and incipient signs of deformations. The combined analysis of these elements might be useful, together with the necessary geotechnical data about the involved materials, to determine the most suitable geological model for instability evolution at the specific site. It is our firm opinion that such documentation is crucial for understanding the instability problems, but, at the same time, cannot be considered the only scientific material on which to base a practical mitigating action.

Figure 1. Massive fall from the vault in a calcarenite quarry.

2. Natural vs. artificial caves

The issue of instability is of interest for both natural and artificial caves, and as such a number of studies have been published over the years in the speleological scientific literature in the attempt to describe and model the process (Davies 1951; White and White 1969; Palmer 1991; White 2005). However, the direct link existing between many artificial cavities and the environment at present used by man for his activities make artificial cavities of particular interest, since these are generally the type of underground voids creating problems, and causing economic losses and damage, to the society. The recent cases of a sequence of collapse sinkholes at Guatemala City in 2006 and 2010 is straightforward at this regard (Hermosilla 2012).

With this, it is not our intention at all to diminish the relevance of instability observations carried out in natural caves. Some of the most common processes of cave evolution, for instance, derive from progressive failures in the rock mass constituting the roof of the cave, until reaching the ground surface, and thus originating collapse sinkholes (Tharp 1995; Klimchouk and Andrejchuk 2002; Delle Rose et al. 2004; Canakci 2007; Waltham and Lu 2007; Parise 2008). Observing and documenting features related to such processes is of crucial importance, for both the understanding of the cave evolution, and the likely consequences this may have in terms of risk as well. But the focus will be in this article essentially on artificial caves, since these are those that have produced the greatest alarm and worrying in many regions of southern Italy during the last 15–20 years, due to a number of sinkholes that had to be recorded in Apulia, Campania and Sicily (Parise and Fiore 2011).

3. Mapping instability features

Due to the geological and morphological setting, many regions of southern Italy presented features such as to allow man since historical times to excavate and use several types of the local rocks for building purposes, and to create underground voids for different uses (Del Prete and Parise 2013). As a consequence, wide areas are characterized by the presence of a huge number of man-made cavities, that have to be added to the natural caves, present in the same regions because of karst processes. As concerns Apulia, the most extensive systems, and the most dangerous in terms of instability, are represented by underground quarries, located at variable depths in a high number of towns, even below urban areas (Parise 2010). The working activity stopped in most of these quarries few decades ago, and since that time many sinkholes have been recorded, due to upward propagation of failures occurring within the underground sites (Parise 2012).

Evolution of instability processes in underground caves is generally dependent upon internal factors, such as the low mechanical strength of soft rocks (Andriani and Walsh 2006), or external natural and/or anthropogenic factors that can modify the boundary conditions, the loading, or the physical and mechanical properties of involved materials. Changes in loading can be, for instance, represented by construction of buildings or infrastructures above the ground surface, that can modify the stress state around the cave, the destruction of pillars within underground rooms with consequent increase in the cave span, as well as seismic loading conditions or man-made vibrations due to traffic, construction works, etc. Changes in the boundary conditions may be represented by the variation of the wetting conditions within the cave due to large incomes of water inside the cave, to condensation processes, and to water percolation from the ground surface. These processes generally promote weathering processes of the rock mass and of the joints leading to a gradual reduction of the corresponding mechanical strength, as also observed in many cases of slope instabilities worldwide (Fookes and Hawkins 1998; Zupan Hajna 2003; see also Calcaterra and Parise 2010, and references therein).

Underground caves can be involved in instability processes affecting the whole overburden, or simply by local failures that may induce a progressive increase in the height of the cave up to eventually reaching a critical configuration which later on can develop towards the complete collapse. The failures or instability mechanisms observed in many caves of southern Italy may be described by grouping them into two main categories (Diederichs and Kaiser 1999a, 1999b; Hatzor et al. 2002; Ghabezloo and Pouya 2006): failures within continuous media (intact rock mass or highly jointed rock mass), and failures within discontinuous media (anisotropic rock mass with specific joint sets). Whilst the first category characterizes soft rock masses such as calcarenites, chalk, and evaporites, the second one relates to stratified and fissured limestone rock masses affected by karst.

Figure 2. Examples of detachments from the vault of natural caves.

