Geomorphology 303 (2018) 393–409

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Rapid subsidence in damaging sinkholes: Measurement by high-precision leveling and the role of salt dissolution

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ARTICLE INFO

Article history:
Received 28 June 2017
Received in revised form 1 December 2017
Accepted 1 December 2017
Available online 7 December 2017

Keywords:
Subsidence monitoring
Sagging
Collapse
High-precision leveling
Transportation infrastructure
Early warning

ABSTRACT

Investigations dealing with subsidence monitoring in active sinkholes are very scarce, especially when compared with other ground instability phenomena like landslides. This is largely related to the catastrophic behaviour that typifies most sinkholes in carbonate karst areas. Active subsidence in five sinkholes up to ca. 500 m across has been quantitatively characterised by means of high-precision differential leveling. The sinkholes occur on poorly indurated alluvium underlain by salt-bearing evaporites and cause severe damage on various human structures. The leveling data have provided accurate information on multiple features of the subsidence phenomena with practical implications: (1) precise location of the vaguely-defined edges of the subsidence zones and their spatial relationships with surveyed surface deformation features; (2) spatial deformation patterns and relative contribution of subsidence mechanisms (sagging versus collapse); (3) accurate subsidence rates and their spatial variability with maximum and mean vertical displacement rates ranging from 1.0 to 11.8 cm/yr and 1.9 to 26.1 cm/yr, respectively; (4) identification of sinkholes that experience continuous subsidence at constant rates or with significant temporal changes; and (5) rates of volumetric surface changes as an approximation to rates of dissolution-induced volumetric depletion in the subsurface, reaching as much as 10,900 m^3/yr in the largest sinkhole. The high subsidence rates as well as the annual volumetric changes are attributed to rapid dissolution of high-solubility salts.

1. Introduction

Active subsidence phenomena caused by natural (endogenous and exogenous) and human-induced processes may affect areas with a broad range of dimensions (<1 m^2–10^6 km^2) and result from a wide variety of deformation mechanisms, which may be characterised by progressive, episodic or mixed kinematics (e.g., Waltham, 1989). The settlement of the ground surface, especially when it occurs in a rapid and differential manner, may cause severe damage on human-built structures and the loss of human lives. An adequate characterisation of ongoing subsidence phenomena should include its monitoring, in order to determine the area affected by displacement, the deformation style, subsidence rates and their spatial-temporal patterns. Subsidence monitoring can be carried out deploying a wide variety of geodetic techniques, both ground-based (e.g., total stations, optical and digital levels, differential GPS) and remote-sensed (e.g., InSAR, LiDAR, photogrammetry). Recently, the investigations dealing with sinkholes have experienced a substantial momentum, largely due to the increasing losses associated with this hazardous process, frequently induced by human activity (e.g., Waltham et al., 2005; Gutiérrez, 2016). It is estimated that karst rocks (carbonates and evaporites) underlie around 20% of the earth's ice-free continental surface (Ford and Williams, 2007). Nonetheless, the precise measurement of subsidence rates in active sinkholes, an essential task for the assessment and management of the associated risks, remains almost unexplored. This fact contrasts with the large number of investigations devoted to the monitoring of other ground instability phenomena like landslides, subsidence related to groundwater withdrawal or mining subsidence. The shortage of sinkhole monitoring data is largely related to the characteristics of the subsidence phenomena in carbonate karst areas: (1) spatially restricted; (2) catastrophic kinematics; and (3) limited spatial and temporal predictability. However, in evaporite karst terrains, where the sagging subsidence mechanism is relatively common, active sinkholes may reach large dimensions, ground settlement commonly operates in a progressive fashion, and deformation rates may reach very high values, especially when related to the dissolution of high-solubility salts (e.g., Frumkin, 2013; Gutiérrez and Cooper, 2013).

