Engineering Geology 102 (2008) 62–73

Contents lists available at ScienceDirect

Engineering Geology

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

A sinkhole susceptibility zonation based on paleokarst analysis along a stretch of the Madrid–Barcelona high-speed railway built over gypsum- and salt-bearing evaporites (NE Spain)

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ARTICLE INFO

Article history:
Received 6 March 2008
Received in revised form 26 June 2008
Accepted 16 July 2008
Available online 30 July 2008

Keywords:
Sinkhole
Susceptibility zonation
High-speed railway
Paleokarst

ABSTRACT

This paper presents a methodology for producing sinkhole susceptibility zonations along linear infrastructures based on the analysis of the subsidence and dissolution features exposed in the adjacent cuttings and the distribution of karstic depressions. The proposed approach have been applied to a 24 km long stretch of the high-speed Madrid–Barcelona railway built on halite- and glauberite-bearing evaporites of the Tertiary Zaragoza Gypsum Formation. More than 100 km of this railway line have been built over salt-bearing Tertiary evaporites and trains run at a cruising speed of 300 km/h. The susceptibility assessment has been restricted to the sections located in karstic depressions (2.98 km) and trenches excavated in the ground (13.93 km). A low susceptibility has been assigned to the sections built on thickened alluvium of the Huerva fluvial system (0.5 km) and those in which the evaporites exposed in the cuttings do not show evidence of dissolution or subsidence (3.52 km). A total of 4.5 km have received an intermediate susceptibility. The cuttings in these sections show sagging structures, cavities above the railway roadbed, irregular rockhead or shallow alluvium–bedrock boundary. A high susceptibility has been assigned to a total of 6.59 km. These correspond to cavities and collapse structures that reach the railway roadbed (3.61 km) and karstic depressions generated by interstratal karstification and subsidence (2.98 km). The paleokarst and geomorphic evidence in these sections reveals that cavities, either air- or sediment-filled, do exist beneath the railway. The distribution of the karst features and susceptibility zones seems to be controlled to a large extent by the lithostratigraphy of the bedrock; wedging out of the evaporites to the SE and increase in the proportion of halite and glauberite to the NW. The proposed zonation could be used as the basis for the selection of the stretches where further investigations and the application of mitigation measures would have a better cost/benefit ratio.

1. Introduction

Deflections caused by subsidence on railways entail a reduction in the safety and comfort of this means of transport (Gourc et al., 1999). Some examples of railway lines damaged by settlements caused by other processes than dissolution-induced subsidence include: (1) Railway lines in the Yangtze Delta, including the magnetic suspension high-speed railway of Shangai, have suffered from differential subsidence due to aquitard consolidation induced by over-exploitation of multilayered aquifers (Yin et al., 2006); (2) Numerous railways built over discontinuous or continuous permafrost in North America (Harris, 1986; French, 2007), Russia (Harris, 1986), China (Yusheng et al., 1983; Wu et al., 2005) or the Alps (Gude and Barsch, 2005) have been adversely affected by subsidence generated by thawing of ground ice (thermokarst), and some of them require frequent and costly maintenance works; (3) Mining subsidence involving in some cases the rapid occurrence of collapse depressions has damaged the Pennsylvania and New York lines in the United States (Klugh, 2001) and the Furness railway in northwest England. In 1974, a sinkhole 90 m across and around 70,000 m^3 in volume formed catastrophically beneath the Missouri–Pacific railroad in Hutchinson (Texas). The crater resulted from the upward propagation (stoping) of a cavity created by solution mining of a Permian salt unit located at a depth of about 130 m (Walters, 1978; Johnson, 1998); (4) Sagging caused by peat consolidation has locally deformed the Rannoch Moor railroad track in Scotland (Waltham, 1989).

