INVESTIGATING A DAMAGING BURIED SINKHOLE CLUSTER IN AN URBAN AREA INTEGRATING GEOMORPHOLOGICAL SURVEYS, GEOPHYSICS AND TRENCHING

V. Rodríguez (1), D. Carbonel (1), F. Gutiérrez (1), JP. Galve (1), M. Zarroca (2), R. Linares (2), C. Roqué (3), J. Guerrero (1), J. McCalpin (4)

(1) Departamento de Ciencias de la Tierra, Universidad de Zaragoza, Edificio Geológicas, C/. Pedro Cerbuna 12, 50009 Zaragoza, Spain
(2) Departamento de Geología, Universidad Autónoma de Barcelona, Barcelona, Spain
(3) Àrea de Geodinàmica Externa i Geomorfologia, Universitat de Girona, Girona, Spain
(4) Geo-Haz Consulting Inc., Colorado, USA

Abstract (Investigación de un conjunto de dolinas que afecta a un área urbana integrando estudios geomorfológicos, geofísica y trincheras): *This work analyses a damaging complex sinkhole cluster within the mantled evaporite karst of Zaragoza city, NE Spain. A detailed map of modern surface deformation indicates two active coalescing sinkholes, whereas two additional dormant sinkholes, currently beneath human structures, are revealed by old aerial photographs. ERT data and a trench excavated in the topographic margin of one of the sinkholes consistently indicate a larger subsiding area. GPR data reveal that subsidence in the central sector of one of the sinkholes is mainly accommodated by sagging. The stratigraphic and structural relationships observed in the trench may be alternatively interpreted by three collapse events, or by progressive fault displacement combined with episodic anthropogenic excavation and fill. Average subsidence rates of >6.6 mm/yr and 40 mm/yr have been calculated using different techniques. This case study illustrates the need of conducting thorough investigations in sinkhole areas during the pre-planning stage including a geomorphic approach.*

Palabras clave: *Valle del Ebro, dolina, riesgo por subsidencia, geomorfología urbana*
Key words*: Ebro Valley, sinkhole cluster, subsidence hazard, urban geomorphology*

INTRODUCTIÓN

The development of sinkholes related to subsurface dissolution of soluble rocks and subsidence of the overlying sediments constitutes a significant hazard in numerous regions worldwide (e.g. Waltham et al. 2005). Dissolution-induced subsidence may produce costly damage on human structures and catastrophic collapse sinkholes have caused human live losses in several countries like South Africa (Benzuidenhout and Enslin, 1979; De Bruyn and Bell, 2001), China (Wenhui, 1990), or Florida, USA. The city of Zaragoza and its outskirts is most probably the area in Europe where sinkhole hazard related to evaporite dissolution has the highest economic impact (Gutiérrez et al. 2008). The literature dealing with the prospection and analysis of dissolution and subsidence features in developed areas is quite extensive. However, most of the works are focused on the application of specific geotechnical and geophysical techniques (Thierry et al., 2005; Buurman and Reuther, 2006; Kim et al., 2007; Delle Rose et al., 2010; Krawczyk et al, 2012; Zisman et al. 2013), and the geomorphological perspective is frequently overlooked. Our work analyses the spatial distribution, historical evolution and activity of a complex sinkhole cluster integrating data gathered from multiple information sources and approaches (aerial photographs, historical maps, geophysics, trenching).

SETTING

The study area is located in the western sector of Zaragoza city, within the mantled evaporite karst of the Ebro River Valley, NE Spain (Fig. 1). Here, the Ebro Valley has been excavated in subhorizontally lying evaporites of the Oligo-Miocene Zaragoza Formation. This formation consists of anhydrite ($CaSO_4$), halite (NaCl), and glauberite ($Na_2Ca[SO_4]_2$) with interlayered claystones and marls. According to mining exploration boreholes