Recent papers illustrate the application of the following techniques to measuring ground displacements associated with active sinkholes. (1) On the Israeli coast of the Dead Sea, the analysis of airborne LiDAR (Light Detection And Ranging) data has allowed the quantitative assessment of temporal changes in sinkholes and the detection of precursory

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https://doi.org/10.1016/j.geomorph.2017.12.004

ground settlement preceding the occurrence of collapse sinkholes (Filin and Baruch, 2010; Filin et al., 2011, 2014). (2) DInSAR (Differential Synthetic Aperture Radar Interferometry) has allowed measuring subsidence rates (e.g. Castañeda et al., 2009; Galve et al., 2015a, 2015b) and anticipating the location of future collapse sinkholes using satellite (Nof et al., 2013; Jones and Blom, 2014; Galve et al., 2015a, 2015b) and ground-based data (Intrieri et al., 2015). LiDAR and DInSAR allow the investigation of large areas, but are expensive methods that require complex data processing. Nonetheless, the cost, spatial resolution and accuracy of these approaches are improving rather quickly, together with their benefit/cost ratio. (3) Differential GPS in combination with tiltmeters have been applied to monitor subsidence on a road at the margin of the Bayou Crone sinkhole, Louisiana. This is a human-induced sinkhole >400 m across formed in 2012 and related to the collapse of a cavern 1.7 km deep created by solution mining in a salt dome (Kent and Dunaway, 2013). Although this method provides real-time displacement data, it is rather expensive and restricted to specific points. (4) 3D laser scanner has been preliminarily tested in the Daisetta sinkhole, Texas (Aiken et al., 2009), and a sinkhole in the Ebro Valley (Benito-Calvo et al., 2016). The acquisition of point clouds at different times allows the construction of 3D deformation models with utmost spatial resolution, but requires complex and time-consuming post-acquisition processing.

Leveling is the measurement of the difference in relative heights between points on the ground surface (Kennedy, 2013). Successive leveling profiles provide accurate measurements of relative vertical displacement on the benchmarks. The performance of this simple and relatively inexpensive technique has increased substantially with the development of digital levels and the electronic reading of bar-coded staffs. Leveling has been satisfactorily used to measure vertical movements related to a wide variety of subsidence phenomena, including mining subsidence (Donnelly et al., 2001), aquitard consolidation related to groundwater withdrawal (Psimoulis et al., 2007; Anderssohn et al., 2008; Ye et al., 2016), volcano-tectonic deformation (de Zeeuw-van Dalfsen et al., 2013; Murase et al., 2016), tectonic subsidence (Amighpey et al., 2015; Islam et al., 2016), coseismic displacement associated with dip-slip seismogenic faults (Clarke et al., 1997; Caputo et al., 2015), or coastal uplift (Wanninger et al., 2009; Refice et al., 2016).

The results of previous works dealing with subsidence measurement in active sinkholes in the investigated area suffered from significant limitations. Soriano and Simón (2002) obtained subsidence measurements in several sinkholes using a home-made device with limited accuracy. DInSAR studies conducted in the area provided ground displacement rates and allowed the identification of previously undetected buried active sinkholes (Castañeda et al., 2009; Gutiérrez et al., 2011; Galve et al., 2015a, 2015b). However, the DInSAR deformation maps, despite their high coverage, suffer from significant limitations: (1) lack of data in numerous active sinkholes due to coherence loss caused by vegetation, high subsidence rates and human alterations; (2) inadequate spatial resolution for the detection of small active sinkholes (<2500 m^2) and the delineation of their boundaries; (3) insufficient precision for capturing slow subsidence (<2 mm/yr); and (4) decorrelation in transportation infrastructure related to traffic. In this work we explore the strengths and limitations of high-precision leveling for sinkhole monitoring investigating five active sinkholes related to dissolution of salt-bearing bedrock in the central sector of the Ebro Cenozoic basin, NE Spain. The main criteria considered for the selection of these sinkholes include: (1) their relatively large size (30–500 m); (2) high activity revealed by rapidly evolving surface deformation features; (3) associated damage on important human infrastructures; and (4) creation of high-risk situations.

