Measuring deformation related to active sinkholes with ground-based 3D laser scanner. A case study in the evaporite karst of the Ebro Valley, NE Spain

Medición de deformaciones en dolinas activas mediante escáneres láser 3D. Un ejemplo en el karst evaporítico del Valle del Ebro, NE de España

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Resumen: Los trabajos de investigación que abordan la monitorización de la subsidencia en dolinas activas son muy escasos, especialmente si se comparan con los dedicados a otros fenómenos de inestabilidad del terreno como los deslizamientos. Recientemente se han obtenido resultados satisfactorios mediante técnicas geodésicas de última generación, tales como el LiDAR (*Light Detection And Ranging*) aerotransportado y el DInSAR (*Differential Synthetic Aperture Radar Interferometry*). En este trabajo, llevado a cabo en el karst evaporítico del valle del Ebro, se explora el potencial de los láseres escáneres terrestres 3D para la caracterización detallada de la subsidencia en dolinas concretas. La utilidad del método se ilustra a través de la dolina de Alcalá de Ebro, la cual afecta a un dique de contención de avenidas del Río Ebro. Esta dolina, con una actividad muy elevada, contribuye a debilitar el dique creando situaciones de alto riesgo durante eventos de inundación.

Palabras clave: alerta temprana, Monitorización 3D, tasas de subsidencia.

Abstract: *The investigations dealing with subsidence monitoring in active sinkholes are very scarce, especially when compared with other ground instability phenomena such as landslides. Recently, satisfactory results have been obtained utilizing some relatively new geodetic techniques such as airborne LiDAR (Light Detection And Ranging) and DInSAR (Differential Synthetic Aperture Radar Interferometry). In this work, carried out in the mantled evaporite karst of the Ebro Valley, NE Spain, we explore the potential of ground-based 3D laser scanner for the detailed characterisation of subsidence activity in specific sinkholes. The practicality of the approach is illustrated through a sinkhole in Alcalá village, which affects a flood-control dike of the Ebro River. This sinkhole with recurrent collapse activity significantly contributes to reduce the mechanical strength of the embankment, leading to high-risk situations during flood events.*

Key words: *3D monitoring, early warning, subsidence rates.*

INTRODUCCIÓN

The investigations dealing with the measurement and monitoring of ongoing deformation related to active sinkholes are very scarce, especially when compared with other ground instability phenomena like landslides (Gutiérrez, 2016). Some recently published articles analyse dissolution-induced surface movements utilising two geodetic methods with contrasting spatial resolutions: (1) Airborne LiDAR (Light Detection And Ranging) data. In the Dead Sea, the analysis of airborne LiDAR data with a high spatial and temporal resolution has allowed the quantitative assessment of temporal changes in sinkholes and the detection of precursory ground settlement preceding the occurrence of collapse sinkholes (Filin *et al.*, 2011). (2) DInSAR (Differential Synthetic Aperture Radar Interferometry), which has been proved to be suitable for measuring subsidence rates under adequate conditions (e.g. Galve *et al.*, 2015) and anticipating the location of future collapse sinkholes using satellite (Nof *et al.*, 2013; Jones and Blom, 2014) and ground-based data (Intrieri *et al.*, 2015). This investigation explores the capabilities and limitations of 3D laser scanner for measuring, with a high spatial resolution, deformation on the ground and human structures related to active sinkholes. To our knowledge, this is the first work that explores the application of the technique to sinkhole-related subsidence. The approach is applied in the mantled evaporite karst of the Ebro River valley, where the karstification of highly soluble halite (NaCl) and glauberite ($Na_2[CaSO_4]_2$) beds leads to the development sinkholes with very high subsidence rates (Castañeda *et al.*, 2009; Gutiérrez *et al.*, 2011; Galve *et al.*, 2015). These rapid sinkholes that affect a wide variety of human-built structures, provide the opportunity of gathering significant data on the subsidence pattern by acquiring point clouds over relatively short time spans. Measurements are being carried out every six months since October 2014 in five active sinkholes (Fig. 1): Alcalá sinkhole, Logroño-highway sinkhole, Europa sinkhole (upstream Zaragoza city), La Puebla sinkhole and Railway sinkhole (downstream Zaragoza city). Alcalá sinkhole is located in the floodplain, Logroño-highway, Europa and Railway sinkholes in the lowermost terrace of the Ebro River, and La Puebla sinkhole on gypsum reliefs at the NE valley margin. The selected sinkholes reach around 100 m in length and include different typologies: sagging-collapse (Alcalá, Ferrocarril), sagging (Logroño-highway, Europa), and collapse (La Puebla). All the sinkholes, with the exception of La Puebla, cause severe damage on human structures involving significant direct and indirect losses. Ferrocarril sinkhole impinges on the conventional Zaragoza-Barcelona railway at a site where a collapse occurred in 1991, resulting in the derailment of a freight train. Logroño-highway and Europa sinkholes cause continuous subsidence on roads, including highway N-232a.