In the following we describe the main mechanisms of failure that can be observed in caves:

Falls from the vault, developing the formation of a single or double arch. This type of failure can be generated by a reduction of the rock strength in the cave roof due to wetting or additional loading. The strength of the rock forming the roof reduced down to the maximum stresses existing in the area, leading to the development of the first fractures. These new joints may propagate through the roof, leading to a complete or local failure mechanism (Fig. 1). This process has also been observed in natural caves, where is characterized by the failure of the central part of the roof and the consequent collapse of blocks from the same area which is followed by failure of the remaining ledges along the sidewalls (Lollino et al. 2004; Lollino and Parise 2005; Parise and Trisciuzzi 2007). The resulting shape in the roof is generally circular, but it may have one or more rectilinear sides, due to control exerted by tectonic discontinuities. Further evolution may lead to upward stoping, with size of the failure decreasing toward the ground surface (Fig. 2).

Falls from the vault, due to lack of support from previously existing pillars. This type of fall is actually an induced failure, since it occurs with the same mechanism as above, but generated by failure of one or more pillars, so that the roof span becomes too long to be sustained by the rock strength (Hutchinson et al. 2002; Fraldi and Guarracino 2009; Ferrero et al. 2010).

Failures from the pillar corners. This type of failure is generated by local accumulation of compressive stress too high with respect to the rock strength (Fig. 3).

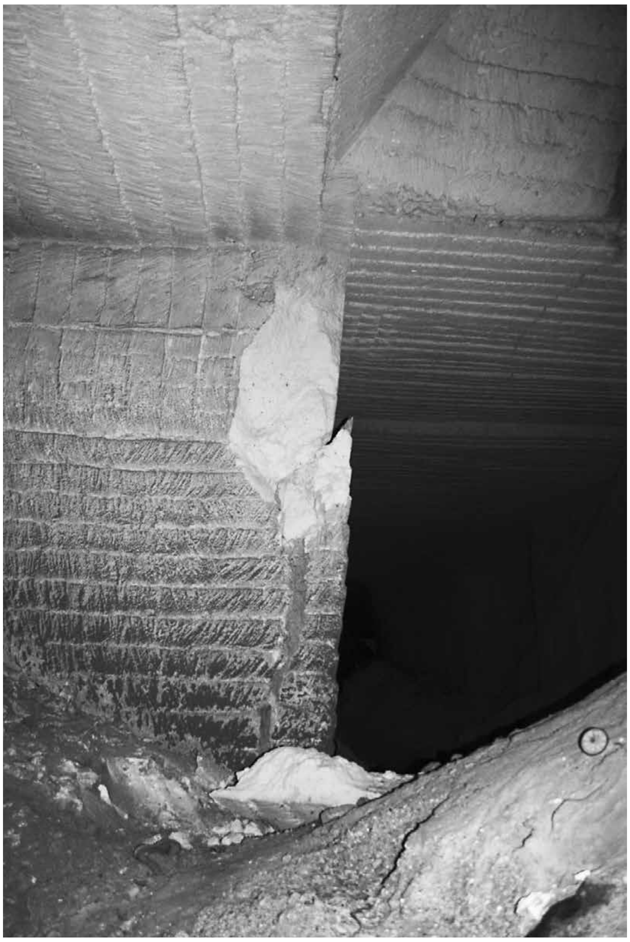

Figure 3. Failure at the upper corner of the pillar.

Lateral failures along sliding surfaces parallel to the walls. This mechanism is generated by the low confinement of the rock mass along the vertical boundaries of the cave, which leads to the development of fractures parallel to the direction of the maximum compressional stress (Fig. 4). This process generally is not directly at the origin of a sinkhole, but may work in producing the progressive enlargement of the cave until it reaches a critical configuration which then leads to general failure.

4. Upcoming instabilities: the incipient signs of deformations

Failures in underground caves do not occur without warning, and measures of the effects produced by the processes active in deforming the rock mass can be generally observed before major displacement occurs (Liu et al. 2000). This has also been documented for slope failures (D'Elia et al. 1998; Senfaute et al. 2003), and is at the origin of the design and implementation of alert system for landslides. As concerns underground caves, the main problem lies in the possibility to observe and recognize such phenomena. Further, it has to be noted that scarce attention has been given in the scientific literature to the issue of precursory signs, as pointed out by Szwedzicki (2000).