2. General geological and geomorphological setting

The investigated sinkholes are located in the middle reach of the Ebro River valley (Alcalá, Papiro, Logroño-highway and Pikolín sinkholes) and in the lower section of the Gállego River valley (Zuera sinkhole), NE Spain (Fig. 1). From the geological perspective these active sinkholes are situated within the central sector of the Ebro Cenozoic basin, which is the southern foreland basin of the Pyrenean Alpine orogen. Here, the bedrock consists of subhorizontally lying evaporites of the late Oligocene-Miocene Zaragoza Formation, deposited in an extensive high-salinity playa-lake system (Quirantes, 1978; Ortí and Salvany, 1997). This formation, >850 m in thickness, consists of anhydrite, halite and glauberite in the subsurface and secondary gypsum in exposure (Salvany et al., 2007; Salvany, 2009). Torrescusa and Klimowitz (1990), based on deep borehole data, differentiated two members in the Zaragoza Formation whose boundary is situated at 350–400 m below the bottom of the Ebro Valley. The upper member, up to 600 m thick, consists of a basal unit 140 m thick dominated by marls and clays, and a thick evaporitic succession whose upper part crops out at the surface. On the basis of boreholes drilled along a 50 km long stretch of the Ebro Valley, this upper evaporitic sequence has been subdivided into four lithostratigraphic units, in ascending order (Salvany et al., 2007; Salvany, 2009): (1) marl and anhydrite basal unit; (2) halite unit; (3) glauberite-halite unit; and (4) anhydrite unit. The Alcalá, Papiro, Logroño-highway and Pikolín sinkholes, laying at elevations between 208 and 221 m a.s.l., are developed on alluvium directly underlain by the lower part of the anhydrite unit or the upper part of the glauberite-halite unit. At La Loteta Reservoir, located 10 km west of the Alcalá sinkhole, the top of the glauberite-halite unit has been identified at 188–196 m a.s.l. (Salvany et al., 2007; Gutiérrez et al., 2015). In the Zuera sinkhole, located in the Gállego valley, a geotechnical borehole identified halite beneath a thick karstic residue at 40–50 m depth. These data indicate that the evaporitic bedrock at the sinkhole sites includes high-solubility salts close to the surface. This is a first-order factor that controls both dissolution kinetics and the rates at which the overlying material may subside. For comparison, the equilibrium solubilities of gypsum ($CaSO_4 \cdot 2H_2O$), glauberite ($Na_2[CaSO_4]_2$), and halite (NaCl) in distilled water at normal conditions are 2.4 g/l, 118 g/l, and 360 g/l, respectively (Langer and Offermann, 1982; Ford and Williams, 2007).

The Ebro Valley, in the reach where it is excavated into the Zaragoza Gypsum Formation shows a markedly asymmetric geometry, with a prominent and linear gypsum escarpment on the NE margin, and a stepped sequence terraces on the opposite side (Gutiérrez et al., 1994) (Fig. 1). The Alcalá sinkhole is located on the floodpain next to the outer side of a meander of the Ebro River channel, whereas the Papiro, Logroño-highway and Pikolín sinkholes are located in the lowermost terrace. The Zuera sinkhole is located on the lowermost terrace of the Gállego River. Therefore, all the sinkholes occur on young and poorly indurated alluvium, in contrast with those developed on old cemented alluvial deposits. Both the Ebro River and its tributary, the Gállego River, are allocthonous drainages that flow through a semi-arid area (i.e. average annual precipitation around 300 mm) and receive great part of the flow from the Pyrenees. Most of the recharge in the alluvial aquifer is related to irrigation; the water-table reaches the highest levels by the end of the summer, coinciding with low discharge in the river. The massive human-induced incorporation of diluted irrigation water into the alluvial-karst aquifer system significantly contributes to enhance karstification and subsidence processes (Gutiérrez et al., 2007; Acero et al., 2013, 2015).

3. Methodology

Before selecting and installing the leveling lines, the sinkholes and their immediate vicinity were mapped in the field using 1:1000 or 1:2000 scale gridded orthoimages. Special attention was paid to ground deformation features like scarps, ground fissures, potholes and tilted surfaces or walls, which were particularly obvious on paved surfaces. Whenever possible, the amount and sense of the deformation were indicated in the map (Cooper, 2008). These deformation features are