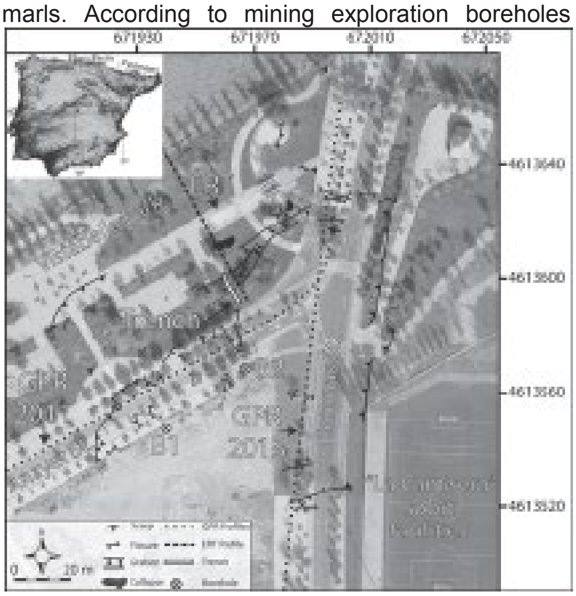

Fig. 1: Location of the study area within the Ebro Depression, NE Spain, and Zaragoza city. The map shows the surface deformation features surveyed in 2013. The distribution of the ERT section, the two useful GPR profiles and the trench is indicated.

drilled southeast of Zaragoza, the top of a 75-m-thick halite unit is situated 15-40 m below the floor of the Ebro Valley. Glauberite units as much as 30 m thick occur within a sequence that extends from 15 m below to 240 m above the valley bottom.
The subsidence area analyzed in this work is located on the southern valley margin, associated with some remnants of the T3 terrace dissected by infilled valleys (Galve et al., 2009; Gutiérrez et al., 2009). It consists of a sinkhole cluster developed in two valleys and the divide between them.

METHODOLOGY
The sinkhole area has been investigated integrating surface and subsurface data gathered from different sources and applying various intrusive and non-intrusive techniques (Fig.1). Information on subsidence surface features and the topographic evolution of the area have been obtained from the analysis of several documents and datasets, including: (1) Detailed topographic maps of the municipality from 1960 and 1971-1974; (2) Old aerial photographs taken in 1945, 1956 and 1986, used for geomorphological interpretations with a stereoscope; (3) Orthoimages from multiple dates spanning from 1998 to 2011, illustrating the transformation of the area from rural into urban. Additionally, in February 2013 we produced a 1:500 scale map depicting surface subsidence features (i.e. scarps, fissures, sags; Fig. 1).

A geophysical investigation was carried out in two different campaigns. In April 2011, eight Ground Penetrating Radar (GPR) profiles with a total length of 818 m were acquired using 180 MHz shielded antennas, as well as a 64 m long Electrical Resistivity Tomography (ERT) line using a Dipole-Dipole configuration array. In March 2013, seven additional GPR profiles with a total length of 874 m were recorded.

Also in April 2011, after the first geophysical campaign, a 14 m long and 3.5 m deep trench was excavated with a backhoe in the Vistabella Park, on the NW sector of the subsidence area. Material datable by the radiocarbon method was collected in the excavated deposits.

INTERPRETATION AND CONCLUSIONS
The comprehensive interpretation of the data indicates that:
(1) The geomorphological interpretation of old aerial photographs, especially those taken in 1956, reveal a NE-SW trending alignment of three closely-spaced sinkholes and an additional subsidence depression to the east, probably formed between 1946 and 1956 (Fig. 2). The northern and intermediate sinkholes of the alignment roughly coincide with the area currently affected by observable surface deformation, covering around 10,200 m^2 as defined by the detailed map produced in the field in February 2013 (Fig. 1). On the contrary, the eastern and southern sinkholes, buried beneath a soccer pitch and a street, respectively, seem to be dormant structures that have not produced any surface deformation up to now.
(2) The ERT section acquired in the Vistabella Park clearly images the graben structure mapped on the western margin of the northern sinkhole. Similar features attributable to collapse faults, including a buried graben, have been inferred within a 20 m long zone situated beyond the marginal graben (Fig. 3A). In the case of the GPR data, their quality was adversely affected by the highly conductive ground related to thick anthropogenic deposits and gardened areas. Nonetheless, two profiles acquired along recently asphalted surfaces image the northern buried sinkhole as obvious synforms (Fig.3B), revealing that subsidence in the central sector of the northern sinkhole is mainly accommodated by passive bending.