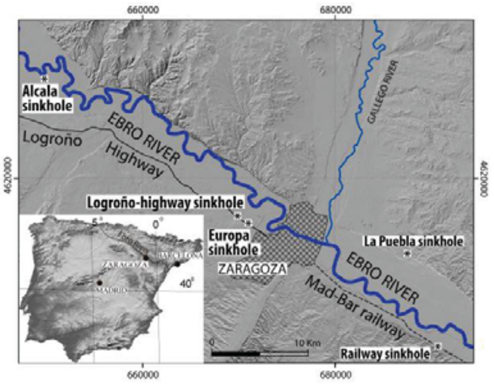

FIGURE 1. *Geographical distribution of the investigated sinkholes within the middle reach of the Ebro River valley, NE Spain*

The Alcalá sinkhole, selected to illustrate the approach in this paper, is located next to the Ebro River channel and affects a flood-control dike, the adjacent street and two buildings

(Fig. 2). This sinkhole with recurrent collapse activity significantly contributes to reduce the mechanical strength of the dike, leading to high-risk situations during flood events.

FIGURE 2. *Image showing the location of the Alcalá sinkhole. The dashed line indicates the approximate limits of the area affected by higher subsidence. Arrow in the lower part of the image points to the northernmost fissure in the concrete wall. The photograph was taken on March 2, 2015, during the February-March Ebro River flood with a return period of 5-10 years. The water stage in the river is well above the ground surface in the village and water from the river was flowing under pressure through and beneath the dike, flooding the sinkhole*

THE ALCALÁ SINKHOLE

The investigated sinkholes are located in the middle reach of the Ebro River valley within the central sector of the Ebro Cenozoic basin (Fig. 1). Here, the bedrock consists of subhorizontally lying evaporites of the late Oligocene-Miocene Zaragoza Formation, which includes significant halite and glauberite units close to the surface (Salvany *et al.*, 2007). The karstification of the bedrock has developed numerous sinkholes, mostly associated with the lower alluvial levels (Galve *et al.*, 2009).

At the present time, the village of Alcalá is located just next to the erosional outer side of a meander of the Ebro River. Figure 3 shows the position of the channel in 1927 and in 2012, as well as the abandoned channel sections mapped using an orthorectified aerial photograph taken in 1957. The relative distribution of the channels, as well as the cross-cutting relationships of the abandoned meander loops, indicate an overall and episodic southward migration of the river towards the villages of Alcalá and Cabañas over the last centuries. The most dramatic change of the river after 1927 occurred in Alcalá. The channel used to be situated at a distance of 540 m from Alcalá, whereas nowadays it flows just next to the village. This indicates an average lateral migration rate of around 18 m/yr, considering that the channel position at Alcalá has not changed since 1957. This alteration in the river channel led to the abandonment of the road and the pontoon passage that used to connect the villages of Alcalá and Remolinos (Fig. 3). In order to prevent the lateral migration of the Ebro River towards the village, six transverse concrete jetties 30 m long and founded on rip-rap were built on the river bed during 1962-1964. The village was also protected by a dike-wall finished in 1982. It was built with loose aggregate covered by rip-rap on the channel-facing side and with a wall of concrete and rip-rap on the flank facing to the village. The embankment is 2.3-2.6 m high above the adjacent ground in the village and its 4-5 m wide crest is used as a dirt road (Figs. 2 and 4).

Sinkholes have caused detrimental consequences in the area since ancient times. Interestingly, in the famous Spanish novel Don Quixote, written by Miguel de Cervantes between 1605 and 1615, the squire Sancho Panza was awarded by his knight Don Quixote with the Barataria Isle, a plot of land in Alcalá that becomes an island during the Ebro River floods. While Sancho Panza was leaving from Barataria towards Pedrola castle, he was suddenly swallowed with his donkey by a deep and dark sinkhole (Part II, chapter 55). In the 1970´s a house in the village of Alcalá was severely damaged by a sinkhole. In the early 1980´s a sinkhole formed around 50 m south of the investigated subsidence area and in the same street. This depression is now filled by 22 m of anthropogenic deposits together with an injected cement-based grout mixture. The distribution of sinkholes, subsidence-related damage in buildings and geophysical anomalies suggest higher karstification and sinkhole susceptibility in the area associated with the river channel (Pueyo-Anchuela *et al.*, 2010).