Figure 4. Lateral failures from the wall in a calcarenite quarry. Note the development of linear sliding surfaces.

Many studies have documented that the structural damage in the rock mass, eventually leading to collapse, requires a long time, and generally occurs through gradual progression in time, intensity, and appearance of recorded precursors. These latter, in the early stages of deformation, may consist of surface cracking, crack opening, shear movement along planes of weakness or vertical and horizontal displacement (Kowalski 1991; Parise and Lollino 2011). Further evolution of the process may lead to ground surface subsidence and the occurrence of localized signs of stress within the underground caves, in the form of floor heaving and roof lowering. In some cases, the last hours before the final collapse have been accompanied by rock noises and falls in the ground.

In the following we describe the main evidence of deformations that can be observed in caves:

Cave walls. Localized swelling can be observed along the walls as a result of pressure by the rock mass close to the cave boundaries (Fig. 5). It may be noticed as aligned bulging and slight deformation, which as a whole bound the sector prone to failure. Locally, the increasing deformation results in outward protrusion of wedges, or, eventually, in a continuous fracture bounding the mass detached or prone

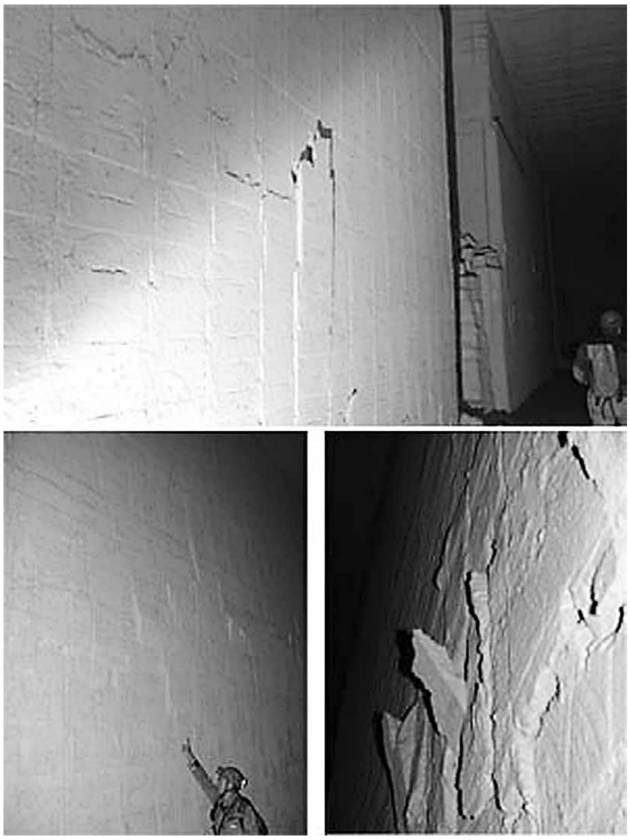

Figure 5. Incipient signs of instability: localized swellings (above, and lower left), and wedges protruding from walls (lower right).

to be detached. All of this generally precedes occurrence of local failures in the wall, with sliding surfaces parallel to the wall itself.

Pillar corners. Regardless of the size of pillars, different stages of deformation may be observed at the corners of pillars: the first are *en echelon* cracks (Fig. 6), from incipient to a few mm in aperture, similar to those observed at the flanks of active landslides as precursory sign of the exposure of the sliding surface at the ground (Fleming and Johnson 1989; Parise 2003). Progression in the deformation brings to developing a well-defined fracture, thus preparing the upcoming detachment, which may occur at the base or at the top of the pillar, or along its entire height. When the vertical stress becomes unsustainable for a pillar, open cracks may develop, even along pre-existing discontinuities, and a network of crossed fractures may be formed (Fig. 7).

Figure 6. Examples of cracks developing at the pillar corners.