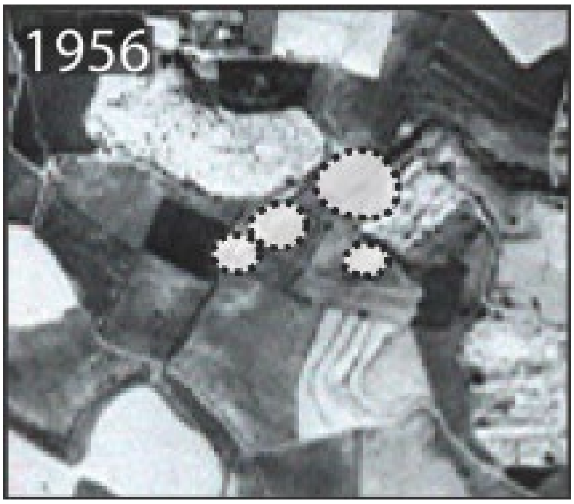

Fig. 2: 1956 aerial photograph of the sinkhole area. The polygons with a dashed outline indicate the approximate location of the depressions interpreted under the stereoscope.

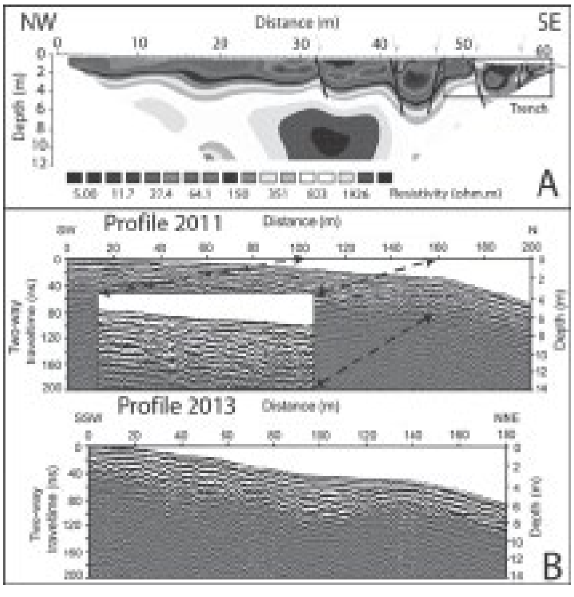

Fig. 3: A: ERT section acquired with a dipole-dipole configuration. B: GPR profiles showing synforms (double arrow) corresponding to the buried northern sinkhole.

(3) The trench, excavated on the W margin of the northern sinkhole, exposed a graben structure bounded by active faults with conspicuous scarps, and a nested buried graben (Fig. 4). The collapse faults affect terrace deposits, valley fill sediments younger than 290 yr BP and modern man-made deposits.

The structural and stratigraphic relationships, including faults truncated by anthropogenic excavation surfaces and deposits, may be explained by (1) three collapse events with vertical displacements of around 0.6 m occurred after 290 yr BP, or (2) progressive displacement on faults, that eventually cease their activity as deformation is transferred to other structures, combined with episodic accumulation of man-made deposits. This is our preferred alternative, since examination and photographic documentation of the graben over the years reveal that the fault scarps have increased their size in a progressive, rather than stepwise fashion.

(4) The structural relationships and the redrodeformation analysis indicate that there should be other synthetic normal faults to the west of the trench, as support the ERT data (Figs. 1 and 3A). Available data indicates a subsidence rate of 40 mm/yr, expected to be higher in the central sector of the sinkhole, where ground deformation is accommodated by a larger number of structures than those exposed in the trench, as reveal the GPR profiles.