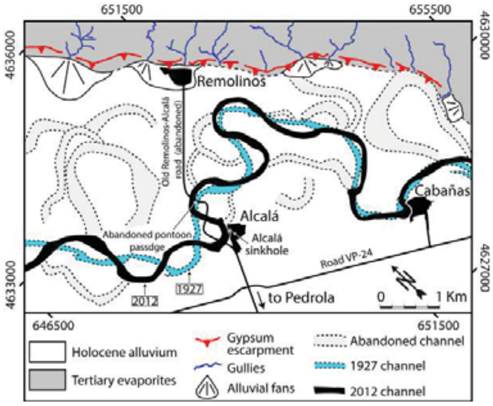

FIGURE 3. *Geomorphological sketch of the Ebro Valley in the surroundings of the Alcalá village. The map shows the location of the Alcalá sinkhole, the position of the river channel in 1927 and 2012, and abandoned channels mapped on aerial photographs from 1957. Note that the old road and a pontoon passage between Alcalá and Remolinos were abandoned due to the changes experienced by the river channel after 1927*

To our knowledge, subsidence was first expressed at the surface by a collapse sinkhole occurred in June 2007. Since then, the site has suffered from continuous subsidence as well as collapse events, and has been the subject of a number of geotechnical reports. A total of 7 boreholes 25-44 m deep have been drilled in the area affected by the sinkhole and the immediate surroundings (Fig. 4). The detrital cover is around 6-7 m thick, comprising an upper man-made deposit up to 4.6 m thick, underlain by alluvium with a high proportion of fine-grained facies. This surficial deposit overlies more than 20 m of dark grey clays and marls with residual gypsum particles that grade downwards into layers of gypsum, halite and glauberite. This material can be interpreted as a karstic residue with a gradational lower contact with the fresh salt-bearing evaporite bedrock. Some boreholes have encountered water- and/or alluvium-filled cavities several meters high well below the water table: S-1 between 13.2-17.8 m; S-1C between 14.4-18.2 m, S-4 between 14.4-19 m, S-5 between 4.8-6.8 and 14.3-15.7 m (Fig. 4). Borehole data reveal the presence of significant cavities beneath the investigated sinkhole and the surrounding zone, mostly concentrated at depths between 13 and 19 m, probably controlled by a salt unit (i.e. halite or glauberite).

On June 20, 2007, a collapse sinkhole occurred suddenly in the street next to the sidewalk of the buildings (Fig. 4). This was a bell-shaped shaft with overhanging edges approximately 8 m across and 15 m deep. It partially undermined the adjacent house, which was evacuated. The hole was filled with 500 tonnes of gravels and boulders, plus sluggish cement, indicating a minimum volume for the subsurface cavity of around 750 m^3, considering a bulk density for the non-compacted aggregate of 1.5 g/cm^3. Probably, the development of the sinkhole was favoured by water level changes in the alluvial aquifer related to a flood in the Ebro River during March and April 2007 (peak discharge of 2230 m^3/s in Zaragoza city on April 5, 2007) and the subsequent flow recession. The house was reoccupied on July 6, 2007, and a few hours later a collapse sinkhole around 2 m across formed next and beneath to the sidewalk (Fig. 5A). In November 2013, a new collapse sinkhole around 9 m long and with overhanging edges formed on the eastern flank of the dike (Figs. 4 and 5B).

A compaction grouting programme was performed during November-December 2013 in the street and beneath the adjacent buildings, in order to increase the bearing capacity of the ground and fill the cavities. An expansive polyurethane resin was injected under pressure through small-diameter borings from 5 to 8 m depth. Soon after the injection, a collapse sinkhole formed in front of the building (Figs. 4 and 5C, D).

