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Structure and evolution of collapse sinkholes: Combined interpretation from physico-chemical modelling and geophysical field work

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ABSTRACT

In karst rocks (limestone, anhydrite, gypsum, etc.), water flowing through fissures and bedding partings can enlarge voids either by physical or chemical dissolution. Within a geologically short period of time, the increase in void space creates a large secondary porosity typical for soluble rocks, which is responsible for preferential flow through the karst rock, often through cave systems with passages reaching the meter-scale and more. This large-scale voids in the sub-surface can initiate collapse of the overburden, either through wall or roof breakdown, and the initial void created by dissolution can migrate upwards and finally cause a surface collapse and create a collapse sinkhole. While the dissolution part of this evolution is in the order of 10,000–100,000 years, the final mechanical collapse can occur on time scales of days.

We have studied a typical collapse sinkhole site in the southern Harz Mountains in Germany, with anhydrite (partly converted to gypsum) as soluble rock in the sub-surface. We discuss geophysical measurements (gravity, electrical resistivity tomography, self potential, magnetics) from the location to identify the local collapse sinkhole signal and the possibility to separate the collapse sinkhole signal from the broader geological signal of the study site. We model the initiation of sub-surface voids with our numerical tool KARSTAQUIFER, a 3D karst evolution model describing flow and dissolution in karst rocks. We apply this numerical model to predict collapse sinkholes in a locality in the Harz Mountains.

1. Introduction

Collapse sinkholes are closed depressions caused by a collapse of the ground underlain by a cavity. They vary significantly in morphological shape and size, being either cylindrical, conical or bowl-shaped, with diameters between 1 and 500 m and a depth extent between 1 and 600 m (see Williams, 2004, for an overview). Several processes are responsible for collapse sinkholes, e.g. the *collapse of cavities* in soluble bedrock regions or the *suffosion of cave deposits* into artificial sub-surface voids. Collapse sinkholes pose a substantial hazard both for life and infrastructure, therefore knowledge about their origin and evolution will help to understand their causes and probably provide methods for mitigation.

Collapse sinkholes have been interpreted as a sub-group of sinkholes, which more generally can be classified into (e.g. Waltham and Fookes, 2003; Waltham et al., 2005; Gutiérrez et al., 2008a,b; 2014):

- *Solution sinkholes*, created by surface lowering in soluble rocks due to uneven dissolutional removal at the surface. Water dissolves rock in the vadose zone along near-vertical fissures, which then capture flow and transmit the water to the phreatic zone. As the surface lowering is a rather slow and continuous process, no sudden collapse is expected in the case of solution sinkholes.
- *Collapse sinkholes*, originating from sub-surface cavities, which result from dissolutional enlargement of fractures and bedding partings in soluble rocks. Once the sub-surface cavity reaches a certain size, the cavity roof can become unstable and starts to collapse. The collapsed blocks accumulate on the bottom of the void and can be dissolved in the cave stream if they consist of soluble material. Collapsed insoluble overburden needs to be removed by erosion of the cave stream. The void created by the roof collapse migrates upwards towards the surface, until a thin ledge finally separates the void from the surface, and once this thin ledge becomes mechanically unstable, a collapse sinkhole forms. While the process of dissolving and removing material can take thousands of years and longer, the final collapse may occur suddenly, often without prior warning.

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- *Suffosion sinkholes* as a special form of cover-collapse sinkholes occur in areas with a thick soft sediment cover, which should be cohesive and brittle. Here, sediment migrates into open subsurface voids and cavities by soil creep, and a void gradually develops upwards. The suffosion process occurs on time scales of months and years, however often being terminated by an abrupt surface collapse.

Typical collapse sinkholes in karst regions occur when water percolates through fissures and bedding partings, dissolves soluble rock (e.g. limestone, anhydrite, or gypsum) and enlarges them to voids and cavities. Once such a cavity becomes mechanically unstable, a collapse sinkhole can form. A classical example of a large collapse sinkhole is Crveno Jezero (Red Lake) in Croatia (Fig. 1), a 528 m deep sinkhole, 200 m in diameter. The sinkhole is partly filled with water (water depth 287 m), and is likely to be the result of a cave collapse (e.g. Gabrovšek and Stepišnik, 2011; Andrič and Bonacci, 2014). A substantial submerged cave passage has been found at the bottom of the lake inside Crveno Jezero by diving, and the roof collapse of this cave river has migrated upwards and finally resulted in the collapse sinkhole.

The sudden appearance of collapse sinkholes is a substantial risk in karst regions, damaging infrastructure and agricultural land (e.g. Parise and Gunn, 2007; De Waele et al., 2011, and references therein). Therefore our understanding of sinkhole initiation, evolution and collapse needs to be improved for proper sinkhole risk mitigation. Here, several strategies can be used: (i) Observation of present collapse sinkholes and prediction of future sinkholes from a combination of statistical methods, field work, and remote sensing (e.g. Buchignani et al., 2008; Gutiérrez et al., 2008a,b; Johnson, 2008a,b). (ii) Geophysical mapping of changes in material properties of the ground (density, magnetic susceptibility, electrical resistivity, seismic velocities, etc.) (e.g. Mochales et al., 2008; Dobecki and Upchurch, 2006; Jahr et al., 2008; Auken et al., 2006; Margiotta et al., 2012; Kaufmann, 2014; Kaufmann and Romanov, 2015).

In Fig. 2, the evolution of a collapse sinkhole is shown as a function of time. Initially, the soluble rock beneath an insoluble overburden is part of an unconfined aquifer, with water flowing from left to right (see gradient in phreatic zone). The water flowing through the aquifer is able to dissolve the soluble rock along fractures and bedding partings, preferably around the water table. The

Fig. 1. Crveno Jezero (Red Lake), a large collapse sinkhole in Croatia (Douchko Romanov).