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Active sinkholes: A geomorphological impact of the Pajares Tunnels (Cantabrian Range, NW Spain)

Pablo Valenzuela [a,*], María José Domínguez-Cuesta [a], Mónica Meléndez-Asensio [b], Montserrat Jiménez-Sánchez [a], José Antonio Sáenz de Santa María [c]

[a] Department of Geology, University of Oviedo, C/ Jesús Arias de Velasco, 33005 Oviedo, Spain
[b] Instituto Geológico y Minero de España (Office of Oviedo), C/ Matemático Pedrayes, 25, 33005 Oviedo, Spain
[c] GEHMA Geología y Geotecnia, S.L. C/ Pérez de Ayala, 1, 3ºC, 33007 Oviedo, Spain

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ABSTRACT

Two parallel base tunnels (Pajares Tunnels) were built from 2005 to 2009 through the Cantabrian Range (NW Spain), crossing an alternation of Paleozoic formations (shale, sandstone, quartzite and limestone) characterized by a complex geological structure. A section of the tunnels was built 450 m depth below Alcedo Valley (León, N Spain). Some evidence of collapse and swallow holes have been appearing from 2007 to present at the bottom of the valley. Although the stream was channeled in 2009 to control water infiltration, the process could not be avoided, constituting a good example of geomorphological impact caused by a base tunnel. The management of hydrogeological, geomorphological and climatological information using a GIS allowed mapping the affected area and estimating the mean water volume of infiltration into the sinkholes, and the runoff decrease in the Alcedo Stream after the drilling of the tunnel. Precipitation data series (1970–2000) and four spatial variables (outcrops, shallow deposits, slope and vegetation) were used to create a rainfall–runoff model. Presently, geomorphological evidence includes 4 main sinkholes (8–12 m long), 13 minor hollows, 7 swallow holes and a 120 m^2 area with subsidence evidence, which developed over Quaternary deposits covering karstified limestone bedrock. These active swallow holes capture the surficial runoff of the Alcedo Stream throughout the year. Because of that, the upper reach of the stream is isolated from the rest of the fluvial network. The sudden development and active growth of cover-collapse sinkholes is consistent with 1) the drop of the water table by tunnel drainage after excavation, 2) the increase in percolation from surficial runoff and 3) the internal erosion of the overlying Quaternary sediments by suffosion processes. The estimated mean water volume of infiltration into the sinkholes is close to 308,903 $m^3\ yr^{-1}$, and the Alcedo Stream runoff in the natural base level has decreased by 35% throughout the year after the tunnel perforation. At present, the process is active and it is expected to progress in the future.

1. Introduction

The development of cover-subsidence and cover-collapse sinkholes constitutes the most common geohazard in karst landscapes. These phenomena can develop naturally due to a cluster of inter-related processes, but their increasing frequency is usually related to sudden changes in the natural hydrogeological system induced by human activities like water pumping, quarry de-watering or tunneling (Newton, 1986; Tihansky, 1999; Waltham et al., 2005; Waltham, 2008; Gutiérrez et al., 2014). Active sinkholes resulting from human activity have been widely reported (e.g. Gutiérrez-Santolalla et al., 2005; Guerrero et al., 2008; Galve et al., 2012; Song et al., 2012).

Tunnels in karst areas may generate multiple engineering and environmental problems (Milanovic, 2004; Casagrande et al., 2005; Alija et al., 2013). A tunnel works as a drain, producing a drop in the water table on the drilled aquifers (Raposo et al., 2010). The extent of the water table depression is conditioned by the depth of the tunnel below the original water table, as well as the aquifer characteristics. For this reason, tunneling usually produces hydrogeological impacts related to the drop of water table, such as the total or seasonal drying up of streams, springs, wells and wetlands (Vincenzi et al., 2009, 2014). This causes important damage on the environment and conflicts with the regional population, creating problems related to drinking water supply, agriculture, tourism and other activities (Sjolander-Lindqvist, 2005; Chiocchini and Castaldi, 2011).