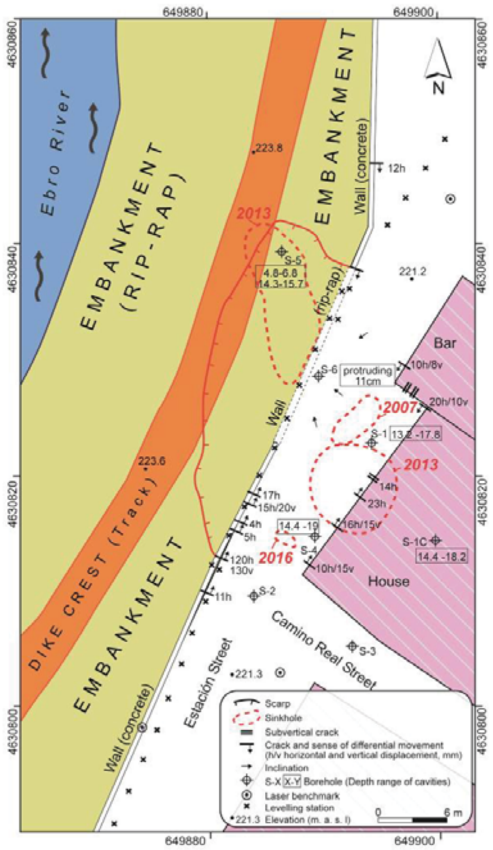

FIGURE 4. *Detailed map of the Alcalá sinkhole showing the approximate location of collapse events, surface deformation features, position of targets, leveling points and boreholes (numbers in parenthesis indicate the depth range of cavities)*

By the end of February and the beginning of March 205, the Ebro River experienced a significant flood with a return period of 5-10 years. Peak discharge was recorded at Castejón station on February 27 (60 km upstream, 2691 m3/s) and at Zaragoza station on March 2 (30 km downstream, 2448 m3/s). water flowed under pressure through and beneath the dike, causing internal erosion and flooding the sinkhole with turbid water (Fig. 3).

FIGURE 5. *Photographs illustrating the evolution of the Alcalá sinkhole since 2007. A: Collapse sinkhole that reappeared in July 6, 2007, after filling a depression formed on June 20, 2007. Image taken on July 8, 2007. Note the lack of cracking in the adjacent buildings. B: Collapse sinkhole occurred in November 2013 on the eastern flank of the dike. C: Collapse-suffosion sinkhole formed soon after the compaction grouting program applied in the street with expansive polyurethane foam during November-December 2013. Note severe cracking in the adjacent buildings. Image taken on December 31, 2013. D: Collapse sinkhole on May 9, 2014*

At Alcalá, during several days, the water stage in the river was well above the ground surface in the village, and river water was flowing under pressure through and beneath the dike, causing internal erosion and flooding the sinkhole with turbid water (Fig. 2). In December 2015, a new consolidation grouting program was carried out along the dike though 84 borings with different depths (17 at 15 m, 22 at 9 m, and 45 at 5 m). Grouting was performed by injecting under pressure a hydro-active polyurethane foam generated by the mixture of two components (MasterRoc© MP355 by BASF). This solvent-free resin has been designed for rapid water stopping, ground consolidation and small-cavity filling within the phreatic zone. In contact with water it rapidly reacts to form a rigid foam. The foaming factor and the mechanical strength of the foam can be controlled by adding different accelerators. According to the technical specifications of the product, this resin is not suitable for large-volume void filling. In March 2006, a new elongated sinkhole around 2 m long was detected in the street, probably related to downward migration (ravelling) of the man-made fill through an extensional fissure (Fig. 4).

3D LASER SCANNER DATA

The 3D monitoring and analysis of the subsidence phenomena has been carried out through the following work flow: (1) Acquisition of point clouds utilizing laser scanners (Leica C10 y Faro Focus X330) and reference stations (targets, spheres). Several 3D scans are performed at each site and the point clouds are merged applying the cloud-to-cloud method. (2) Georeferencing of the merged point clouds using the reference stations. (3) Removal of points that may distort the deformation measurements (e.g., moving objects, vegetation). (4) Comparison between the point clouds acquired at different dates in order to identify the areas affected by changes and quantify the deformation. The assessment of the changes was carried out by measuring the distance between the 3D data sets by various approaches: cloud-to-cloud comparison (C2C), cloud-to-cloud comparison with local interpolation, cloud to mesh model comparison (C2M), model to model comparison (DEM or mesh) (Girardeau-Montaut *et al.*, 2005; Lague *et al.*, 2013).

In the Alcalá sinkhole, the comparison of point clouds (October 2014, April 2015, October 2015) has been performed so far using methods C2C and C2M with local interpolation. Point clouds showed a final spatial resolution of approximately 1 cm. Mean errors were 1.7 mm for the cloud-to-cloud registration and 2.1 mm for the georeferencing using the reference stations. Considering the accuracy of the laser scanners (2-6 mm) and these registration errors, results should allow accurately measuring deformation in the portion of the sinkhole affected by displacements of ≥1 cm.