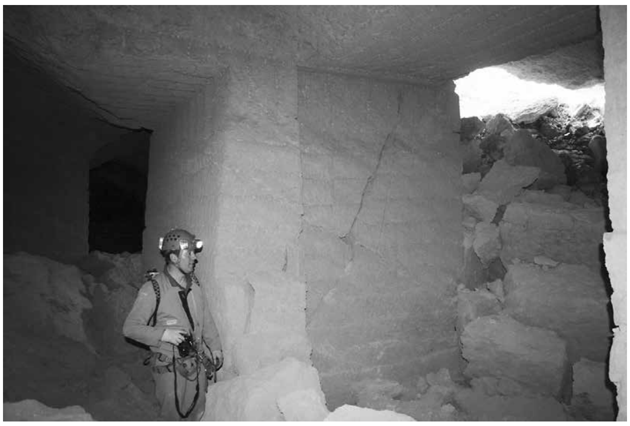

Figure 7. Cracks crossing a pillar, along primary (clino-stratification, dipping to the right in the picture) and secondary (open cracks) discontinuities.

Vault. Precursory evidence of failure appear in the vault as long and continuous cracks, locally opened a few mm, and often ending in an already occurred fall (mostly located at the crossing between two discontinuity systems; Fig. 8). Massive falls from the vaults may determine the formation of a single arch covering the whole span of the cave, or of a doube arch in the case a more resistant spur in the rock mass subdivides the detached area (Fig. 9). On the basis of the data so far collected, no clear relationship has been ascertained between shape and size of the passage and the development of a single or double arch.

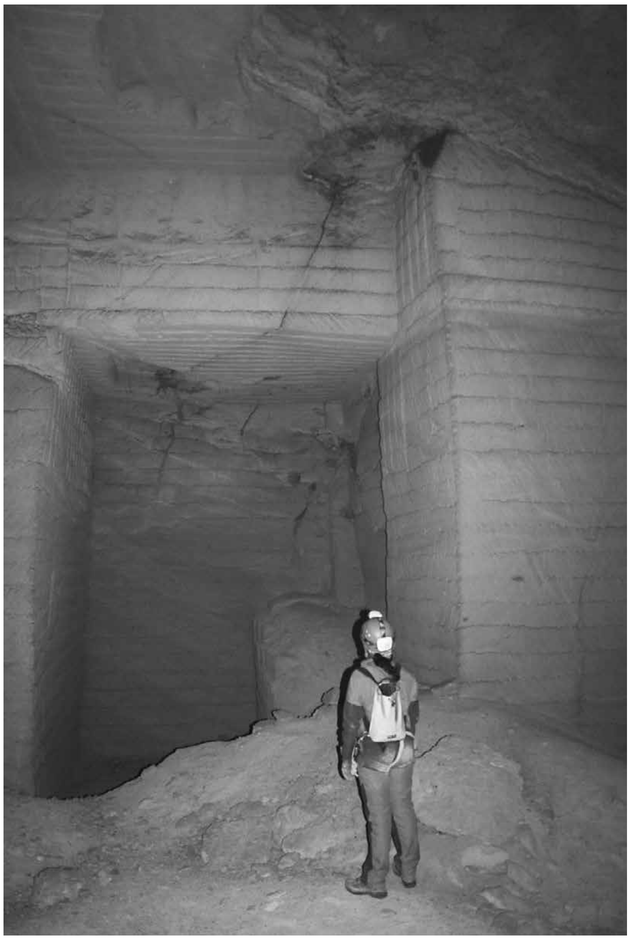

Figure 8. Fall from the vault, occurred at the intersection between two discontinuities.

Figure 9. Double (above) and single (below) arches produced by failures at the vault.

5. Conclusions

There are of course several topics that have not been dealt with in the present article. First of all, the type of failures depends also upon type and characteristics of rocks. In this sense, there are great differences among hard rocks as limestones, and soft rocks as calcarenite, and in turn between carbonates and evaporites, which respond to stresses with more plastic behavior (Iovine et al. 2010; Fig. 10). All these should be properly taken into account for evaluating the stability conditions of underground voids, and the likely evolution to sinkhole occurrence.

Nevertheless, aimed at an audience of cavers, the focus was here dedicated to direct observations in caves, that are considered a precious, and very difficult to obtain, element in the evaluation of the hazard related to failures occurring in underground settings.

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Figure 10. Plastic and fragile deformations in evaporite rocks of a gypsum cave of Calabria.