Drilled from 2005 to 2009, Pajares Tunnels are framed within the project for the Pajares Railway By-pass, which aims to replace the

* Corresponding author.
E-mail addresses: pvalenzuela@geol.uniovi.es (P. Valenzuela), mjdominguez@geol.uniovi.es (M.J. Domínguez-Cuesta), m.melendez@igme.es (M. Meléndez-Asensio), mjimenez@geol.uniovi.es (M. Jiménez-Sánchez), joseantonio@saenzdesantamaria.es (J.A.S. de Santa María).

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current railway line over the Pajares Mountain Pass by a new high-speed line between Asturias and León (NW Spain) (Fig. 1). The tunnels cross the Cantabrian Range, a mountainous area characterized by a complex geological structure and a great lithological variety, which can be grouped in three main kinds of Paleozoic materials (Míguez Bailo, 2005): (i) shale and shale–sandstone (San Emiliano, Oville, Formigoso, Huergas, La Vid, San Pedro, Ermita and Subhullero Fms.); (ii) sandstone and quartzite (Herrería, Barrios, San Pedro, Oville and San Emiliano Fms.); and (iii) calcareous materials (Láncara, La Vid, Alba, Portilla, Santa Lucía, Barcaliente and Valdeteja Fms.).

Pajares Tunnels constitute a complex underground structure with the characteristics of the biggest high-speed railway base tunnels. Their layout between Pola de Gordón (León) and Telledo (Asturias) has a NNW–SSE orientation and reach a maximum depth of 1100 m. It bridges an altitude difference of 414.6 m, showing a continuous longitudinal 16.386‰ gradient descending toward the Asturian side. The structure consists of two parallel single track tubes with a length of 24.9 km and an interior free diameter of 8.5 m in a free circular section of 51.3 m^2. Both tunnels show a separation among axis of 50 m and are connected to each other by means of perpendicular by-pass galleries of 41.25 m long at every 400 m. Its central sector is connected to the outside with two evacuation tunnels: Buiza intermediate access adit (5.5 km long and 6% gradient) and Folledo intermediate access adit (2.1 km long and 13% gradient) (Míguez Bailo, 2005; Míguez Bailo et al., 2007). The characteristics of these tunnels comply with the aerodynamic and safety conditions required in a high-speed railway line. In this context, the groundwater inflow into the tubes poses a serious challenge, taking into account that the railway line was designed to allow speeds over 250 kph (Míguez Bailo, 2005).

Different drilling methods were used during the construction of the Pajares Tunnels. The perforation of the two main tunnels was performed through the use of TBMs (Tunnel Boring Machines). The support of the tubes consists of high-strength concrete precast rings with a thickness of 50–60 cm. Each ring is divided in 7 segments. Concrete with different characteristic strength (between 40 and 110 MPa) was used to fabricate the rings depending on the structural requirements in each section of the tunnels (Segura Pérez and Martínez Díaz, 2009; Arlandi Rodríguez et al., 2009). The Buiza gallery was also drilled with a TBM, but the Folledo gallery and the by-pass galleries were drilled by using NATM (New Austrian Tunneling method). In those cases, different support methods were used in each case taking into account the lithology variations (Arroyo Cedrón et al., 2009). The complexity of the project made it necessary to divide it into four different contracts. The southern sector of the tunnels, under the study area, was included in the Contract 1, awarded to the Spanish companies FOMENTO DE CONSTRUCCIONES Y CONTRATAS S.A. and ACCIONA INFRAESTRUCTURAS S.A. In this section, the main tubes were perforated through the use of two single shield TBMs: a NFM-Wirth single shield in the east tube and a Herrenknecht single shield in the west tube (Míguez Bailo, 2005).

Apart from the aforementioned geotechnical and constructive aspects, the construction of the Pajares Tunnels remained a major challenge in other aspects, such as the management of the extracted material (Ferreras González et al., 2009; Campomanes Sánchez, 2009; Cayón Martínez et al., 2009) or the design of a pumping system and the pumping water treatment (Arnanz González et al., 2009; Díez Cadavid and Luengo Troitiño, 2009).