The literature review carried out for this study indicates that one of the main causes of subsidence-related damages and accidents in conventional railways corresponds to the occurrence or activity of sinkholes in carbonate and evaporite karst terrains. In a significant proportion of the documented cases, subsidence results from the reactivation of pre-existing sinkholes and/or has been triggered or accelerated by human-induced hydrological changes. The Manchester-Crew line in northeast England requires frequent maintenance works (raising the track, reballasting) along an active subsidence

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doi:10.1016/j.enggeo.2008.07.010

depression whose activity was accelerated by uncontrolled extraction of brine from the karstified rockhead of a halite-bearing Triassic formation (wild brining) (Waltham, 1989; Cooper, 2001). In the Harz Mountains of Germany, near Bad Sachsa, dissolution of gypsum has caused a railway to settle more than 40 cm. A laser monitoring system was installed across the subsiding section, which has a slow speed limit. In 1997, a sinkhole around 30 m in diameter formed beneath the track of the Burlington Northern Santa Fe railway in Missouri, causing the derailment of 22 railroad cars, fire from spilled fuel and injuries to personnel. This sinkhole, induced by dewatering to allow mining of limestone in a nearby quarry, has undergone reactivations in 1999, 2000 and 2002 despite intensive grouting programs (Abkemeier and Stephenson, 2003). In Allentown, Pennsylvania, a sinkhole triggered by a rapid decline in the water table provoked by the interception of a phreatic conduit in a limestone quarry undermined a pier of a railway bridge over the Bushkill Creek (Waltham et al., 2005). Other sinkhole damages on railways in the United Sates have also been reported in Pennsylvania (Perlow, 2003), Birmingham, Alabama (Newton, 1984) and Deland, Florida. In Russia, cover collapse sinkholes formed beneath the Moscow–Nizhny Novgorod line have caused the train to derail two times (Tolmachev et al., 1999). In China, sinkholes induced by water withdrawal have caused service interruptions in the Beijing–Jiulong railway line (Lijun, 1997). According to Chenguoliang (1990), as many as 7 sinkholes, all of them located close to pumping wells, have occurred beneath the Litang–Zhanjiang railway line. This author also reports that a 32 km long stretch of the Guiyang–Kunming line between Ganhaizi and Yangtianchong cities is frequently affected by collapse sinkholes. In Fakou city area (China), where more than 1950 new sinkholes have been inventoried, subsidence has led to the abandonment of a total length of 45 km of railways (Yu, 1994; Gongyu and Wanfang, 1999). Wenhui (1990), in a compilation of “geological calamities” in Chinese railways, indicate that the detrimental effects generated by the numerous sinkholes reported in the railway network include the derailment of two trains, more than 2000 hours of traffic suspensions and maintenance and repair costs of thousands of millions of RMB (1 renminbi ≈ 0.13 US$).

van Hecke et al. (2003) indicate that high-speed railways are those that allow trains to run at speeds higher than 250 km/h. It is considered that 15 mm is the maximum settlement tolerable for a train running at that velocity. With higher vertical deflection the train may derail and with lower values of vertical strain, velocity reductions may be necessary to diminish vibrations (Miura et al., 1998; Woldringh and New, 1999). At least three high-speed railways have been adversely affected by subsidence: (1) In Sweden, the speed of the train that connects Goteborg and Malmö had to be reduced due to vertical deflections of 6 mm related to the presence of soft soils in the ground (Woldringh and New, 1999); (2) According to the newspaper Taiwan News, in 2006 a high-speed train derailed two times during the testing period due to differential settlements related to consolidation of aquitards in the Yangtze Delta; (3) In 1993, a TGV train derailed at a speed of 294 km/h at Haute Picardie (France) due to a sinkhole formed over a buried trench from World War One and triggered by heavy rain (Cui et al., 1995; Brabie, 2005).