Deformation maps for the periods October 2014-April 2015 and April 2015-October 2015 are displayed in Fig. 6. In agreement with the surface deformation map (Fig. 4), the subsidence structure is imaged as an elongated basin around 28 m long along the dike and 8 m wide on its southern sector. Maximum subsidence values reach 25 cm for the period October 2014-April 2015, corresponding to a nested circular collapse structure, which was filled with a mound of gravels before October 2015. Apart from this collapse, the centre of the subsidence structure is characterised by displacements between 10-14 cm for the period October 2014-April 2015, and 14-17 cm for the period April 2015-October 2015. These values yield subsidence rates of 20-26 cm/yr and 28-34 cm/yr, respectively, indicating acceleration in the subsidence phenomenon. The external zone of the detected subsidence area is defined by a band with displacements of 3-5 cm. Towards the N and the W, the boundary of the captured sinkhole area is outlined by a “fault-zone” clearly recognisable through the comparison of scanner data. The displacement on the dike wall was measured at 4-5 cm between October 2014-April 2015, while during the period April 2015-October 2015 the deformation increased up to 7-10 cm (Fig. 6). This acceleration is most probably related to the internal erosion occurred beneath the dike during the February-March 2015 Ebro River flood (Fig. 2). Deformation also affected to the northern building, as revealed by spalling features on the house wall. During the period April 2015-October 2015 point cloud comparison also shows deformation with a significant toppling component in the sector of the southern building close to the door, with wall displacements between 1 and 2 cm.

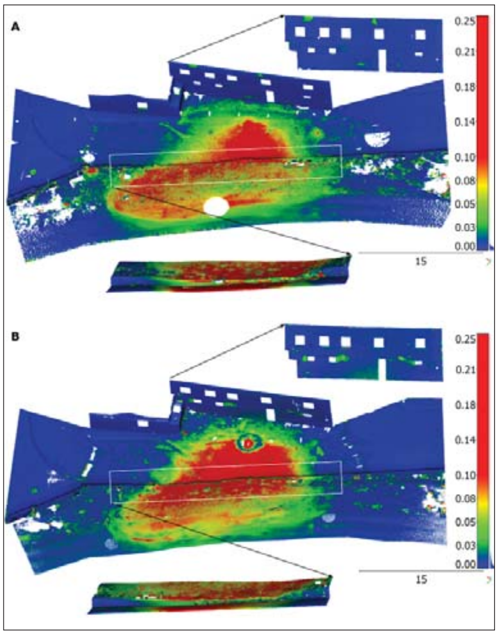

FIGURE 6. *Subsidence in Alcalá de Ebro sinkhole measured through laser scanner 3D data comparison. A) Distance between point clouds captured in October 2014 and April 2015. B) Distance between point clouds captured in April 2015 and October 2015. Units are expressed in meters*

With the available data, covering a limited time span, the deformation models produced with the point clouds do not capture an external zone a few meters wide affected by inward tilting, as revealed by subcentimetric settlements measured by precise levelling along the foot of the dike wall. This limitation is related to the lower accuracy of the method and in some sectors to the presence of loose gravel, frequently disturbed by the passage of people. Further data acquisition and analysis will allow us to better constrain the displacement threshold for the system in this context and the actual sinkhole edges.

FINAL CONSIDERATIONS

The preliminary results indicate that ground-based 3D laser scanner is a suitable method for measuring surface displacement with a high spatial resolution in sinkholes undergoing rapid subsidence and affecting human structures. The progress of our investigation will allow us to assess the performance of the technique on active sinkholes under less favourable conditions (e.g., slow subsidence, natural vegetated surfaces). Although the application of the method involves the use of relatively expensive systems and significant processing efforts by qualified personnel, it offers the possibility of measuring surface changes with utmost spatial resolution (~1 cm at Alcala sinkhole). Moreover, the displacement measurements, in comparison with other methods such as precise levelling, have a three-dimensional character, providing information on the vertical and horizontal components of the deformation. The minimum displacement that can be measured (accuracy of ca. 1 cm at Alcala sinkhole) is around one order of magnitide higher than precise levelling. In fact, subtle subsidence measured on the marginal zone of the Alcala sinkholes by precise levelling, including paved areas, are not captured by the 3D laser scanner data.

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