(5) Geomorphic mapping using old aerial photographs may be essential for the investigation of concealed sinkholes in urban areas, allowing: (1) Understanding of the geomorphic context, which may have been obliterated by human-induced topographic alterations; (2) Recognizing dormant buried sinkholes with no surface expression, but that may reactivate in the near future; (3) Bracketing the age of some sinkholes and inferring their spatial-temporal evolution; (4) The geomorphic model constitutes the basis for properly designing the site investigation and interpreting the data (e.g. layout of geophysical profiles and trenches, distribution of boreholes).

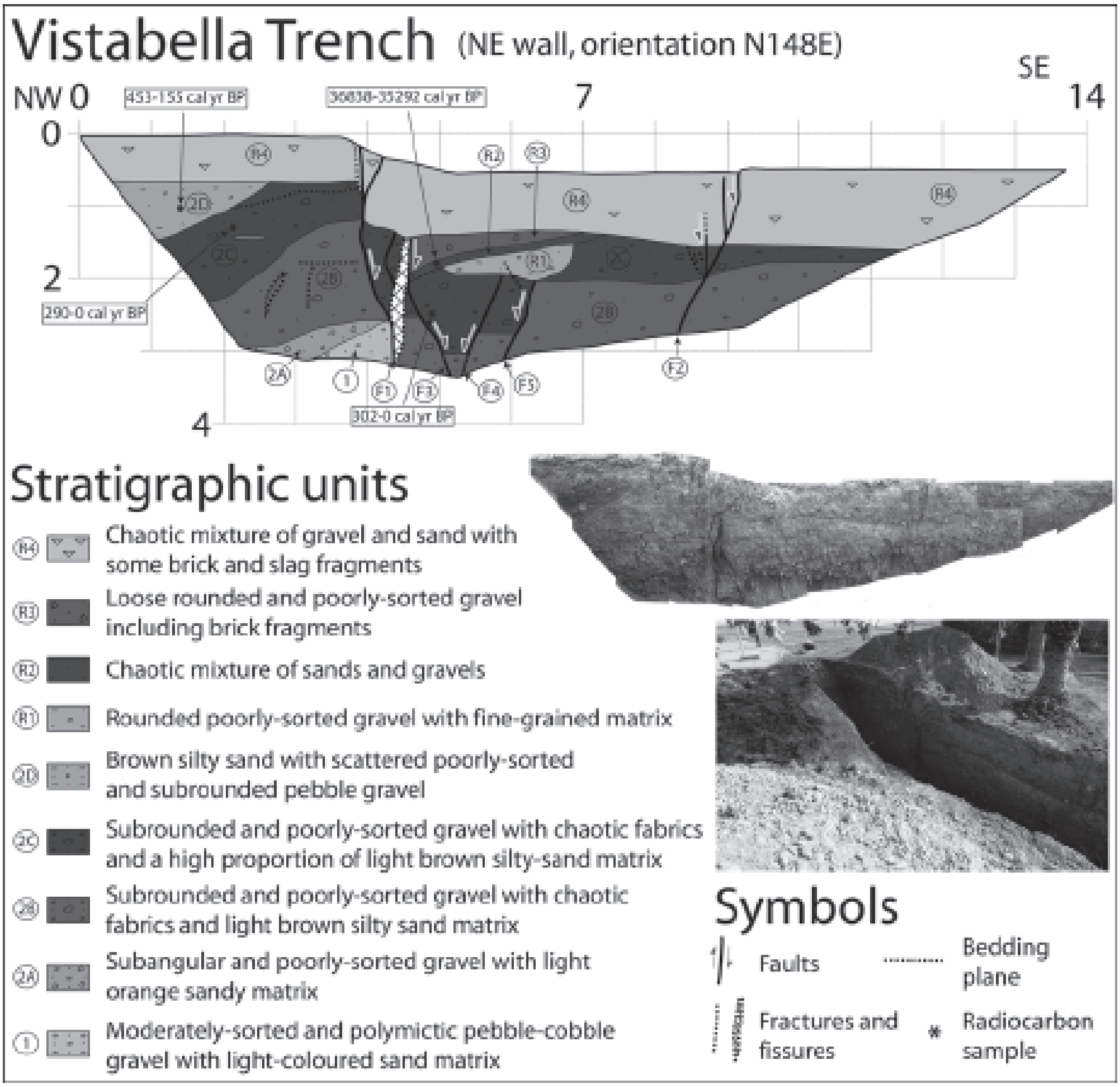

Fig. 4: Log and photomosaic of backhoe trench dug across the graben depression in Vistabella Park and image of the trenching site showing the scarp associated with the master fault.