In March 2007, a section of the tunnels (within the Contract 1) was drilled 450 m below the Alcedo Valley (León, N Spain) (Fig. 1). In the following summer, two sinkholes appeared at the bottom of the valley, affecting the main stream, and another six sinkholes appeared over the following 14 months; due to this situation, in April 2008, the Alcedo Stream was losing 40% of its flow (43 l s^{-1}) (Álvarez Díez et al., 2009). Although the stream was channeled with concrete along a 370 m-long section in 2009 to prevent water infiltration, water loss into the underlying aquifer was not avoided. In 2010, an intense rainfall period

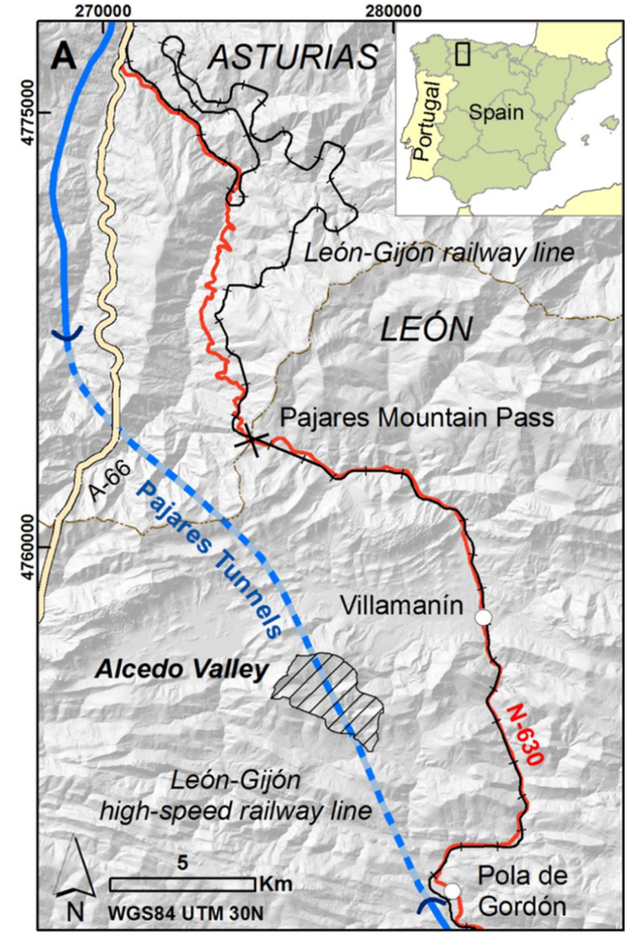

Fig. 1. Geographical location of the Alcedo Valley.

produced the flooding of the stream and the undermining and fracturing of the channel due to the development of new sinkholes. Presently, some of these active sinkholes keep on growing and drain all the surficial runoff from the upper catchment of the Alcedo Valley, drying up the Alcedo Stream throughout the year.

Some hydrogeological studies before and during the perforation of the tunnels have been undertaken, but very few hydrogeological data have been published (Álvarez Díez et al., 2009; Garrido Ruiz et al., 2009; Arnanz González et al., 2009). Nowadays, works continue on the tunnels and in the Alcedo Valley, constituting a controversial issue.

The main goals of this paper are (i) the geomorphological characterization of the sinkholes developed on the Alcedo Valley and (ii) the estimation of the mean water volume that drains into these sinkholes and the subsequent runoff decrease in the Alcedo Stream.

2. Description of the study area

The Alcedo Valley is a small watershed (6.87 km^2) located on the southern flank of the Cantabrian Range (Sierra del Rozo, N of León, Spain) with an altitude ranging between 1803 and 1160 m a.s.l. (Fig. 1). The area, characterized by continental high mountain weather, is under pluvionival conditions with average temperatures below 10 °C and mean precipitation between 1000–1300 mm yr^{-1}, reaching a peak during the winter–spring period (Galán, 1990; Garrido Ruiz et al., 2009). Most of the valley preserves its natural vegetation of beech, oak and birch alternating with bushland and grassland. Due to its ecological interest, this uninhabited area has been included in the UNESCO Biosphere Reserve "Alto Bernesga" (Rodríguez Fernández, 2011).