The presented literature review reveals that railways are particularly sensitive to ground subsidence, especially collapse sinkholes. The presence or occurrence of a sinkhole in a railway track may imply costly maintenance works, service interruptions and in the worst situations, the derailment of the train accompanied with losses in human lives. Some of the factors that affect the probability of a train derailment due to sinkholes in karst areas depend on: (1) The length of the railway built on ground susceptible to sinkhole activity; (2) The sinkhole hazard including the probability of occurrence of sinkholes and their severity, which refers to the size of the sinkholes and the velocity at which the settlement occurs (subsidence rate) (Gutiérrez et al., 2008b, d). Obviously, collapse sinkholes that form in a sudden way without showing any previous noticeable sign of instability are the most hazardous ones; (3) The vulnerability of the infrastructure, which depends largely on the incorporation of sinkhole protection measures in its design and the installation of monitoring devices linked to a warning system capable of detecting subtle deformations and anticipating the formation of collapse sinkholes (Tolmachev et al., 1999; Guerrero et al., 2004); (4) The frequency of the trains and their velocity. The latter determines their tolerance to settlements and the breaking distance (Miura et al., 1998; Esveld, 2001).

In this paper we present a methodology for producing sinkhole susceptibility zonations along linear infrastructures based on the analysis of the subsidence and dissolution features exposed in the adjacent cuttings. The proposed approach has been applied to a 24 km long section of the high-speed Madrid–Barcelona railway between the Huerva and Ginel River valleys in NE Spain (Fig. 1).

2. The high-speed Madrid–Barcelona railway and the underlying evaporite karst

The high-speed Madrid–Barcelona railway, with a total length of 636 km, connects the two largest Spanish population centres and passes through the cities of Guadalajara, Calatayud, Zaragoza and Lérida (Fig. 1). The Madrid–Zaragoza–Lérida stretch (447 km), with an initial budget of 4300 million euros, was inaugurated on October 2003. The first commercial high-speed railway arrived in Barcelona on February 2008. Trains run on this railway at a cruising speed of 300 km/h, may reach 200 m in length, a weight of 322 tones and a capacity of 316 passengers. In 2007, around 2.5 million passengers travel annually on this high-speed railway (Madrid–Lérida stretch), with an average of about 40 commercial journeys/day. The safety measures implemented against subsidence include daily reconnaissance journeys to check the state of the railway before the commercial trips.

Previous to its construction, the governmental body in charge of this railway line (Gestora de Infraestructuras Ferroviarias, GIF) detected three main sectors with potentially unstable ground between Madrid and Lérida (Fig. 1): (1) around Calatayud city, a 12 km long stretch within the Calatayud Tertiary Basin where the railway has been built on alluvium-mantled evaporites; (2) in Zaragoza area, a section with a total length of about 90 km built on evaporites of the Ebro Tertiary Basin extensively covered by pediment and terrace deposits (Pérez del Campo, 1989); (3) a stretch which starts around 30 km to the southeast of Zaragoza, at the northern margin of the Ebro River valley, where the railway track is underlain by swelling shales (not shown in Fig. 1).

In Calatayud city area (Fig. 1), the high-speed railway runs along 12 km on soft and water-saturated alluvium of the Jalón River floodplain underlain by strongly karstified evaporites (Gutiérrez et al., 2008a). Here, the horizontally lying evaporites of the Calatayud Gypsum Formation include halite and glauberite units in the subsurface (Ortí and Rosell, 2000; Sanz-Rubio et al., 2003). Cover collapse sinkholes and large subsidence depressions as much as 1 km long have been reported in the Jalón River floodplain (Gutiérrez, 1996, 1998; Gutiérrez and Cooper, 2002). In November 2003, a collapse sinkhole 600 m^3 in volume formed suddenly beneath a five-storey building with pad foundations in Calatayud city (Fig. 2A). The building, located at about 0.6 km from the high-speed railway, was finally demolished and the direct losses have been estimated at 4.8 million euros (Gutiérrez et al., 2004). On September 2006, a sinkhole attributable to evaporite dissolution was detected on a paved road located next to the high-speed railway nearby Calatayud city (Fig. 2B).

In Zaragoza city area, approximately 90 km of the high-speed railway is underlain by the halite- and glauberite-bearing Zaragoza Gypsum Formation. The railway splits into two branches in Zaragoza (Fig. 1); the southern one bypasses the city crossing the Huerva River valley over a viaduct and the northern one crosses the city through the train station. Two main sections can be differentiated in this area (Fig. 1): (1) between Lumpiaque village and the Huerva Valley, the railway, including the northern branch in Zaragoza, is mostly built on permeable mantled