This case study clearly illustrates the need of conducting thorough investigations in sinkhole areas during the pre-planning stage, incorporating a geomorphological perspective. Accurate mapping of sinkholes and concealed subsidence structures is essential for the application of a preventive mitigation strategy by avoiding construction on unstable areas.

References

Bezuidenhout, C.A. & Enslin, J.F. (1970). Surface subsidence and sinkholes in the dolomitic areas of the Far West Rand, Transvaal, Republic of South Africa. In: Land Subsidence. *International Association of Hydrological Sciences*, Publ. nº 89, 482-495.

Buurman, N. & Reuther, C.-D. (2006). Profiling of sinkholes in the metropolitan region of Hamburg and Lüneburg with ground penetrating radar (GPR). *Geophysical Research,* Abstract 8, 01878.

De Bruyn, I.A. & Bell, F.G. (2001). The occurrence of sinkholes and subsidence depressions in the Far West Rand and Gauteg Province, South Africa, and their engineering implications. *Environmental and Engineering Geoscience*, 7, 281-295.

Delle Rose, M. & Leucci, G. (2010). Towards an integrated approach for characterization of sinkhole hazards in urban environments: the unstable coastal site of Casalabate, Lecce, Italy. *Journal of Geophysics and Engineering,* 7, 143–154.

Galve, J., Gutiérrez, F., Lucha, P., Bonachea, J., Remondo, J., Cendrero, A., Gutiérrez, M., Gimeno, M., Pardo, G. & Sánchez, J. (2009). Sinkholes in the salt-bearing evaporite karst of the Ebro River valley upstream of Zaragoza city (NE Spain). Geomorphological mapping and analysis as a basis for risk management. *Geomorphology,* 108, 145–158.

Gutiérrez, F., Calaforra, J.M., Cardona, F., Ortí, F., Durán, J.J. & Garay, P. (2008). Geological and environmental implications of evaporite karst in Spain. *Environmental Geology,* 53, 951-965.

Gutiérrez, F., Galve, J.P., Lucha, P., Bonachea, J., Jordá, L. & Jordá, R. (2009). Investigation of a large collapse sinkhole affecting a multi-storey building by means of geophysics and the trenching technique (Zaragoza city, NE Spain). *Environmental Geology,* 58, 1107–1122.

Kim, J.H., Yi., M.J., Hwang, S.H., Song, Y., Cho, SJ. & Synn, J.H. (2007). Integrated geophysical surveys for the safety evaluation of a ground subsidence zone in a small city. *Journal of Geophysics and Engineering*, 4, 332–347.

Krawczyk, C.H., Polom, U., Trabs, S. & Dahm, T., (2012). Sinkholes in the city of Hamburg—New urban shear-wave reflection seismic system
enables high-resolution imaging of subrosion structures. *Journal of Applied Geophysics,* 78, 133–143.

Thierry, P., Debeglia, N. & Bitri, A. (2005). Geophysical and geological characterization of karst hazards in urban environments: application to Orléans (France): *Bulletin Engineering Geology and the Environment*, 64, 139–150.

Wenhui, S. (1990). Geological calamities research in chinese railways. In: *Proceedings of the Sixth International Congress of the International Association of Engineering Geology (*Price, D.G. ed.). A.A. Balkema, Rotterdam (The Netherlands), 2401-2407.

Zisman, E.D., Wightman, M. & Kestner, J. (2013). Sinkhole investigation methods: the next step after special publication n.57. *Carbonates and Evaporites*, doi 10.1007/s13146-013-0